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High-resolution global cost advantages of stand-alone small-scale hybrid PV-Battery-Diesel Systems

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Abstract

Rural electrification is a crucial factor for the development of countries globally. A lack of access to an electricity transmission and distribution grid due to a remote location leads to a widespread use of diesel generators to produce electricity. This is cost-intensive and leads to high CO_2 emissions. The present paper summarizes the results of a least-cost modeling approach which is designed to compare electricity generation costs from ubiquitous diesel generation with a hybrid PV-Battery-Diesel system. The inclusion of PV in the generation process will reduce the electricity generation costs in the long-term, as on a global scale many areas possess high potentials for PV applications through strong solar irradiation. Regarding the future, an energy system with a high share of renewable energies is the key to produce cost-efficient electricity.

Keywords: rural electrification; infrastructure; spatial cost modeling

Introduction

Globally still a significant share of population has no or only limited access to electricity (IEA, 2011). Most of these people live in rural South Asia and Sub-Saharan Africa (UNDP-WHO, 2009). Access to electricity is a crucial element for the overall development of a country. For instance, education, economic development and public health depend on the availability of electricity (Doll & Pachauri, 2010). A lack of reliable and affordable electricity therefore presents a main barrier for the progress of certain countries and regions.

As many of the remote areas are not covered by electrical transmission grids, isolated diesel generators are the prevailing standard to produce electricity in these areas (Platts, 2009). Other advantages of diesel gensets lie in the comparably low investment costs and an easy operational and maintenance structure. Distributed small settlements and overall low population densities in rural areas are the key problem regarding centrally organized electric power supply systems (Chaurey & Kandpal, 2010). The resulting dependency on local diesel generators in the above described "off-grid" areas leads to a strong dependence on the crude oil price. In times of menacing shortage of fossil fuel resources in the future and environmental concerns, this approach is no promising concept for the future. With regard to the steep learning curves and achieved grid-parity of small renewable energy systems under certain scenarios (Kost et al., 2012; Schleicher-Tappeser, 2012), investigations in this direction are the key to achieve global electrification.

Infrastructure is an essential element for the overall development of a country, transportation infrastructure being the base element. Energy infrastructure, as e.g. power transmission lines is not existent in many areas and expensive in remote locations, as there is only a comparably low demand for electricity (IEA, 2012).

Characteristics of the insufficiently electrified rural areas are low population densities (Zvoleff et al., 2009) with low load profiles, which make the installation of transmission lines expensive and less efficient and hence the hybrid renewable system more feasible.

Electrification influences several parameters as e.g. the Human Development Index (HDI) and the Gross Domestic Product (GDP) of a country. Infrastructure elements like roads, railways and power transmission lines are also considered here. The local situation in non-electrified areas is a result of the co-occurrence of different factors. Political stability, corruption and resource availability can be decisive elements in this development process.

Many areas with low electrification rates are located in areas where a high photovoltaic (PV) potential can be expected (Breyer et al., 2011). Solar irradiation as a local source holds the advantage of overall spatial availability which is only limited by climatic factors as well as the day and night rhythm. As a consequence, there are no transportation costs connected to PV resulting from fuel use, only the initial cost of transportation of the system to its designated site and the backup diesel genset.

Research Objectives

This paper presents the results of analyzing global electrification costs using a PV-Battery-Diesel system on a spatially refined resolution. The remoteness and accessibility of each location is regarded by considering the distance or more exactly the travel time to the next major settlement of more than 50,000 inhabitants. This factor is needed as the local diesel price differs from the national base price with remoteness being a significant impact factor. This is mainly associated with logistical expenditures increasing with diminishing accessibility. A model for assessing the economic potential of hybrid PV-Battery-Diesel systems versus diesel stand-alone

systems including this aspect is compiled. Diesel stand-alone systems are the prevailing electricity generating technology in off-grid areas.
The following research questions are developed:

- What are the potentials to electrify areas with renewable energies in form of hybrid PV-Battery-Diesel systems?
- How competitive are these renewable energy solutions compared to traditional energy generation mostly based on diesel gensets?
- What is the local amortization time for the adopted system and where is it most feasible regarding the amortization rate?

Methods

This section describes the different methodologies used for the present study. The combination of diverse data requires a comprehensive analysis with two different approaches.

Geospatial analysis

GIS (Geographic Information System) analysis of spatial data is used to assess the global variability of environmental parameters regarding rural electrification.
The global travel time raster (Nelson, 2008) is analyzed and validated regarding the infrastructure data which can be drawn from the VMap0 data which origin from the Digital Chart of the World compiled by the National Imagery and Mapping Agency (NIMA) of the United States. The global travel time raster is a product of spatial infrastructure assessments, land cover analyses and a digital elevation model amongst other input parameters.
It therefore reflects the impact of missing infrastructural elements which is especially important for electricity generation and electricity access.
Furthermore, geo-referenced transmission lines, roads and railways[1] were extracted for each country, summed up and normalized to the respective country size to reflect their importance regarding low rural electrification rates. GIS is also used for the final depiction and interpretation of the cost model.
For this the resulting maps comprising the output of the cost calculations are summarized on the basis of the country classification to allow concluding propositions.
GIS analysis is carried out using ESRI Arc Map[2].

