A Methodology to Consider Combined Electrical Infrastructure and Real-Time Power-Flow Impact Costs in Planning Large-Scale Renewable Energy Farms

Sreenivas R. Sukumar[1], Mallikarjun Shankar[1], Mohammed Olama[1], James Nutaro[1], Sergey Malinchik[2] and Barry Ives[2]
[1]Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN, 37830.
[2]Lockheed Martin Corporation, 3 Executive Campus, 6th floor, Cherry Hill, NJ, 08002.
Email: {ssrangan@ieee.org, shankarm@ornl.gov, olamahussemm@ornl.gov, nutarojj@ornl.gov, sergey.b.malinchik@lmco.com, barry1.ives@lmco.com}

***Abstract* -- The U.S federal government's strategic vision encouraging renewable energy production has motivated several new energy generation projects. Among them are large-scale renewable energy farm building efforts, where one considers the renewable resource potential along with land, equipment, and installation costs. The goal in the planning phase of these efforts is to maximize the return on investment and resource utilization. The challenge, which is specific to integrating new generation is the need to include the operational cost (both construction as well as run-time) of introducing power to the existing infrastructure. In this paper, we propose a methodology to account for and include energy transmission line proximity (a construction time cost) as well as thermal-overload, and voltage out-of-range (an infrastructure cost) factors when we plan to "tap" into an existing infrastructure. We present results for a study over regions in Texas, Kansas, Colorado, New Mexico and Oklahoma and discuss the findings.**

***Index Terms*-- renewable energy integration, power-flow costs, energy planning.**

I. INTRODUCTION

Resource abundance drives the spatial feasibility of renewable energy farms more than energy demand and construction convenience. This means that we have to transport the power generated from such sites of resource abundance into existing energy transmission interconnects. As transmission line costs can go up to $1 million for a mile of 345KV line [1], the distance to the infrastructure becomes a key cost factor.

As is also well known, resources like wind and solar energy are intermittent (variable) means of energy production. There may be several days in a year when the energy production falls below expected production efficiency and times with spurts of higher than expected production within the same day. On the other hand, the system must be designed for the maximum power scenario with the existing transmission and control infrastructure, which is expected to operate within certain voltage and power specifications. A typical transmission bus is designed for operation between ± 6% of its voltage rating [2]. Exceeding or falling below the range must be avoided as it may severely damage company and customer equipment. Therefore, before adding the new power into the transmission network we have to make sure that expected line and transformer loadings are upgraded to handle spurts of energy production without violating ratings of the installed equipment. In other words, the existing infrastructure at the point of the "tap" must sustain the electrical and thermal limits of the newly injected power. Infrastructure improvements to prevent overload is thus another critical cost factor.

The distance and infrastructure costs can separately and jointly dictate site feasibility. For example, a nearby bus may not be appropriate to connect new generation (even if it reduces the transmission line construction cost) if the power network topology is such that the new generation causes an overload. In a different example, the risk of thermal overload may be minimal, but the cost of installing a new transmission line can overwhelm the allocated budget.

This paper is organized to address the need to consider the combined transmission and infrastructure costs in the planning phase. The question that we address is how can we systematically quantify and call out the cost of new electrical transmission construction as well as system topology infrastructure improvements to handle the influx of renewable energy during the site planning phase.

II. RELATED WORK

Large-scale renewable energy generation has been in the wish list of several developed and developing countries over the last three decades. Several books and research papers [3-6] document issues associated with siting renewable energy generation facilities bringing forth factors such as project scale, technical feasibility and complexity, independent investment and operation risks, environmental concerns and demographic impacts. Some of the solutions presented in these papers have been made available as software tools. These software tools implement different models concerning renewable energy integration like supply–demand prediction, seasonal forecast, optimization, and emission estimation. Conolly et al. presents a comprehensive survey of these software tools in [7].

Recently, Vajjhala [8] conducted a spatial analysis for understanding the promises and pitfalls of siting renewable energy farms to conclude that green energy generation is challenged by economic, environmental, and infrastructure-support hurdles. Her study also revealed that states with the most demand for energy within the U.S ironically face scarcity in renewable resources or have to address geographic and infrastructural siting issues.

