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Wind and solar generation sources have the potential to significantly replace fossil fuel-based generation in electricity grids and mitigate anthropogenic climate change. Their rapidly decreasing costs, along with policy incentives, have made them the world's fastest growing generation sources.

However, many challenges remain for scaling up wind and solar resources, especially for their cost-effective and environmentally sustainable development from an overall system perspective. The best wind and solar resources can be geographically diverse and heterogeneous, meaning they can be spread out across a region, requiring expensive transmission interconnections to bring power to cities or demand centers. Further, their dependency on uncontrollable factors such as weather and cloud cover result in both variability and uncertainty in their generation patterns that imposes additional costs to the overall system. Some of these resources are also found in environmentally sensitive areas, details of which may not be available to developers and planners. My doctoral research aims to address these challenges in low carbon electricity systems, specifically in the developing countries of India and in Africa.

I focused on three main areas of research. First, I developed a methodology to quantify the potential and cost of wind and solar, and a multi-criteria framework to plan these resources. Second, I developed simulation models to estimate the cost of integrating high shares of wind and solar in electricity grids, and evaluate different strategies to cost-effectively manage the variability of these resources. Third, through the use of optimization models, I quantified the value of wind and solar resources to future electricity systems for different renewable energy targets and mixes, and estimated the resulting cost of mitigating carbon emissions. With the support of the Link Foundation Fellowship, I focused on the first topic of my dissertation – **Multi-criteria Analysis for Planning Renewable Energy**. Under this topic, I conducted two studies in collaboration with colleagues at the Lawrence Berkeley National Laboratory, University of California at Berkeley, and the International Renewable Energy Agency. One focused on 20 countries in the Eastern and Southern African Power Pools (Wu et al. 2017) and the other on India (Deshmukh et al. 2017).

Both study regions are expected to double or triple their electricity demand by 2030 from present levels. Policymakers and planners have the option to meet this demand through conventional generation sources such as coal and large hydro, or via much more environment and climate-friendly sources of wind and solar. Our studies show that strategic site selection can help identify "no-regrets" siting options – or those that are low cost, low impact, and highly accessible and thus can be justified from multiple-stakeholder perspectives of risk – and make wind and solar viable alternatives for large-scale development.

Key results

Using geospatial techniques and energy economics, we developed the Multi-criteria Analysis for Planning Renewable Energy (MapRE) methodology and identified and valued spatially explicit wind, solar photovoltaic (PV), and concentrated solar power (CSP) zones across India and 20 countries across eastern and southern Africa. For each of these zones, we estimated values for multiple criteria such as levelized cost of energy for generation, transmission interconnection, and road, capacity value (how well the generation profile matches the regional electricity demand pattern), human impact factor (an environmental impact metric), distance to nearest water body, slope, and population density. Considering these criteria in site selection could avoid difficult-to-monetize barriers, such as ecological impacts or challenging transmission extensions and upgrades, which often stall projects.

In both study regions, we found abundant cost-effective wind and solar resources that are also low environmental and social impact (See Figure 1 for results of Africa study). However, these resources are unevenly spread, necessitating transmission interconnections and inter-regional trade.

