Energy for Sustainable Development 31 (2016) 14–23

Contents lists available at ScienceDirect

Energy for Sustainable Development

Global cost advantages of autonomous solar–battery–diesel systems compared to diesel-only systems

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ARTICLE INFO

Article history:
Received 31 May 2013
Revised 31 July 2015
Accepted 29 December 2015
Available online 19 January 2016

Keywords:
Rural electrification
geo-spatial analysis
Off-grid
Spatial cost modeling

ABSTRACT

Isolated diesel systems are the main electricity generation method in many rural areas nowadays and represent a viable option to supply un-electrified villages in the Global South. However, this generation scheme leads to a dependency on fossil fuels and their price volatility on a global market with a projected increase of costs in the future. At the same time, high carbon dioxide emissions increase environmental costs. Up to date, many hybrid mini-grid pilot projects and case studies were performed globally to assess how the inclusion of renewable energy in these systems can enhance technical and economic performance. This provides insights in local characteristics and challenges of that approach on a case by case basis. This study, on the other hand, takes a look at the overall global potential for solar–battery–diesel mini-grids for rural electrification and derives a comparative analysis of the respective regions. The introduction of a GIS-based analysis in combination with a sophisticated mini-grid simulation allows a highly automated approach to draw global conclusions with the option to downscale to local regions. The results of the methodology show that in many regions substantial LCOE reductions are achievable by introducing solar–battery–diesel systems compared to pure diesel systems. Furthermore, the crucial role of spatial varying of diesel fuel prices over different regions and the impacts on the feasibility of solar–battery–diesel systems can be observed.

Introduction

Access to electricity is still a huge challenge for more than 1.3 billion people globally. Highly affected regions are located in rural remote regions in Sub-Saharan Africa, Southeast, and South Asia (IEA, 2014a). Rural remote regions are facing the great challenge that the population densities are often low, the demand is difficult to assess and the reliability regarding the ability to pay for electricity is unclear(Zvoleff et al., 2009; Winkler et al., 2011). Low local demand for electricity makes the installation of transmission lines expensive and less efficient and hence the hybrid renewable system more feasible. Centrally organized power supply systems are not designed for small settlements, and their costs are often underestimated (Cader, 2015; Chaurey et al., 2004). These are reasons for utilities and power companies to be careful about investing in that area and opening the space for decentralized energy solutions (Narula et al., 2012).

Electricity is a key requirement for development: education, health sector, and economic sectors benefit from it. A clear relation between the gross national product (GDP) and the national energy consumptions can be shown (Doll and Pachauri, 2010). In addition, the human development index (HDI) is also positively influenced by having access to electricity (Kanagawa and Nakata, 2008). Electricity access is not given because the national electricity transmission and distribution infrastructure does not reach far enough, the grid is facing regular power outages, or the electricity from the grid or alternatives such as small fossil fuelled generators are not affordable for the respective inhabitants (Kaundinya et al., 2009). In particular, the latter option – small diesel generators – is a frequently used method of electricity generation for remote locations (Bertheau et al., 2014). With the international agenda of universal access to electricity by the UN accompanied by other global institutions and emerging national development policies and the new goals and efforts regarding low carbon development, renewable mini-grids are becoming more and more important. The International Energy Agency publishes statistics regarding urban, rural, and total un-electrified population per country (IEA, 2014b). In addition, a newly developed multitier framework also includes the quality of electrification, such as the duration of availability of electricity per day and their affordability (Worldbank/ESMAP, 2014).

Solar–battery–diesel mini-grids are a possible solution for providing high quality access to electricity in different regions, such as Laos (Blum et al., 2015), Burkina Faso (Ouedraogo et al., 2015), or Nigeria (Dada, 2014; Ohiare, 2015) and Cameroon (Nfah et al., 2010; Nfah, 2013). Hazelton et al. (2014) provide a comprehensive overview of benefits

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http://dx.doi.org/10.1016/j.esd.2015.12.007
0973-0826/

and risks of hybrid mini-grids. Bhattacharyya (2013) discusses challenges of decentralized options for rural electrification from a multidisciplinary perspective. The expansion or so-called hybridization of existing diesel grids with renewable energy systems could significantly reduce the electricity costs and the emission of air pollutants (Dekker et al., 2012). IEA's New Policies Scenario suggests the generation of 26 TWh for only Sub-Saharan Africa by mini-grids until the year 2040. The two most prominent technologies to achieve that are solar photovoltaic (PV) and oil, followed by hydro power (Fig. 1).

Within this study, a comparable analysis is carried out to evaluate where mini-grids powered by solar PV and diesel will be the most economical solution. This paper presents a novel methodology on how to scale up a local mini-grid potential analysis at one specific site to a global comparative assessment for solar–battery–diesel mini-grids by combining a GIS-based approach with an energy system simulation. The paper provides an overview to the following discussions:

1. Where will solar–battery–diesel systems be more economical than pure diesel systems under actual technology costs in the developing world?
2. Which percentage of solar power should be installed in the optimized hybrid systems and which parameters influence that?
3. What is the optimum size of batteries in the systems and how is it related to low carbon development?

