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Off-grid solar photovoltaic systems for rural electrification and emissions mitigation in India

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ABSTRACT

Over one billion people lack access to electricity and many of them in rural areas far from existing infrastructure. Off-grid systems can provide an alternative to extending the grid network and using renewable energy, for example solar photovoltaics (PV) and battery storage, can mitigate greenhouse gas emissions from electricity that would otherwise come from fossil fuel sources. This paper presents a model capable of comparing several mature and emerging PV technologies for rural electrification with diesel generation and grid extension for locations in India in terms of both the levelised cost and lifecycle emissions intensity of electricity. The levelised cost of used electricity, ranging from $0.46–1.20/kWh, and greenhouse gas emissions are highly dependent on the PV technology chosen, with battery storage contributing significantly to both metrics. The conditions under which PV and storage becomes more favourable than grid extension are calculated and hybrid systems of PV, storage and diesel generation are evaluated. Analysis of expected price evolutions suggest that the most cost-effective hybrid systems will be dominated by PV generation around 2018.

1. Introduction

Developing countries with ambitions both to expand access to electric power and to meet national and international carbon emissions targets need to consider the emissions implications of alternative development pathways [1]. Such countries may also benefit from the opportunity to adopt more innovative energy technologies than developed nations, whose energy economy may already be 'locked in' to conventional, and typically high carbon, power sources.

Diesel generators are a common source of off-grid electricity as they provide low-cost power [2] but with a high carbon intensity [3]. Connection to an electricity grid is often aspired to, allowing flexibility in the power mix and avoiding the need for energy storage, but requires expensive and energy-intensive infrastructure, is slow to reach remote areas and suffers poor reliability in such regions [4,5]. Renewable sources offer the lowest carbon intensity of generated power but suffer from varying availability and high initial costs, with intermittency in supply leading to the need for storage.

Solar photovoltaics (PV) is the most universally available of the renewables but normally engenders the highest price of electricity. The historically high costs of crystalline silicon based PV have stimulated the development of alternative PV technologies with lower production costs [6], some of these still pre-commercial [7], and others with higher efficiency [8]. These alternatives may be appropriate solutions for the limited capital environment of developing countries but the lack of operational and production experience makes their actual cost and carbon intensity uncertain. Moreover, the relationship between cost, emissions and useful energy for any renewable power source is strongly influenced by the availability of the resource and the demand patterns at the point of energy use.

In planning energy development pathways, policy makers and technology developers need to consider a number of factors. These

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include the life-cycle cost and emissions of the possible solutions (for example diesel, grid extension and renewables) and combinations thereof, the distance to the grid, the renewable resource, the demand profile and how well it matches the generation profile, and finance models. Such factors are particularly important in the evaluation of new technologies in comparison with the incumbents. Whilst previous studies have addressed the performance [9–11], cost [12–17], and carbon intensity [14,18] of PV electricity, sometimes in an off-grid context [19,20], few combine all three [21–25] and none encompass emerging PV technologies. In particular, no previous approaches have addressed mitigation potential from a whole system life-cycle perspective, including storage and accounting for the electricity actually used to satisfy demand.

Here we present a model that combines the levelised cost of used electricity (LCUE), emissions intensity and marginal abatement cost (MAC) of PV power for village electrification, incorporating the options of emerging and established PV technologies in comparison with diesel power and grid extension. We use LCUE as the primary metric of performance as it incorporates issues of mismatch between supply and demand that the levelised cost of generated electricity (LCGE) does not.

The model is applied to locations in rural India, as the country is particularly relevant given its large rural population without electricity [13,26], its rate of economic development, its commitment to emissions reductions of 20–25% in the carbon intensity of its GDP by 2020 relative to 2005 and its national commitment to solar PV. This is embodied in the Jawaharlal Nehru National Solar Mission which targets 20 GW_p of solar PV capacity by 2022, of which 2 GW is expected to be off-grid [27]. Recent announcements by the Indian government suggest this could be extended further, to a 100 GW_p target by the same year [28]. Despite its growth and emissions targets, India's current reliance on imported diesel for off-grid generation is undesirable from economic, emissions mitigation and health perspectives.

