What are the greatest opportunities for PV to contribute to rural development?

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Abstract

Minigrid systems powered by solar photovoltaics and battery storage are being deployed around the world to provide basic energy access and facilitate economic development. We use a minigrid simulation and optimisation tool that we have developed to assess various minigrid options in meeting the growing electricity demand of a community in rural Uttar Pradesh, India, in terms of the reliability of the service they provide, the cost of electricity, and total greenhouse gas emissions. We assess the breakeven distance at which off-grid minigrids are favourable in comparison to extending an unreliable grid network with a minigrid backup system, both with and without a carbon price. We suggest that policy recommendations that would encourage the use of minigrids for sustainable rural development, for example allowing subsidies to be available for system expansions and minimum service reliability requirements.

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1. Introduction

Over one billion people live without access to electricity and many more lack a safe, reliable and legal source of power [1]. Countries with aspirations to increase energy access to their populations regularly rely on extending the existing grid network but this requires significant infrastructure investments and the reliability of service is often poor which hinders the potential for economic development. The use of decentralised electricity systems known as minigrids, independent of the national grid network, can provide locally generated power to communities in rural and remote areas. Minigrids powered by solar photovoltaics (PV) and battery storage are becoming increasingly attractive for rural electrification across the world owing to the decreasing costs of the technology, but detailed analyses of their effectiveness at meeting growing electricity demand in the long-term are limited.

Evaluating the comparative effectiveness of minigrids supplied by PV and storage, incumbent technologies like diesel generators, or a combination of the two options can provide insights into the policies the would best promote rural development in the future. Furthermore, the prospective coexistence of minigrid systems and the expanding grid network has not been explored in detail and their potential to work together to provide reliable power to communities together is largely unknown. Finally, the greenhouse gas (GHG) emissions associated with the deployment of these systems are often disregarded as the price sensitivity of the communities receiving them is the determining factor in the design of the systems. Omitting the impact of the GHGs emitted by deploying the system, and those mitigated by reducing the usage of kerosene lamps or diesel generators, overlooks a key criterion in delivering sustainable development for all.

Here, we analyse opportunities for PV and battery storage minigrids to provide power for economic development and to mitigate GHG emissions in comparison to other minigrid options and grid-tied systems. Using a simulation and optimisation tool, CLOVER (Continuous Lifetime Optimisation of Variable Electricity Resources), we predict the impact of deploying systems in an example village in India and assess the suitability of current policies in meeting this objective.

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2. Methods

2.1. Community description

India has the largest off-grid population of any single country in the world [2] and despite ambitious plans by the Government of India to bring power to every village and household, many communities continue to live without access to electricity. In this work we consider a typical community in rural Bahraich District in the northern state of Uttar Pradesh, India. Inhabitants of this district are predominantly subsistence farmers and manual labourers with incomes well below the poverty lines of both the World Bank and India, and access to electricity is uncommon [3]. Most households rely on traditional fuels for lighting and cooking, for example kerosene lamps and firewood stoves, which are expensive, have serious negative health impacts and emit large quantities of GHGs [3]. Extension of the national grid network is a common strategy for rural areas in developing countries, but the reliability of service is
often low. Grid power is heavily subsidised [4] but in rural areas of Bahraich District an average of only around nine hours of supply per day is available.

We consider a typical community of 100 households with no prior access to electricity, and model the situation where such a community receives a minigrid installation. The minigrid system is designed to meet the basic domestic needs of the households, such as lighting, phone charging, fans and televisions, as well as income-generating productive uses such as workshops, agro-processing mills, and home industries to facilitate and encourage the development of the village. The power demand by the village is modelled to evolve over time in such a way that demand for electricity for productive use increases over the years; this is a model of economic development of the community and is described in Section 2.5.

2.2. CLOVER minigrid simulation and optimisation tool

We have developed a minigrid simulation and optimisation tool called CLOVER (Continuous Lifetime Optimisation of Variable Electricity Resources). CLOVER uses real-life meteorological data and statistically generated load data to simulate and assess a minigrid system of a given size at an hourly resolution over a user-defined time period by calculating the energy produced by the generation sources, the load demand of the community, and the available power accumulated in the battery storage [5]. At the end of each time period, typically several years, the performance of the system is calculated and analysed using several metrics including the amount of energy from each source which was generated, used, and dumped; times and amounts of unmet energy demand; the times of blackout periods when power is not available; a breakdown of costs incurred and GHGs emitted in deploying the system; the cost and GHG savings from mitigating the usage of kerosene lamps; and the levelised cost of used electricity (LCUE). LCUE differs from the more common metric of levelised cost of electricity (LCOE) in that only electricity used by the community is counted towards the LCUE, which provides a better assessment of the value of the power to the community by omitting energy that is dumped. These measures can be used to quantify how well a given system meets the community demand.