Furthering analysis done in [8], Vajjhala and Fischbeck [9] identify the need for quantifying economic, geographic, construction, and perception indicators of siting difficulty. They formulate each of these indicators to capture the variability in the consumption market, physical distances separating generation and demand, additional infrastructural demands such as new transmission lines, and societal/cultural opposition. Grijalva et al. [10-11] analyze the location value of new generation plants with respect to grid security to present methods that can estimate operational costs (both construction and run-time) for siting renewable energy farms. Our emphasis in this paper is on thermal and voltage overload cost considerations, similar to the contingency support costs presented in [11]. Although, we share similar motivation as the papers [8-11], the methods we present in this paper estimate hidden costs of siting renewable energy from an investor's decision-support standpoint rather than the state-level policy and electrical-feasibility viewpoints.

III. Proposed Approach

A typical site planning effort for renewable energy generation begins with identifying regions with dependable renewable resource potential. In Figure 1, we present the pink polygons as a set of potential sites $\mathbf{S} = \{s_j\}$ for j = 1,2..N_s considered for investment in a region overlapping Texas, Kansas, Colorado, New Mexico, and Oklahoma. The input that our approach requires in addition to sites of interest for renewable energy is the topology of the existing electric grid. We represent the grid network as a network graph $\mathbf{G} = <\mathbf{V}, \mathbf{E}>$ where $\mathbf{V}$ is the (vertex set $\{v_i\}$) of bus stations/generators geographically associated with a latitude and longitude pair (x_i, y_i) . $\mathbf{E}$ (the edge set) is the set of transmission line links between generators and substations. The interconnected green lines in Figure 1 is a Google Earth visualization of the graph network $\mathbf{G}$ representing the electric grid. The green lines in the figure represent transmission lines and the end points of those line segments are generators or sub-stations.

Our goal in this section is to present methods that assign proximity and infrastructure costs to these user-selected sites. The idea is that if we have an estimate of a maximum allowable budget associated with each of these regions to cover for the land, equipment, and grid-integration costs, our methods can help eliminate and rank the sites based on grid-integration feasibility and convenience.

A. Proximity costs

Given $\mathbf{G}$ and $\mathbf{S}$, we compute answers to three specific questions, namely: (1) How far away is each site s_j in $\mathbf{S}$ from its nearest transmission bus in $\mathbf{G}$? (2) Are there other sites in the vicinity of s_j so that a cluster of these sites can be linked to a single substation? (3) How many buses are within a specified radius of s_j to accept extra power?

We compute and store the distance in miles between each site and the nearest bus in $\mathbf{V}$ (Equation 1). We used the specifications in [12] to convert the latitude and longitude data to a Cartesian system of three-dimensional (3D) co-ordinates. The function d in Equation 1 is the Euclidean distance between two points in the transformed 3D space. N_b is the nearest bus to a site of interest s_j.

$$d_{N_b}(s_j) = \min_{v_i} \mathrm{d}(s_j, \mathbf{V}) \tag{1}$$

$$N_b(s_j) = \arg\min_{v_i} \mathrm{d}(s_j, \mathbf{V}) \tag{2}$$

We leverage tools and software development kits available for the popular Google Earth visualization platform to conduct our spatial analysis. However, the generic formulation of the proximity costs lends itself to easy implementation in other commercial mapping tools such as ArcGIS [14].

