Sustainable Deployment of Photovoltaics: What's Wrong with the Current Policy and Technology Focus?

Current support programs for renewable energy do not encourage an efficient integration of photovoltaic (PV) systems, light-emitting diodes and batteries. Further, most PV and storage R&D investments are not dedicated to technologies that are likely to address current techno-economic issues. More specifically, most PV feed-in-tariff programs do not yet encourage solar electricity producers to achieve efficient on-site utilization.

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I. Introduction

With about 40 GW of cumulative installed capacity,[1] solar photovoltaic (PV) is moving from a niche application to a major contributor to the global energy mix. When compared to other sources of electricity, PV power generation has several advantages in allowing a reduction in fossil fuels dependence. Solar energy is widely distributed, abundant, clean, has zero fuel costs, and is renewable. However, it has one major drawback: most installation options are still expensive, even with recent cost reductions in PV modules. This article examines the policy and technical shortcomings that currently hamper cost-effective and large-scale adoption of integrated local solar electricity solutions. Most renewable energy market support mechanisms currently favor grid-integrated

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solutions and therefore discourage self-generation, distributed generation, and local power use. Consequently, efficient local integration, such as PV-powered lighting combined with battery storage, receive comparatively less attention than they deserve.

II. What is Wrong with Current Feed-in Tariff Approaches?

Feed-in tariff (FIT) programs are widely recognized as an essential market development tool for the support of renewable energy technologies. However, most FIT programs in major PV markets have not yet evolved to provide adequate incentives for smart local deployment of renewable electricity sources that incorporate storage and complementary demand-side management strategies. Although Germany has began to address some of these shortcomings (with a new residential tariff system), most of the 57 nations that have FIT programs in place still favor grid-connected systems without storage or demand-side management (such as efficient lighting). Furthermore, the bulk of current PV (and wind power) systems installed in European FIT jurisdictions are designed to sell their electricity to local utilities or national grids instead of prioritizing on-site consumption. As a result, most PV systems today are designed to optimize their return on investment (ROI) instead of optimizing overall energy efficiency and demand-response dynamics. This approach implies resistive electricity losses (during transport and distribution)[2] and entails higher transmission and distribution costs.[3] In addition the variable nature of solar energy requires new technical arrangements to ensure grid stability when high penetration levels are reached. Appropriate grid integration architecture and policies need to be adopted to take full advantage of renewable power generation and to foster wider adoption by individuals and local communities.[4] Viable technical integration options such as distributed solar-charging systems for electric vehicles, combining PV-wind production to match peak and baseload demands, and solar-powered street lighting are all promising examples of high value-added solutions to reduce the overall financial and environmental costs of satisfying future electricity needs.[5] Furthermore, proper electricity pricing, accurate generation forecasts, and a more rational responsive policy are needed to allow large-scale load shifting, full-scale development of renewable energy resources, and to achieve significant reductions in GHG emissions.[5,6,7]

Most PV systems today are designed to optimize their return on investment instead of optimizing overall energy efficiency and demand response dynamics.

III. Solar-Powered Street Lighting

To illustrate the shortcomings of current feed-in-tariff programs, consider the case of current street lighting systems, which in most locations require electricity from the grid. Lighting uses more than 20 percent of the electricity generated in modern countries.[8] Therefore, incorporating higher-efficiency lighting technologies such as compact fluorescent lighting (CFL) and solid state lighting based on white light emitting diode (LED) technologies has been long favored as a strategy to decrease electricity use and thus reduce GHG emissions. Today, cost-effective, durable, and low-maintenance LED lighting options are already widely used in automotive and traffic signals. Commercial LED solutions are also available for street lighting markets.

In addition, large-scale LED deployment combined with distributed power generation are promising options for addressing the energy scarcity that characterizes life in areas of the planet poorly serviced by electricity grids. Furthermore, according to the International Energy Agency (IEA), more than

1.6 billion people still do not have access to electricity although they often live in zones with decent solar irradiation. Instead of solar power, expensive and polluting kerosene lighting and small disposable dry batteries are still widely used in rural households. Autonomous lighting systems powered with PV power can be highly competitive, particularly in remote areas and in grid-connected areas serviced by old distribution networks. For example, using solar power can save 60 L of kerosene if a PV-powered lantern is operated for 1,200 hours per year.[9] This carbon abatement potential can reduce the cost of these PV-powered lighting systems by around 19 percent if the carbon price is set at a meager $10/tCO_2$[10] However, to properly match the time scale of solar irradiation with lighting requirements, energy storage needs to be included. Typically, an 8,000 lumens system requires a battery storage system of about 3 kWh capacity, and a solar panel of 0.49 kW power output (providing up to three days' autonomy).