We focus on off-grid systems for this first demonstration of the model because off-grid PV is expected to be an important option for more remote locations, it is compatible with subsequent grid extension and it allows direct comparison of technologies within a closed system [29]. Furthermore, the cost and emissions impact of off-grid solar PV act as upper bounds for solar PV in general. In contrast to previous models we have included full life-cycle cost and emission analysis of both existing and pre-commercial PV technologies. Modelling emerging technologies in this way enables critical production or design issues that influence relative cost and emissions intensity to be identified and optimised prior to finalisation of the production route.

The model, although applied here to small standalone PV systems, can readily be extended to other technologies, regions and application contexts. The approach may be useful to policy makers in assessing the economic and policy case for technology deployment because, as we demonstrate below, the LCUE and MAC of renewables are strongly situation dependent.

2. Methods

2.1. Scenario and data

In modelling the off-grid PV system, we consider a village minigrid comprising PV generator, battery storage and low voltage distribution network. We examine four PV technologies at different stages of maturity: monocrystalline silicon (c-Si, mature), cadmium telluride thin-film (CdTe, maturing), concentrator PV (CPV, emerging), and organic PV (OPV, pre-commercial). We also investigate future scenarios in which the costs and embedded energy of OPV reduce dramatically [30–32] as a result of manufacturing innovations such as roll-to-roll processing [7].

The scarcity of reliable production and field performance data for emerging technologies, especially in the context of rural electrification, means that the data used and results presented should be viewed with appropriate caution. For OPV, the current case is based on devices demonstrated with a large-scale installation [33]; the costs are derived from the corresponding technological parameters applied to upscaling manufacturing scenarios [32] and is applicable to deployment in the near-term. Owing to the rapid progress being made in the field of OPV these form a representative estimate of current deployable devices based on the available literature, but with improvements in efficiency, lifetime and stability being reported the performance of the technology is consistently increasing. For this reason we also present the future OPV case, representing the long-term potential of the technology, which uses lifetime and efficiency data predicted for improved devices manufactured at the industrial scale [31,32]. Both the present and future OPV cases consider roll-to-roll processed ITO-free devices to reduce the cost and environmental impact [30]. For comparability to mature technologies the costs of materials and labour for balance of systems and installation are assumed to be the same, although innovative mounting structures made possible from the roll-to-roll production of OPV could reduce the price and embedded energy in the future [33].

Data in this investigation is given in Tables 1–3, which also include assumptions of performance degradation rates and balance of system costs [34,35]. For production of system components in China we assume specific emissions of 1000 gCO_2/kWh and 450 gCO_2/kWh for electricity and thermal energy production respectively [26], and 788 gCO_2/kWh for that of the Indian electricity grid [36].

We consider lithium-ion battery storage technology as significant cost decreases and performance improvements are expected in the future [42]; this could drive the replacement of the incumbent lead-acid batteries that are currently more commonly deployed. For a given PV array size, battery capacity and demand profile the model calculates the net present value (NPV) of the system, the levelised cost of used and generated electricity (LCUE and LCGE), the shortfall of unmet demand, the lifecycle specific emissions and, combined with corresponding data for grid and diesel, a marginal abatement cost (MAC). The LCUE is more useful than LCGE when considering off-grid systems since, particularly for PV and battery systems, excess energy is often generated and dumped which has no value to the end consumers [22]. By considering primarily the LCUE it allows an accurate cost of electricity to be considered and favours well-optimised systems. We use the

Table 1
Key specifications and costs of PV technologies considered.

Parameter	c-Si	CPV	OPV	OPV (Future)	CdTe
Efficiency (%)	16.0 [37]	30.0 [38]	2.0 [30,33]	7.0 [39]	11.9 [37]
Degradation (% p.a.)	1.0	0.5	4.0	2.0	1.0
Cost (Wp)	$0.89 [40]	$1.60 [38][a]	$1.40 [32]	$0.15 [31,32]	$0.75 [41]
Installation (Wp)	$0.51	$0.77	$0.51	$0.51	$0.51
Operation and maintenance (% total cost)	0.5	2.0	0.5	0.5	0.5
Energy meter (Wp)			$0.04		
Inverter (Wp)			$0.55		
Charge controller (Wp)			$0.21		

[a] Including tracker cost.