Cost-comparing model design

Model formation to calculate electricity costs for the two scenarios, diesel stand-alone systems and hybrid PV-Battery-Diesel systems, is carried out using Matlab[3].
The design of the approach is based on the modeling approach by Szabó et al. (2011). - Their spatial concept is adopted and extended from an African perspective to a global scale. Furthermore, input parameters and model assumptions were changed and updated.

Diesel transport costs are calculated using the global travel time raster by (Nelson, 2008). We assume that diesel is purchased for the national diesel price (Ebert et al., 2009) in the next major settlement. Transport costs of 4 per cent of the national diesel price[4] are added for every hour of travel time to the considered location. Initial PV costs are set to 2,000 €/kW$_p$, battery costs are assumed to be 120 €/kWh. The interest rate is 8 % per annum. For the whole system a genset efficiency of 0.33 l/kWh$_{el}$ is adopted, the operational expenditure is set to 0.02 €/kWh$_{el}$. Solar irradiation is given as hourly global horizontal irradiation in a raster with a 27'-pixel size (DLR, NASA). With this input the local diesel costs, the levelized cost of electricity, the share of PV in the optimized system and the amortization time of the system is calculated at each point.

Results

The calculation of the local diesel costs clearly shows the dependency of the price on local oil resources in the respective countries as well as diesel subsidies and tax policies. Also the raising of prices in remote areas due to higher transportation costs is observable (Fig. 1). The latter is especially recognizable in the large known remote areas like the Tibetan Plateau, the Saharan region as well as in parts of the Amazon Basin. The local diesel electricity costs range between 0.02 €/kWh and more than 2.00 €/kWh in remote areas.
The difference between electricity costs evolving from the pure use of diesel generators compared to optimized hybrid PV-Battery-Diesel generation (Fig. 2) shows the clear dependency on the diesel price – in regions with a low diesel price there is no cost advantage in the inclusion of PV in the system. This mainly occurs in countries with oil production, e.g., in the Middle East and North African (MENA) region.
The optimized share of PV in the local systems (Fig. 3) illustrates similar characteristics to the cost differences, however there exist some locations (e.g., South-Eastern Australia and Eastern Brasil) which include a comparatively higher share of PV in the system and have the same costs as a conventional fossil fuel based systems. This results from the remoteness of a location as well as from varying diesel prices. Here the advantage lies more in the mitigation of carbon emissions than in the direct financial savings compared to conventional systems.
The local amortization time for the optimized hybrid system varies between 1 and 15 years (Fig. 4) according to the percentage of PV in the system as well as the local diesel price at a given location.
The amortization time is especially important when considering the low financial possibilities for most people in rural less developed areas. In addition, a short amortization time allows people to benefit from the low cost electricity through low operational costs, as in systems with a high PV share, less diesel fuel is used as costly operational contingent.

[1] VMap0 Data.
[2] ESRI ® Arc Map™ 10.0.
[3] MATLAB. ® Version R2011b. The MathWorks, Inc.

[4] National diesel prices are given in USD converted to € with an exchange rate of 1.40 USD/€.

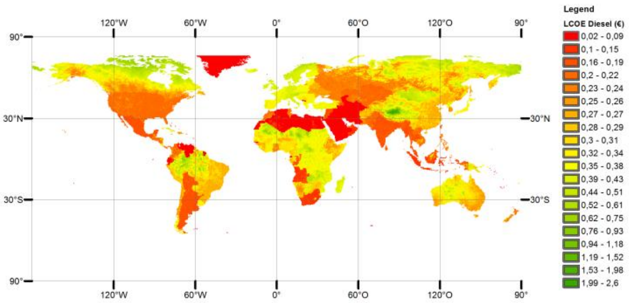

Figure 1: Local diesel cost (€/kWh). Red areas indicate low diesel costs; orange medium and green areas high diesel costs.

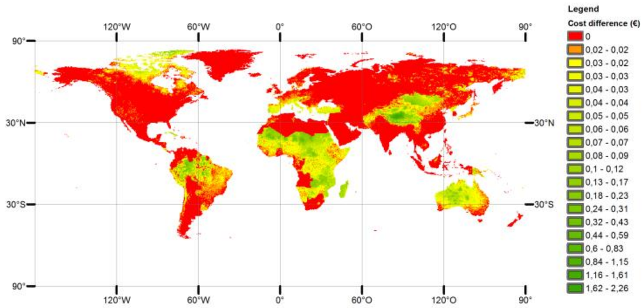

Figure 2: Difference between electricity costs generated by diesel and hybrid systems (€/kWh).