IV. The Same Old Problem: Storage for Clean Dispatchable Power

Electric power storage is currently a key component in vital sectors including vehicle transportation, consumer electronics, and utility power generation. Matching demand and supply of electric power is critical for the large-scale deployment of renewable energy sources, as the current experience of leading jurisdictions such as Spain and Denmark illustrate.[11] This is particularly the case of wind and solar, two fast-growing power generation sources that require technical, regulatory, and policy modifications to accommodate their variable nature. For many years, PV power generation has been successfully demonstrated to provide off-grid power cost effectively for water pumping, lighting, telecommunication, portable power, and cathodic protection in remote areas. PV off-grid street lighting using LED is currently attracting significant interest even when grid power is available.[12] As illustrated in **Figure 1**, off-grid lighting could be adapted to operate under grid-connected architecture, allowing an optimized and utilization of solar energy.

LED technology provides high electricity-to-light efficiency with a system lifetime comparable to PV modules. However, the lifetime of current lead acid battery technologies is comparably quite short and regular servicing is required. Furthermore, the actual operating conditions of PV–battery systems strongly influence the battery lifetime.[13]

Bulk power storage using batteries is one of the most mature and widely accepted technologies to provide continuous power from intermittent sources.[14] For small-capacity systems, battery storage is also a proven technology providing numerous advantages. There are dozen options of battery storages. Specific criteria should be considered when evaluating different battery technologies and the importance of each criterion may depend on the specific application. For example, in the case of stationary applications, installed cost per kWh and lifetime of the batteries are the most important criteria. Lifetime prediction of battery under specific operating conditions is critical to

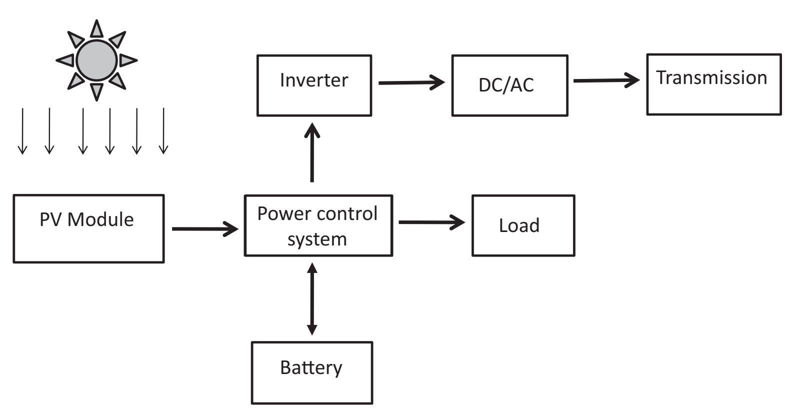

Figure 1: Schematic Representation of a Grid-Connected PV–Battery–LED system
Note that the load (LED), battery, and PV module operate under direct current, which is not the case for distribution and transmission lines.

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identify the most suitable technology.[15] Other parameters including safety, recycling, environmental impact, and raw materials availability are also important but their analysis is beyond the scope of this article.[16]

Currently conventional lead-acid batteries are mostly used for off-grid PV systems. Lead-acid batteries are cost effective in spite of shorter lifetime. Innovative technologies have been developed to improve lifetime and reduce field maintenance of lead-acid batteries.[17] For example, longer lifetime has been obtained using tubular lead-acid batteries design.[18] Other advanced battery technologies with higher number of cycles have been also developed although often at higher initial capital cost.