Decentralized systems allow electricity generation without the need for a national grid. In this study, the economic performance of solar–battery–diesel systems is compared to diesel-only systems, as the latter are frequently used in many regions (Bertheau et al., 2014). Advantages of diesel generators are low investment costs, simple operation, and a well-known technology. Recent calculations of an analysis in Nigeria show that they are the optimum choice in some locations if compared to grid extension or small-scale PV solutions (Ohiare, 2015). Furthermore, fossil fuelled generators can be run flexibly and therefore allow varying electricity demands. However, diesel generators contribute to local and global environmental pollution (Ramanathan and Feng, 2009). In addition to pure financial benefits, also the aspects of CO_2 savings and independency of fossil fuel supply are reflected with an establishment of hybrid mini-grids. Solar–battery–diesel mini-grids are chosen as an alternative to pure diesel powered generations as many areas with low electrification rates are located in areas where a high photovoltaic potential can be expected (Breyer et al., 2011). Solar irradiation as a local resource holds the advantage of overall spatial availability, which is only limited by climatic factors as well as the day and night rhythm. With regard to the steep learning curves and achieved grid parity of small renewable energy systems under certain scenarios (Schleicher-Tappeser, 2012; Breyer and Gerlach, 2013), investigations in the potential of solar energy (photovoltaic) are the key to achieve global electrification. Due to the progress in the technical development, generation costs of renewable energy drop, thus becoming more and more economically feasible. In addition, battery costs are declining fast, which makes storage options much more viable today (Juelch et al., 2015; Nykvist and Nilsson, 2015).

In the past few years, more and more pilot projects and detailed mini-grid case studies were developed, implemented, and analyzed. This provides helpful insights in local environments and performance of individual systems. However, to get an overview of the overall potentials of mini-grids, a broader research framework is necessary. This global comparison of potentials is especially helpful when it comes to business model development for different regions. The utilization of GIS allows an in-depth study of a large spatially disaggregated data set. In particular, when it comes to renewable energies, local resource variation needs to be accounted for. As diesel prices vary on a national level and are also subject to transport costs, these local characteristics need to be taken into consideration. GIS tools allow the processing of large data sets to account for the preparation of automation to optimize LCOE-based mini-grids for many different locations at once.

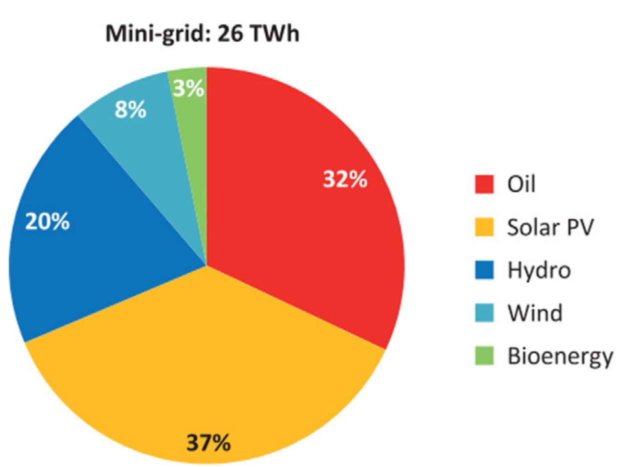

Fig. 1. Projection of the role of mini-grids in the IEA New Policy scenario. Source (IEA, 2014a, 2014b).

Methodology and input data

The work described in the paper is based on the approach described in Fig. 2. Data sources are listed in Table 1. In the first step of the analysis a GIS-based approach is chosen to select all countries with rural electrification rates of 90% or below based on 2013 data (IEA, 2014b). For these countries, a high spatial resolution raster is defined. The raster cell size (length of sides) is set to 1/6 degree. The pixel size corresponds to about 18 km at the equator. This value is chosen to reflect the recommended grid resolution which compromises between the coarsest and finest legible grid resolution (Hengl, 2006). It is adopted to correspond to the spatial properties of the input data and still allow a simulation in a conceivable time frame. The sample countries are classified into 131,147 pixels in total. For each of these raster cells (pixel) the input parameters for the simulation (hourly solar irradiation, travel time, national diesel price, and transport costs) were extracted for the centre coordinates from global data bases. This automation allows the bulk processing of the spatially dissolved simulations.

The calculations aim at the distinction of two different scenarios:

1. Areas where the use of renewable energies applying a solar–battery–diesel system is more cost-effective than the use of conventional diesel generators and which would produce less emissions.
2. Areas where diesel-generated electricity is the cheapest option because here the investment in renewable energy technologies might be difficult due to a lower potential and existing cheap alternatives.

Model formation to calculate electricity costs for the two scenarios, diesel stand-alone systems and hybrid solar–battery–diesel systems, is carried out using a modeling tool developed by the RLI (Fig. 3). This tool simulates the techno-economic optimization based on LCOE. The design of the approach is based on the modeling approach by Szabo et al. (2013, 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 a global travel time raster. The global travel time raster (Nelson, 2008) is analyzed and validated regarding the infrastructure data, which can be drawn from the VMap0 data derived 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 analysis, and a digital elevation model among other input parameters. It therefore reflects the impact of missing infrastructural elements, which is especially important for electricity