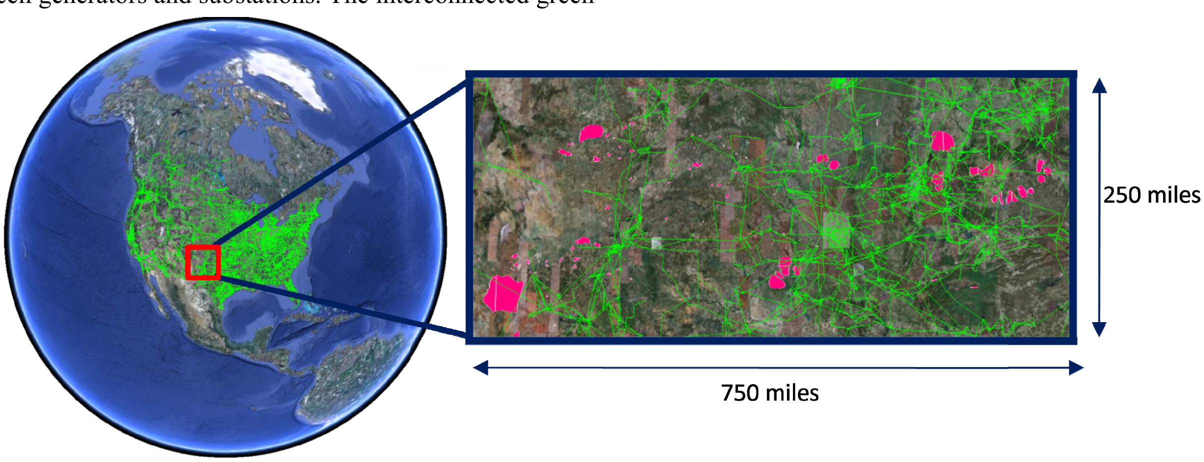


Fig. 1. We use the knowledge of the energy interconnects to compute the transmission and power-flow costs to inject renewable energy. The regions shown in this figure are user selected regions for the study presented in this paper. The selections are based on the land and resource availability.

The result of the nearest-bus assignment to sites is illustrated in Figure 2a. In some cases, especially for sites near populated cities that have surplus electrical infrastructure capacity, we might actually be able to consider distributing the power generated from a single site to several bus nodes in proximity while still bounded by the allocated budget. We include such favorable siting-feasibility conditions by quantifying grid-resource availability for each site as the amount of extra generation that can be distributed to nodes within a distance threshold. As illustrated in Figure 2b, we look within the radius of a budget-driven distance threshold and compute $R(s_j)$ as the maximum new power the set of bus nodes within the specified radius of the site can handle.

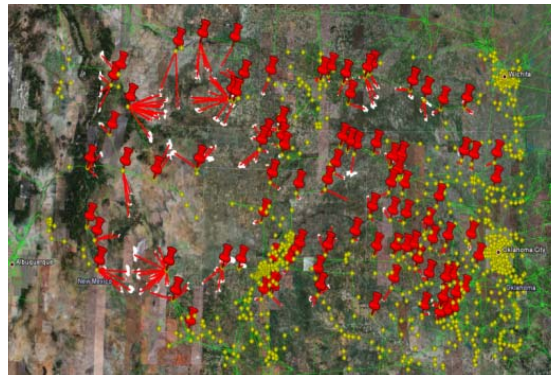
The next measure that we compute is based on the spatial clustering of potential sites in **S**. The logic behind clustering sites is that it may be more economical to create a new bus node and required transmission capabilities to the new bus rather than try and pump the energy into an existing bus and spending on several parallel transmission lines. We modify the iterative winner-take-all clustering approach described in [13] to suit our purpose. Instead of using the standard Euclidean distance as the threshold parameter for inter-cluster separation, we define a 'effective-transmission-distance' measure as shown in Equation 3.

$$d_{eff}(s_j) = \min\left(n_g * d(s_j, \mathbf{V}), \sum_{k=1}^{n_g} d(s_j, s_k) + d(s_j, \mathbf{V}) \right) \quad (3)$$

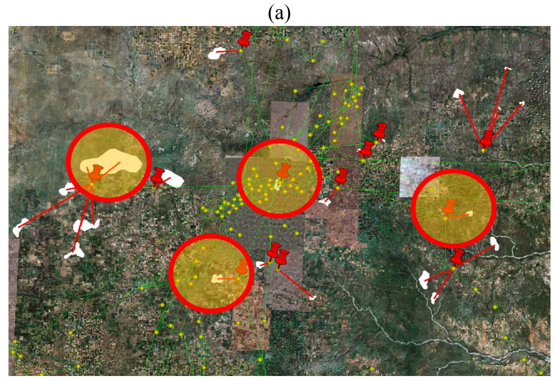
where n_g is the number of sites in each cluster-group within **S**.

As we iterate through the clustering process, this measure favours site clusters that reduce the cost of new transmission lines. We show results of clustering using the distance metric in Equation 3 in Figure 2c. The "Group ID" assignment shown in the figure acts as the label for the n_g clusters. We are able to see that it is economical to leave certain sites to be on their own when they are close to an existing bus that is capable of handling the expected power from the site. We also observe that it is beneficial to treat a group as a cluster when the intra-cluster distances are small compared to the bus and cluster-center distance. The results using this metric suggest that what may be an expensive proposition as a single site of interest can turn feasible when considered as a group of sites.

We combine the three proximity related costs and visualize the extent of siting-difficulty as a bar graph in Figure 2d. Some sites in **S** can already be eliminated from consideration if the physical distance challenges electric transmission requirements. We will be leveraging the information about the nearest bus while conducting simulations to estimate the run-time infrastructure costs.



