Socio-Economic Planning Sciences 55 (2016) 14–24

Contents lists available at ScienceDirect

Socio-Economic Planning Sciences

journal homepage: www.elsevier.com/locate/seps

How effective are heuristic solutions for electricity planning in developing countries

Yakubu Abdul-Salam [a, *], Euan Phimister [b]

[a] The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, UK
[b] Aberdeen Centre for Research in Energy Economics and Finance, University of Aberdeen, Aberdee, UK

ARTICLE INFO

Article history:
Received 27 September 2015
Received in revised form
20 April 2016
Accepted 24 April 2016
Available online 28 April 2016

Keywords:
Electricity
Algorithms
Mixed integer programming
Grid/off-grid
Monte Carlo simulation
Parshall et al. algorithm

ABSTRACT

Heuristic algorithms have been widely used to provide computationally feasible means of exploring the cost effective balance between grid versus off grid sources for universal electrification in developing countries. By definition in such algorithms however, global optimality is not guaranteed. We present a computationally intensive but globally optimal mixed integer non-linear programming (MINLP) model for electricity planning and use it in a Monte Carlo simulation procedure to test the relative performance of a widely used heuristic algorithm due to [28]. We show that the overall difference in cost is typically small suggesting that the heuristic algorithm is generally cost effective in many situations. However we find that the relative performance of the heuristic algorithm deteriorates with increasing degree of spatial dispersion of unelectrified settlements, as well as increasing spatial remoteness of the settlements from the grid network, suggesting that the effectiveness of the heuristic algorithm is context specific. Further, we find that allocation of off grid sources in the heuristic algorithm solution is often significantly greater than in the MINLP model suggesting that heuristic methods can overstate the role of off-grid solutions in certain situations.

1. Introduction

It is estimated that up to 1.3 billion of the world's population have no access to electricity and a majority reside in rural areas of the world's developing regions [16]. The situation is most pronounced in sub Saharan Africa where the overall electrification rate is about 30% only, with some countries such as Chad, Liberia and South Sudan having less than 5% electricity coverage [40].[1] There is a positive correlation between access to electricity and development [15] and although access to electricity in itself is not a panacea for development [9], modest access to it can have significant impact on the general wellbeing[2] of the poor [18]. In many cases however, the poor in developing countries live in rural locations that are thinly inhabited and remote from existing national grids so that high fixed costs of grid extension means grid access to these locations is often uneconomical. Meanwhile potential for the use of off-grid technologies in these countries, particularly drawing on renewable resources such as wind, solar and (bio)diesel has been promoted by a range of authors including [11,27].

A range of algorithms focussing on cost effective planning methods for universal electrification, incorporating both the economic and networking aspects of grid and off-grid electricity planning in developing countries have been proposed. Among these are the algorithms by [2,5,12,20,21,28,35]. Owing to the complexity and large scale nature of the underlying optimization problem,[3] mathematical models based on combinatorial optimisation techniques are impractical. These algorithms are therefore based on heuristic methods. Being ad-hoc heuristics however, there is by definition no measure of the degree to which they are cost effective and they may in fact provide very different solutions not just in terms of cost but also in terms of the spatial frontiers of the competing grid and off-grid technologies [2].

In this paper, we present a mixed integer non-linear

* Corresponding author.
E-mail address: yakubu.abdul-salam@hutton.ac.uk (Y. Abdul-Salam).

[1] Inadequate maintenance of ageing grid network infrastructure as well as insufficient generation capacities among other financial, technical and management issues means that even for electrified locations, service is often unreliable.

[2] For example, electricity used for lighting can decrease the incidence of respiratory diseases which result from use of smoke producing biomass based indoor lanterns.

[3] In Ref [28] 6612 nodes were modelled, in Ref [12] between 700 and 1000 nodes were modelled and in Ref [2] 1086 nodes nodes were modelled.

http://dx.doi.org/10.1016/j.seps.2016.04.004

programming (MINLP) formulation of the underlying cost minimization problem and use it to test the relative performance of the heuristic algorithm by [28] (herein referred to as the PA algorithm). We choose the PA algorithm for two reasons. First, it has been widely adopted in the literature and its advanced user interface program is freely available online.[4] The algorithm has been used to study electricity planning in Kenya [28], Senegal [31], Ghana [2,17], Nigeria [4,26] and gas network planning in East Africa [13]. Second, it has been tested against two existing heuristic algorithms and have been found to yield better cost effective results (see [2]). For these reasons, the PA algorithm can be regarded as the benchmark heuristic for cost effective electricity planning in developing countries. By definition, the MINLP model introduced in this paper yields globally optimum solutions hence provides a basis for testing the performance of the PA algorithm. However the complexity of the cost effective universal electricity planning problem renders the MINLP model to be NP complete hence it is only able to reliably solve small scale planning problems involving up to 40 settlements only.[5] Although this limit is small, many rural electrification projects in developing countries typically involve sub-regional planning situations involving small numbers of communities considered at a time (e.g. [22,37,39] hence making the MINLP model a practically useful tool in those circumstances. We present an example sub-regional planning problem in Section 4.3 to show how the model might be used for such situations.