V. An Integrated Solution Using Optimized Technologies is Needed

When considered separately, PV systems, battery storage, and LEDs are all relatively expensive in comparison to conventional technologies. However, they are potentially more cost-effective when integration and utilization conditions are optimized. Off-grid street lighting is a good example to illustrate how proper integration of different clean technologies lowers the overall cost. Autonomous street lighting, if deployed in significant numbers, can provide what people need (e.g., reliable illumination, safety) and greatly help to defer, or even avoid, building expensive fossil-fuel-based peak power generation and capital investments in power grid expansions and distribution upgrades.

Optimized PV design to power LED applications is a potentially cost-effective lighting solution in advanced, developing, and low-income countries. LED systems provide two important advantages. First their longer lifetime will lower cost of ownership when compared to other options in stand-alone and grid-connected lightings. Second, given the fact that LED systems operate under direct current (DC) voltage, inverters for DC–AC conversion are not required (since PV power output is DC). Eliminating DC–AC and AC–DC conversions will not only reduce cost but also improves overall energy efficiency.

Optimized PV design to power LED applications is a potentially cost-effective lighting solution.

Currently, significant investments are provided to support specific PV and battery technologies developments without proper efficiency and costs analysis.[19] Merit comparisons based on the specific needs of the different battery storage options is important to craft the most appropriate market and R&D policies. Many current battery technologies remain expensive even though they have reached advanced commercialization levels. For example, lead-acid battery initial capital cost is at least five times cheaper than Li-ion batteries.[20] Other battery concepts are also currently developed.[20,21] Li-ion batteries are attracting more attention from funding agencies and R&D organizations mostly because of their higher energy density, a critical criterion for electric vehicles. However safety requirements and raw materials scarcity may amplify this cost gap in favor of lead-acid batteries.

VI. Comparing Battery Technologies for Autonomous Solar-Powered Street Lighting

Off-grid street lighting system powered by photovoltaic panel is used here as an illustrative example to compare the merits of different battery storage technologies. For street lighting systems, an 89 W LED system with a luminous flux output of 90 lumens/W is used. This LED system will generate a white light intensity of about 8,000 lumens. We will assume that the LED and PV panel lifetimes are about 20 years each. Battery lifetime is assumed to be less than five years,

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depending on the technology option and utilization conditions. Thus, the battery should be changed more often during the LED system lifetime. Since the LED lighting operates in direct current, there is no need for an inverter, although a DC–DC converter and a charge controller are required. For simplicity, we will assume that the lifetime of these two components is about the same as the LED system. A summarized analysis of a solar-powered system indicates that luminaries and battery storage represent more than 80 percent of the overall cost, depending on the lighting system autonomy.

Five rechargeable battery technologies are analyzed in this study: conventional lead-acid (CLS), tubular lead–acid (TLA), sodium nickel chloride (Na–NiCl), lithium ion (Li-Ion), and nickel metal hydride (NiMH). Other battery technologies are not considered here, given the similarities with CLS, TLA, Na–NiCl, Li-Ion, and/or NiMH. For example sodium sulfide (Na–S) is not considered given similarities with Na–NiCl battery. To compare the economic value of these battery technologies, three important parameters are considered in this study:

- Initial capital cost per unit storage capacity ($/kWh)
- Overall storage efficiency (η)
- Number of cycles for a given depth of discharge (DOD)

Other parameters including self-discharge and recycling are not considered. Recharged batteries are used within one to three days following charging; thus self-discharge is low for most batteries.

VII. Current vs. Future Scenarios

Field data obtained under similar conditions on different battery technologies are critically lacking. There is a significant discrepancy in the effective value reported for each parameter in the literature. This discrepancy is due mostly to a variety of design for each technology and differences in operating conditions. Another common error found in several studies is the use of parameters obtained from technologies at different development stages. Costs will be higher when sophisticated architectures and chemical compositions are used to improve lifetime, efficiency, and/or safety of a given battery technology.

Two scenarios are considered in this study. For the first scenario (today), we have tried to use a single source for the value of the three battery parameters. Thus lifetime (cycles), efficiency (η), and unit cost of the CLS, Na–NiCl, Li-ion, and NiMH are taken from Ref. 22. In the case of TLA, we considered a nameplate lifetime of 1,000 cycles although up to 1,800 cycles have been reported elsewhere.[21] Efficiency is assumed to be the same for both CLA and TLA. We assume the cost of TLA to be 10 percent higher than CLA to account for a potentially slower manufacturing process. Utilization of tubular structure for the cathode is the only difference between the two lead acid battery technologies. Table 1 summarizes the input data for the first scenario.