(a)



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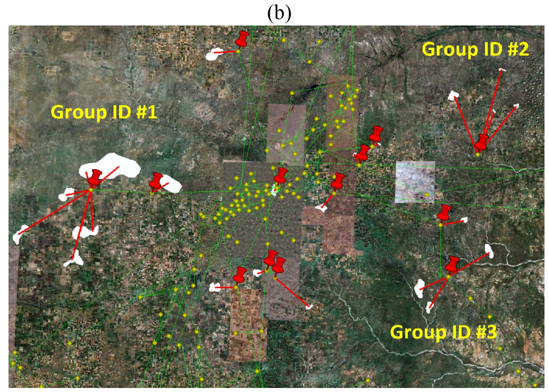

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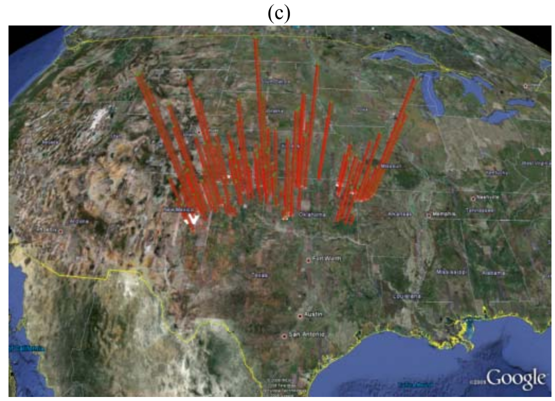


(d)

Fig. 2. The proximity module computes the cost of making the infrastructural connections for renewable energy to the existing grid. (a) Distance from the nearest bus. (b) Number of buses within a radius. (c) Clustering of sites to optimize transmission line costs. (d) Minimum cost for each proposed site visualized as bars.

B. Infrastructure costs

Using our distance analysis, we identified the nearest substations that are candidates to receive the generated power. We now have to understand the impact that the new power will have on the existing infrastructure. We considered the topology of the entire U.S electric grid consisting of approximately 65000 bus, 10500 generators, and 85000 transmission lines [15,16] to run a power-flow simulation treating the site as a new generator adding extra power. We use the true values of generator and power line capacity preserving the geographic locations within our simulations. We note here that simulations using the real topology of the electric transmission system produces analysis along the lines of real-time transmission contingency planning. The results presented in this paper are based on the power-flow solver provided as part of the Power World simulator [17,18]. Other commercial and open-source tools like Siemens PSS/E [19] and ORNL's THYME [20] used in energy transmission planning may be leveraged for this computation. We chose Powerworld solver for its simplicity and functionality in providing base-case overloads with contingency analysis considerations similar to [11]. The process flow we followed in quantifying these results is summarized in Table 1.

TABLE I

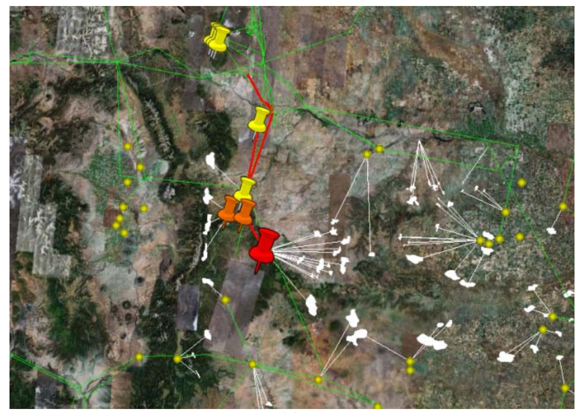
PROCESS FLOW TO ESTIMATE POWER-FLOW COSTS WHILE ADDING NEW RENEWABLE ENERGY.

Step 1: Determine the expected power output at each potential farm site (based on average resource potential and energy conversion efficiency of equipment).
Step 2: Inject the total power generated for the farm (from step 1) to the closest geographical bus $N_b(s_j)$.
Step 3: Run power-flow solver.
Step 4: Check for transmission lines carrying power more than its thermal limit in the simulator's solution.
Step 5: Check for buses that carry voltage more or less than 6% of its specifications in the simulator's solution.
Step 6: Repeat Steps 2 to 5 by adding generated power for a different sites and site clusters.