CLOVER can be used to simulate various renewable generation sources and storage capacities, either individually or in concert as part of a hybrid system, in order to provide recommendations about the most appropriate system design to meet the needs of the community over a given time period. The technologies available in the model are PV, battery storage, wind turbines, micro-hydropower, diesel generation and a grid network of any level of reliability. The optimisation process simulates the performance of each combination of components, within a range of sizes, and evaluates each system in turn. The systems that perform satisfactorily according to a user-defined sufficiency threshold condition are then compared against one another through a user-defined optimisation criterion, which selects the optimum system design. For example, in this work we assess systems to be sufficient if they meet a defined threshold of hours of electricity service per day, and the optimum system to be the one that does this at the lowest LCUE.

2.3. Optimisation process

Once an optimum system $O_i$ is chosen for the $i$th time period $T_i$, the optimisation process continues for the next time period $T_{i+1}$. The system $O_i$ is now the smallest combination of components considered for $T_{i+1}$ and a range of system sizes larger than this are simulated, and the process continues as before. By considering several re-optimisations over time the process allows the system to expand to meet growing demand efficiently and effectively as infrastructure investments are made only when necessary. This avoids oversizing the system and reduces the wastage of resources, mimicking the process undertaken by many minigrid developers operating in the field of rural electrification. An outline of this continuous optimisation process is shown in Fig. 1 with solid lines showing which sizes of systems considered by the process and the dashed lines showing which configurations are deemed sufficient. The numbered green squares show the optimum systems $O_1$, $O_2$ and $O_3$ selected by the process for the time periods $T_1$, $T_2$ and $T_3$, respectively.
2.4. Incorporating conventional generation technologies

Renewable technologies are favoured by minigrid developers owing to their relative autonomy, sustainable energy production and decreasing costs; however, conventional sources can still provide benefits to rural communities and as such are integrated into the CLOVER modelling framework.

A backup diesel generator can supply the minigrid when power from renewable generation and storage is not available; such a situation is defined as a blackout period. To do this the simulation identifies the times when it would be most appropriate for the diesel generator to be used, for example during a blackout period when demand for electricity is the highest, and switches itself on for as many hour-long periods as necessary to make the minigrid system meet the sufficiency condition. This ensures that every configuration of system sizes is deemed sufficient. Systems that meet the sufficiency condition via renewables and storage alone do not use diesel as a backup.

CLOVER incorporates an unreliable grid network by forming a grid-tied minigrid: when grid power is available the community uses it via the minigrid distribution network, or when it is not the minigrid system is used as an independent backup. This can be used to increase system reliability as a whole and all system performance metrics are considered for the holistic system. Furthermore the charging of minigrid battery storage using grid power for later usage during grid downtime periods, referred to as grid charging, can be incorporated if permitted by the user.

2.5. Community electricity demand

The electrical load demanded by the community is one of the key inputs into the CLOVER model. The demand will vary not only during the day but also throughout the year in response to seasonal changes, affecting for example the times when lighting is required and when agricultural processing activity is highest. For this reason we incorporate a dynamic and varying load profile that increases as the village economy develops.

As described in [3], the utilisation of each electrical device in the community (the probability that it is in use or not at a given time) is assumed to be independent from all others and varies both hourly and seasonally. By considering the total usage of all devices at a given time we calculate the cumulative load profile, and this load profile of total electricity demand comprises the underlying requirements of the community to be met by the minigrid system. Figure 2 shows the average daily electricity demand of the community (radial axis) that follows a continuous anticlockwise path from the centre and grows over time (twenty years shown).
2.6. Performance analysis criteria

We have used CLOVER to simulate minigrids with three combinations of options for power generation: 1) PV and battery storage, 2) a diesel generator only, and 3) a hybrid system of PV and battery storage with a backup diesel generator. First these are assessed as an off-grid minigrid and later as part of a grid-tied system, both with and without grid charging. The range of component sizes was unbounded to the extent that a suitable system could be designed to meet the sufficiency condition without other constraints before the optimum was selected. We consider five consecutive optimisation periods of four years each.