For the second scenario (Future), we will assume

Table 1: Assumptions on Four Battery Storage Technologies Based on Today (Top) and Future (Bottom) State of Development

	Cycle life	Efficiency, η (%)	Cost ($/kWh)
CLA	500	70	350
TLA	1,000	70	385
Ni–NaCl	2,000	90	425
Li-Ion	400	85	1,563
NiMH	500	80	750

	Cycle life	Efficiency, η (%)	Cost ($/kWh)
CLA	750	70	263
TLA	1,500	70	289
Ni–NaCl	3,000	90	319
Li-Ion	600	85	1,172
NiMH	750	80	563

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improvements in all five battery technologies. We hypothesize that the number of cycles is expected to increase by a factor of 50 percent. On average, we will assume that efficiency will not change significantly. A cost reduction of 25 percent will be achieved in the second scenario for all five battery technologies. For the sake of simplicity, we have kept the parameters for other components (LED and PV) constant. This cost reduction will be obtained mostly through large-scale battery mass production. Note that we have included the cost of implementing technology innovations allowing cycle life improvement. We expect these improvements to occur within a five- to 10-year period. If more aggressive policies are implemented (e.g., advanced feed-in tariffs, smart tax rebates) a more significant cost reduction is achievable.

VIII. Considering Overall System Cost

Although initial capital cost is important, estimating the overall cost of ownership over the proposed lifetime is critical. Based on an average operation of 10 hours per day, for three days of operation autonomy, a storage capacity (SC) is required to continuously power an LED lamp system rated at 89 W:

$$\begin{aligned} \mathrm{SC} &= 3\,[\text{days of autonomy}] \\ &\quad \times 10\,[\text{hours per day}] \\ &\quad \times 89\,[\text{LED rated power}] \\ &= 2,670\,\mathrm{Wh} \end{aligned}$$

For this study we will use irradiation levels typical of southern Europe. This irradiation level represents a compromise between irradiation levels in northern Europe and North America and those higher levels in areas closer to the equator or in desert locations such as Atacama or the Sahara. Using a nominal irradiation of $I = 1{,}600$ kWh/kW per year, a module power rating P is obtained from the following equation:

$$\mathrm{SC}\,[\mathrm{kWh}] = \frac{PI}{365}$$

Where ''365'' corresponds to the number of a days in a year. The storage capacity for the proposed street lighting system is thus 2.67 kWh for a nominal PV module of 0.49 kW. To compare the different storage options, initial capital (IC) and lifetime cost (LC) have been calculated for each option (**Table 2**). To estimate a present value for the LC a discount rate of 7 percent is used. In the case of CLA batteries, storage, PV and LED represents around 23 percent, 25 percent, and 52 percent of the initial overall system cost respectively. In the case of the Li-ion batteries, the contribution of storage, PV and LED represents around 52 percent, 16 percent, and 32 percent of the initial overall system cost respectively.

Initial capital costs of the lighting system using CLA, TLA, and Na–NiCl batteries are relatively the same. Li-ion and to less extent NiMH, based systems have the highest IC for both scenarios. Based on the lifetime cost, Na–NiCl and TLA are the best storage technologies. Li-ion batteries give rise to the highest initial and lifetime costs for the present and future scenarios. Overall, the LC numbers are significantly reduced in the second scenario for all five battery technologies. Thus technology development incentives should be pursued more aggressively.