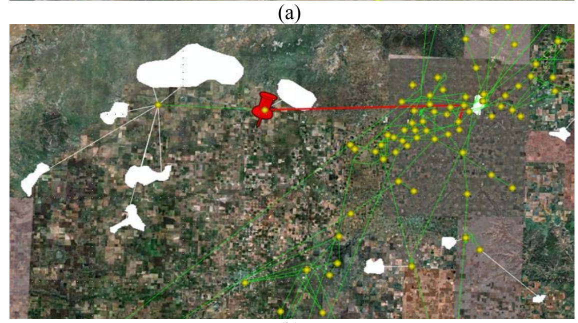
We analyzed the output of the simulation and identified buses that would be forced to operate over or under-voltage as well as lines operating beyond their maximum capacity limits. We present results from a few test cases by simulating power-flow in the existing grid infrastructure in Figure 3. In each figure, the red pin denotes the bus that receives the renewable power. The yellow pins and the orange pins are the result of our power-flow simulation representing under-voltage and over-voltage buses respectively. The red lines denote overloaded lines.

The results in Figure 3a and 3c suggest that building a new bus to handle a group of proposed farms may be more economical. On the other hand, Figure 3b indicates that it may be sufficient to upgrade the 3 overloaded lines to higher capacity.

With market rates for a new bus, a new transmission line or an upgrade to a higher capacity transmission line available to us [1], these violations are converted into a quantifiable cost for the renewable energy integration. Again, the costs here are a new layer in the spatial area of interest akin to those developed in Section 2.1 and can be visualized similar to Figure 2d.



(a)



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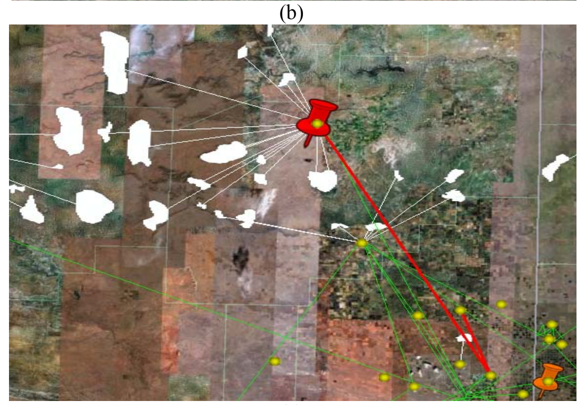

(c)

Fig. 3. The power-flow effect of adding new power into existing infrastructure. (a) Adding 831 MW of renewable energy from all the nearby sites results in 8 under-voltage, 15 over-voltage buses and 24 over-loaded lines (not all visible). (b) An isolated site generating 134 MW new power overloads 3 lines (only two are visible). (c) Another example when 773 MW of renewable energy is generated from several potential sites in proximity.

IV. SUMMARY

We have focused on building a computational framework for estimating two types of costs associated with introducing renewable generation as: (i) the investment required for the upgrade of equipment (to handle the new power injected) and (ii) the proximity costs (as the amount needed to transport the power from the farm to the grid). We presented the two-pass approach that allows for the spatial optimization of renewable energy sites. The simulations that revealed the number of over-loaded lines and number of under- and over-voltage buses helped us identify installation sites more likely for successful cost-effective integration while considering electrical stability. The transmission costs captured the feasibility from an infrastructural viewpoint. The transmission costs combined with the power-flow costs helped us assess the financial aspects of integrating renewable energy beyond just the equipment purchase and installation.

In studying close to 500 potential sites for renewable energy farming, we observe that the integration and transmission costs can be as exorbitant as the cost of the renewable energy equipment themselves. With a mile of transmission line costing close to a $1M, upgrades to lines costing about $0.5M, and building a new sub-station costing a few millions of dollars, the importance of having to consider integration and transmission costs cannot be over-emphasized.

The contributions of this paper are two-fold: (i) we have described a methodology to integrate electrical infrastructure related costs together with the proximity costs while planning for renewable energy investment in an evaluation study considering an actual US electric grid network, and (ii) we have demonstrated the construction of the two constituent cost layers - spatial proximity cost and power-flow cost to quantify and anticipate the impact of installing new energy generation capabilities.

This methodology lends itself to systematic inclusion of land cost, resource potential, policy considerations, etc., that feed into an optimization program [21,22] for feasibility evaluation and investment enabling the integration of diverse cost measures.

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