We use the blackout percentage, i.e. the proportion of time when electricity is unavailable, as the sufficiency threshold. This is the most important performance metric from the point of view of the community as the availability of power is critical in facilitating energy access and economic development. We choose the lowest LCUE to be the optimisation criterion; this ensures that electricity is supplied at the lowest cost for each blackout percentage. This benefits both the community who receive the most affordable electricity and the minigrid developer who can generate the best return on investment for the system. These two criteria are some of the most important considerations in minigrid designs for rural areas of developing countries.

We also consider the climate change impact of deploying minigrids for rural electrification. GHGs are emitted during the production, transportation, installation, usage and maintenance of minigrid components and using life cycle analysis we assess the total GHGs emitted during the considered lifetime. We also consider the additional impact of kerosene usage for lighting under the assumption that during blackout periods occurring in times of darkness the community will revert to using kerosene lamps to meet their lighting requirements. Less reliable systems with greater blackout percentages will result in more kerosene usage and therefore greater GHG emissions.

Finally, we consider the distance at which off-grid minigrids become preferable in comparison to grid-tied systems. The extension of the grid can provide low-cost power but requires significant infrastructure investments [6]. At a certain distance a breakeven point occurs at which the cost of grid extension, and the minigrid required to boost its reliability to a given threshold, outweighs the cost of an equivalently reliable off-grid minigrid system. This is known as the breakeven distance and is the point beyond which an off-grid system should be installed instead of investing in grid extension.

3. Results and discussion

3.1. Off-grid minigrids

PV and storage, diesel, and hybrid minigrids were simulated for the community over five consecutive 4-year periods at a variety of blackout percentage thresholds from 1% to 50%, or around 15 minutes per day to 12 hours of blackout periods per day. For each blackout fraction, the optimisation process selected the system configuration with the lowest LCUE at the end of each time period. The solid lines in Fig. 3 show a) the total lifetime LCUE (the sum of the lifetime discounted costs divided by the sum of the discounted energy used) and b) the total GHG emissions.
from the power system, while the dotted lines in Fig. 3(b) show the additional GHGs emitted from the community using kerosene lighting when electricity services were unavailable.

Fig. 3. (a) The LCUE of three types of minigrid systems and (b) their total GHG emissions (solid lines) and the additional impact of kerosene used for lighting (dotted lines).

The LCUE of all minigrid types is higher for smaller blackout thresholds as additional generation or storage capacity is required to meet the final fractions of demand. For PV and storage systems, this means that there is a significant premium on installing the most reliable systems: when blackout percentage of 10% is permissible the LCUE is only $0.35/kWh, but for one of 1% the cost of electricity increases to over $0.50/kWh. Diesel systems also become more expensive at low blackout percentages. This is because diesel generators must run at around 35% of their rated capacity or higher [7] and when the demand is lower than this threshold then the excess generation is dumped, reducing their efficiency and increasing the cost of electricity.

PV and storage systems are the lowest-LCUE option for blackout percentages of 5% or more: this is because PV and storage installed early in the system lifetime yield a consistent energy return with low operating costs. The opposite is true for diesel systems. Investing in a diesel system is cost-effective in the short term, but in the long term being locked-in to a system with high running costs is more expensive. Hybrid systems at high blackout percentages are supplied mainly by renewable power, but for more reliable hybrid systems the final fractions of demand are met by diesel. Using both generation options avoids the high LCUEs experienced by PV and storage systems at low blackout percentages and constitutes the lowest-cost option.

Similarly to the system LCUE, the most reliable systems require greater generation and storage capacity and hence experience higher system GHGs. Despite considerable GHGs embedded in the manufacture of PV and storage systems, their negligible emissions during usage means that renewable generation emits only around half of the GHGs of either diesel or hybrid systems at any level of reliability, as shown in Fig. 3(b). When GHG emissions from kerosene are included, however, they perform comparatively less favourably than before in terms of emissions: if periods of blackouts occur for PV and storage systems they are most likely to happen in the evenings and nighttime periods, when there is no PV generation and the stored energy in the batteries has been depleted by earlier use, that correspond exactly with when demand for kerosene lamp usage is the highest. Diesel-based systems do not suffer from this issue as they are used most frequently during these high-demand periods, however PV and storage systems remain the lower-GHG option overall at any blackout percentage considered here.