Lead acid batteries and Na–NiCl technologies development market status are quite different. CLA and TLA are mature technologies, and have the lion's share of the current battery market. Toxicity issues of lead have been addressed by the industry through automatization of the fabrication process. Furthermore, more than 95 percent of lead acid batteries are recycled in developed countries, which represents one of the best recycling programs in existence today. In the

Table 2: Initial and Lifetime (20 years) System Costs for the Two Scenarios

	Present		Future	
	IC ($)	LC ($)	IC ($)	LC ($)
CLA	5,793	16,635	5,462	11,856
TLA	5,927	12,917	5,561	9,428
Na–NiCl	5,719	11,184	5,405	7,632
Li-Ion	9,364	57,452	8,137	33,436
NiMH	6,960	25,954	6,337	16,981

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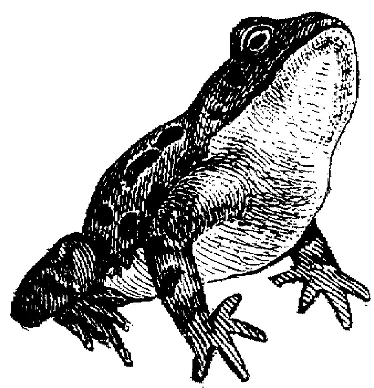
case of Na–NiCl chemistry, these batteries do not have toxic materials components, but they are not yet commercialized on a large scale. Na–NiCl is not yet a fully commercial mature technology although pre-commercial demonstrations have been successfully reported.

The overall higher initial capital cost of solar-powered lighting systems and the absence of adequate support systems for their deployment currently relegate this valuable option to niche markets. This reality is hindering both wider market development and further technological improvements. An economic comparison between off-grid solar powered LED, grid-powered LED, and conventional grid-powered lighting systems has been recently reported.[13] In this study a 10 km roadway lighting system requiring 667 lamps to carry this comparison has been used. Per unit installed lighting system, the initial capital cost is $4,632, $3,370, and $2,820 for off-grid solar-powered LED, grid-powered LED, and conventional grid-powered lighting system, respectively. Estimated initial cost for the off-grid lighting is slightly lower than our estimation. However, the main finding in this study is the fact that solar-powered LED is about 40 percent more expensive. However, that study did not include maintenance costs. Furthermore, fuel costs for grid-powered lighting systems are estimated to range around $100–300 per year, depending on the type and fuel price. Note recent cost reductions related to PV and LED components will make CLA, TLA, and Na–NiCl based lighting systems even more affordable.

IX. Environmental Impacts and Policy Implications

Potential GHG abatement should be also included when



evaluating different battery and lighting options. Life cycle analysis of a 4.2 kW stand alone crystalline silicon PV system showed that PV module and lead-acid batteries represents about 44 percent and 45 percent of embodied CO_2 emissions, respectively.[22] Embodied CO_2 emissions in this standalone PV system is estimated to represent 131 g/kWh, comparing to an average 800 g/kWh in the case of fossil-fuel-powered generation.[23] This estimate does not include the CO_2 embodied in the grid system, which undoubtedly would increase carbon intensity. Carbon abatement potential has been predicted to reduce the cost of these PV-powered lighting systems by about 19 percent if the carbon price is set at a mere $10/tCO_2$.[10]

X. Conclusions

Off-grid solar powered lighting systems provide a cost-effective solution. Depending on the battery technology, electricity storage and PV module are the main capital cost contributors. Conventional acid batteries have higher lifetime costs although their initial cost is the lowest. In spite of its attributes, Li-ion batteries are very expensive options. Thus, for stationary applications, Li-ion batteries are likely not the best option. Tubular lead acid batteries and Na–NiCl provide a promising long-term storage solution for street lighting. If proper policies are implemented, we expect solar-powered LED lighting to become more competitive in the future. This analysis illustrates the high potential of combining renewable energy applications with end-use analysis to develop cost-effective solutions that can increase local energy security, climate protection, and to help remediate environmental problems. The importance of ensuring that practical policy programs such as feed-in tariffs for renewable energy evolve to encourage self-supply and the combination of storage and practical

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demand-management options is highlighted as an area requiring additional research.■

Endnotes:

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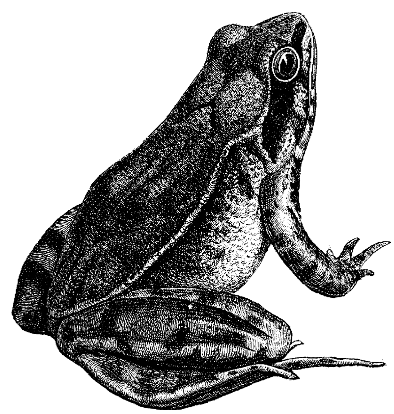

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