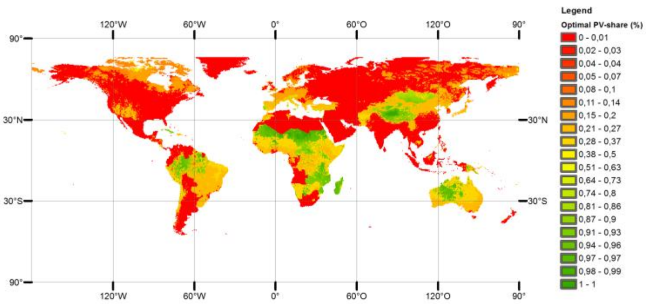

Figure 3: Share of PV in the modelled hybrid PV-Battery-Diesel system (%).

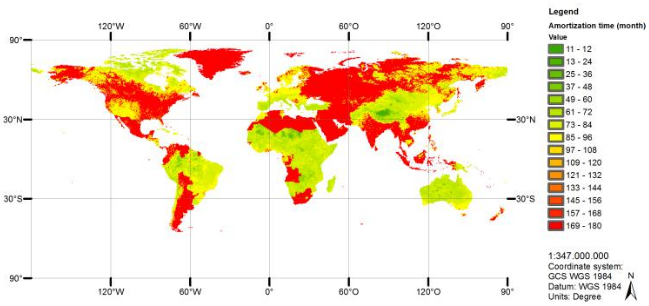

Figure 4: Time of amortization.

The country-wise analysis of this output shows that especially the poor underdeveloped countries in Sub-Saharan Africa and South Asia (except the countries with an extremely low diesel price) can benefit from the inclusion of PV in the electricity generating system.

Extracting the data from the cost difference raster for each country and normalizing it with the respective country size yields to the countries which can achieve the highest savings through an implementation of a hybrid PV-Battery-Diesel system compared to a conventional diesel system under the respective local conditions (Tab. 4). The outcome shows that the highest savings are mainly possible in African countries with low or medium development rates regarding their ranks in the HDI of the year 2011.

Table 4: Countries with the highest savings through implementation of hybrid PV-Battery-Diesel systems and their corresponding HDI rank 2011 from very high development to low human development (1. – 187. rank) (UNEP 2011).

Country (HDI rank 2011)	**Average saving (€/kWh)**
Zambia (164.)	0.16
Chad (183.)	0.15
Suriname (104.)	0.15
Malawi (171.)	0.13
Cent. Afr. Republic (179.)	0.11
Mauritania (159.)	0.11
Niger (186.)	0.10
Israel (17.)	0.10
Guadeloupe (20.)	0.09
Mongolia (110.)	0.09

Discussion

Regarding the research objectives the following conclusion can be drawn:

The results show that potentials for the upgrade of diesel systems or the new implementation of renewable PV-Battery-Diesel systems exist in many regions. However – these systems are only capable of competing with pure diesel systems in remote regions and in countries were the diesel price does not drop under a certain threshold.

Considering the amortization time the focus of the implementation of these systems is clearly on the most remote areas globally, as in these regions transport costs of diesel add significantly to the diesel costs for electricity generation. In addition, an implementation of these hybrid systems is also feasible in the long term perspective in regions where the optimized system consists of a lower share of PV – as it will still pay off in the future.

The developed cost calculation maps depict the strong influence of the high diesel price differences between neighboring countries as an effect of political structures and resource distribution (Nguyen, 2007). High subsidies and low taxes yield to the consequence that in many areas the inclusion of PV is not cost-effective, notwithstanding high solar irradiation.

Furthermore, the strong impact of the diesel price infers that the results are subject to changes regarding a change in the input diesel price which can easily result from political and economic decisions. That means that these results depict the current situation which is an artificial composite of political, economic and natural factors. In consequence, when transferring these results to future scenarios – all parameters have to be updated.

Comparing the countries with the highest saving opportunities (Tab. 4) in regard to their respective HDI rank, the huge electrification potential of hybrid PV-Battery-Diesel systems becomes apparent as a low HDI rank implies a low electrification rate, especially in rural areas (Narula et al., 2012).

Also, lowly developed countries are faced with high shares of rural population, e.g., in Niger about 83 % of the population lives in rural areas, comparable to about 80 % in Malawi (UNEP, 2011). This means that large targets of electrification objectives can be reached with an adoption of hybrid systems in these regions.

Presuming rising diesel prices in the long term the results suggest that the hybrid off-grid solution will be feasible in even more regions.

Summarizing the results and limitations it is possible to conclude that in many locations the lack of transmission grid infrastructure and access to electricity can be balanced and enhanced by the introduction of the described hybrid PV-Battery-Diesel systems instead of the single use of prevailing diesel generators or the connection to a centralized transmission and distribution grid. As most of the non-electrified regions are remote areas, the scope of this application is huge.

The inclusion of other renewable energy sources in the calculation can extend the approach. Spatially disaggregated hydro- and wind-potentials can drastically increase the share of renewable energies in the distributed electricity generating progress.

In the long term perspective these systems are also advancing with the development of more efficient, affordable batteries as a more capable storage option to minimize the share of backup diesel use.

Considering the strong relation to the diesel price, the ownership structures of grid operators and the electricity generating companies, the importance of distinct policy development in decision making processes becomes apparent.

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