3.2. Minigrids and an unreliable grid network

In this section we consider two options: an off-grid PV and storage minigrid, and an unreliable grid connection with a minigrid backup. Both configurations are optimised to yield the same blackout percentage at the lowest LCUE over the five time periods of four years each. Of the grid-tied systems, two cases are simulated: one where any battery storage is charged through the minigrid only, and one where electricity from the grid is used to charge the batteries. We also consider the impact of a carbon price of $30/tonneCO$_{2eq}$ to assess the long-term viability of
the deployment strategies, as carbon prices may be introduced in the future. Figure 4 displays the breakeven distance at which off-grid minigrids become more cost-effective to deploy rather than extending the grid network in each of the four scenarios and at a range of blackout percentages and community sizes.

When no carbon price is considered, the dominant variable in both cases is the community size. When the grid is extended to larger communities the cost is shared between more households and this makes any grid-tied system more cost effective. High breakeven distances of 60 km or more were found at all blackout percentages, so that only the smallest communities furthest from the grid would be suitable for off-grid systems. Maximising the usage of grid electricity in the grid charging case results in a lower LCUE and higher breakeven distances as a result.

The blackout percentage becomes a significant factor in the grid-tied case when a carbon price of $30/tonneCO₂eq is introduced. Carbon-intensive grid electricity is disincentivised and this favours off-grid PV and storage minigrids, in particular at lower reliabilities. This is owed in part to kerosene usage: although PV and storage systems are less effective than other systems at meeting evening demand, grid-tied systems perform even worse as the grid is most commonly unavailable during the evening peak times. When considered in addition to the high GHG output of grid-tied systems when electricity is available, this results in off-grid systems being more favourable than grid extension for larger communities that are closer to the grid in comparison to the case with no carbon price. Furthermore, the smallest communities would benefit from off-grid systems even if the grid were immediately available, for all but the highest reliability requirements. Despite the premium charged on carbon-intensive grid electricity by the introduction of the carbon price, its subsidised price is too low for this to make a significant impact in the grid-charging case. The breakeven distances are increased slightly compared to when no carbon price is introduced, however, and this would enfranchise a limited number of small rural communities into favouring off-grid minigrids.

3.3. Policy implications

We have shown that PV and storage minigrids can be effective in facilitating rural development through electricity access, but current policy mechanisms could be modified in order to be more effective. Often, minigrid subsidy schemes provide support only for the initial deployment [8], and this can incentivise developers to install systems that are too large in order to take fullest advantage of the available funding, wasting resources. If subsidies were available for developers who wish to add capacity to existing minigrid systems, as modelled in this work, the allocation of resources would be more effective at distributing funds when appropriate.

If policies aim to encourage sustainable development and mitigate GHG emissions through the deployment of PV and storage minigrids, then the reliability of the system should be prioritised. Current reliability requirements of
supplying power for at least 14 hours per day [8] could be ineffective at fully mitigating kerosene usage, and GHG emissions could remain high. Furthermore, to provide uninterrupted power via PV and storage, minigrids may be counterproductive; however, at blackout percentages of around 5%, or just over one hour of blackouts per day, total GHGs are minimised and PV and storage systems have the lowest LCUE of any generation type. This could provide a more suitable target.

Introducing a carbon price of $30/tonneCO$_{2}$eq would incentivise the deployment of off-grid PV and storage minigrids, but only if grid power is not used to charge batteries. To mitigate the high GHG emissions associated with grid charging either off-grid systems could be subsidised to make them more financially attractive, or greater renewable generation could be integrated at the utility scale.

4. Conclusions

We have modelled and analysed the effectiveness of PV and storage, diesel, and hybrid minigrid systems in meeting the growing electricity demand of a rural community as its economy develops. By selecting the lowest-LCUE systems for a given blackout percentage we have shown that PV and storage systems are the most cost-effective option for all systems other than those with the highest reliability requirements, and are also the option which yields the lowest lifetime GHGs both with and without the consideration of kerosene emissions.

Through comparison to an unreliable grid network improved by grid-tied backup minigrids, we have assessed the break even distances at which off-grid systems become favourable for a range of community sizes and blackout percentages. Introducing a carbon price would incentivise more communities to be given access to electricity via an off-grid minigrid, however, if grid charging is available, then utility-scale interventions may be required to mitigate the high GHGs from this option. Current minigrid policies could be modified to incorporate expanding system sizes and deliver more appropriate financing in response to growing demand as the village economy grows.

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References

[1] International Energy Agency (IEA) and the World Bank. Sustainable Energy for All 2017 - Progress toward Sustainable Energy (Summary), 2017; World Bank, Washington, DC.