We test the relative performance of both methods by applying them to a small and simplified version of the universal electricity planning problem. To provide a more realistic setting for the simulations we use grid and off-grid electrification cost data from Ghana. Spatial factors are known to be important determinants of electrification costs [41]. To explore how these factors affect the relative performances of both methods, we simulate the location of the settlements which are to be electrified using Monte Carlo simulation and explore how the relative costs of the two methods vary with respect to two spatial metrics, namely degree of dispersion between the simulated settlements, and their degree of remoteness from the existing grid network.

We show that the overall average difference in performance between the two solutions is small. Across all Monte Carlo trials, the average percentage absolute error between the two solutions is only 0.7%, with the maximum of around 3.8%. This suggests that the PA algorithm is in general an effective planning tool, and that it provides a good yardstick against which to judge other heuristic algorithms in use for large scale electricity planning. However, we do find that the relative performance of the PA algorithm deteriorates with increasing degree of dispersion between unelectrified settlements, and increasing remoteness of the settlements from the existing grid and that more off-grid technology use is implied within the heuristic PA algorithm than the MINLP model.

The remainder of the paper is organised as follows. In Section 2, we describe in more detail the nature of the electricity planning problem and then outline the PA algorithm and the MINLP model developed in this paper. We also use a stylised example to show how both methods work. In Section 3, we describe the Monte Carlo simulation procedure, the data and the evaluation measures used. In Section 4, the Monte Carlo simulation results are discussed in detail. We also present results of the MINLP model applied to a sub-regional planning problem from Ghana. Section 5 concludes with policy implications.

2. Methodology

2.1. The nature of the problem

Figure 1 provides an illustration of the spatial nature of the planning problem for Ghana, showing the existing centralised grid infrastructure and some unelectrified settlements (represented by the isolated dots). Point settlements and high voltage (HV) transmission lines are actual data for Ghana (see [33]). The medium voltage (MV) lines are suggested grid extension frontiers shown in [2]. Given the policy objective of achieving universal access to electricity at minimum cost, the problem posed here is to determine where and how to extend the centralised grid and where to provide off-grid solutions incorporating renewables.[6] Clearly the potential solution to this problem will be sensitive to the relative economics of networked grid extension and the competing off-grid renewable system options, which in turn will depend on spatial resource availability. It will also be sensitive to factors such as demand for electricity in individual settlements, closeness of settlements to the existing grid, their demographic and economic characteristics (e.g. population, population density), etc.

The complexity of the underlying optimization problem arises from the need to determine simultaneously the optimal balance between grid and off grid systems, with the optimal configuration of the distribution network for grid assigned nodes. Typically, a minimum spanning tree (MST) method is used to route grid assigned nodes, forming a radial electricity distribution network. However, finding the MST of a set of nodes analytically is challenging as it belongs to the class of NP-complete problems including the travelling salesman problem [42]. Fast heuristics for the MST algorithm however exist (e.g. [19,29]). This has naturally led to the use of heuristics in order to deal with large scale universal electricity planning problems where thousands of unelectrified nodes need to be considered.

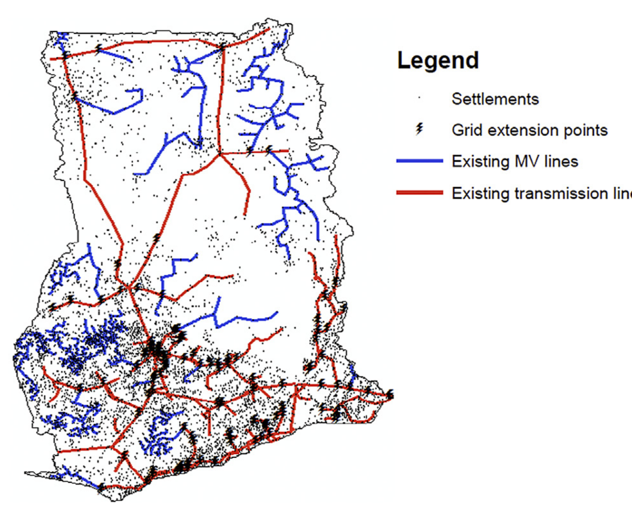

Fig. 1. The cost effective universal electrification problem configured for Ghana. Source: Adapted from [1].

[4] The PA algorithm is accessible at http://networkplanner.modilabs.org/docs/. We however implement both the MINLP model and PA algorithm in GAMS. The codes are available upon request.

[5] This limit regards running the model on a standard desktop computer with a 4 GB RAM, a 64 bit operating system and 2.70 GHz frequency. With greater computing resource, this limit could be extended.

[6] The off-grid systems we consider are standalone household solar and wind systems and autonomous biodiesel mini-grid systems.