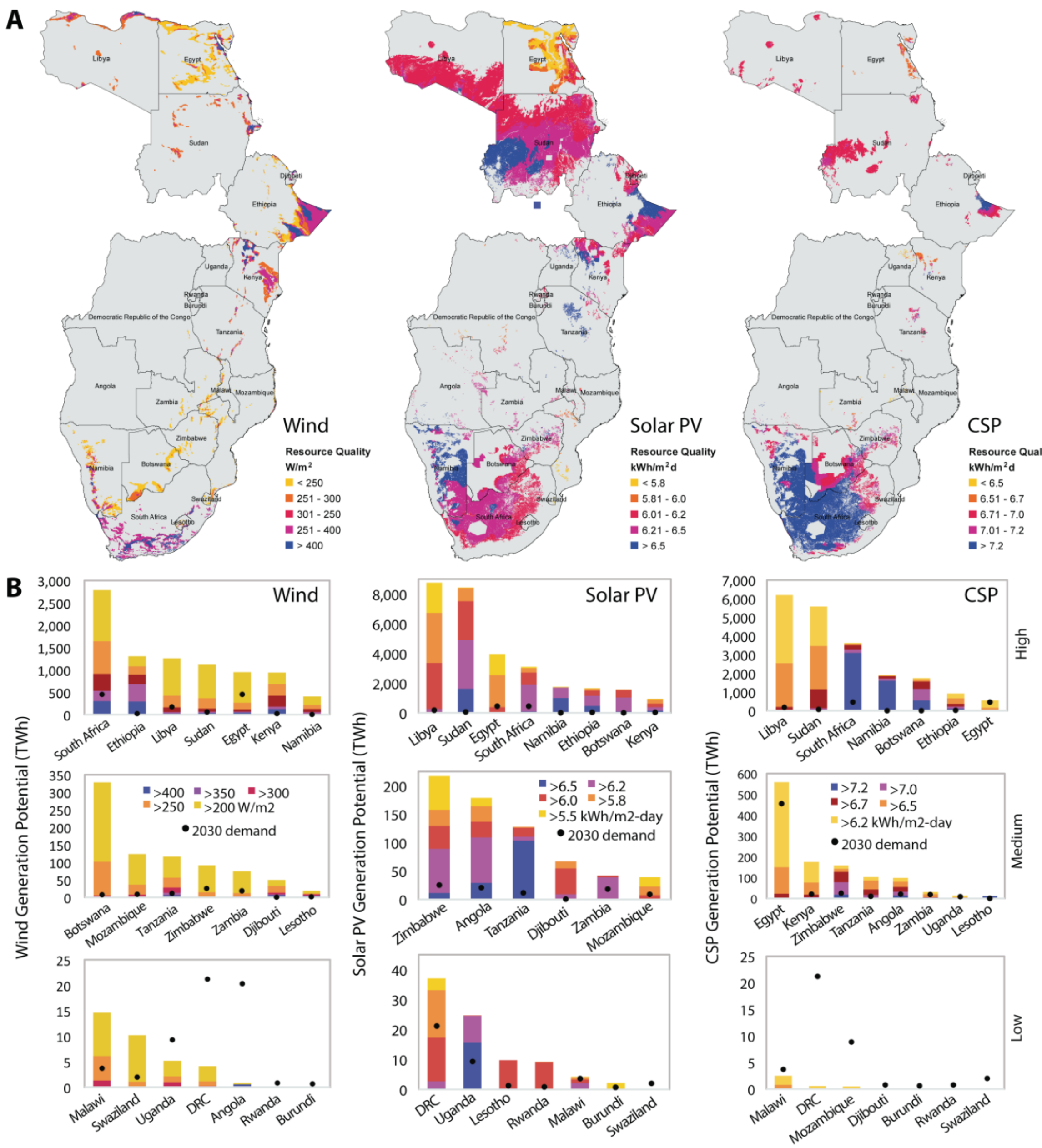

Figure 1: Location and potential (TWh) of each country's renewable resources within the Southern and Eastern African Power Pools. (A) Maps show the location and quality of renewable energy potential. (B) Corresponding bar charts for each technology show the generation potential (TWh) of each resource quality range (in kWh/m²/day for insolation and m/s for wind speed) for each country. The 2030 demand projection for each country is provided as a reference point.

We further examined the benefits of strategic siting of wind projects and regional transmission interconnections in the 9 countries of the Southern African Power Pool (SAPP). We found that instead of choosing sites with the lowest levelized cost of generation, which is the prevailing paradigm, selecting sites to better match their temporal generation profiles to regional electricity demand patterns can help manage the temporal variability of renewable energy and reduce the need for conventional generation capacity, resulting in lower overall system costs. Interconnections between the countries of the SAPP increase the diversity of available wind sites, and reduce the variability of net demand (demand minus wind), increasing potential savings. For a high-wind scenario (~30% wind energy generation by 2030), interconnections and selecting wind sites to match demand reduced the need for SAPP-wide conventional generation capacity by 9.5% resulting in a 6-20% cost savings (USD 0.8 – 2.6 billion), depending on the avoided conventional technology (coal, large hydro, or natural gas). To examine trade-offs between economic costs and other siting barriers, we limited resource areas across the SAPP that are in the top 50% of areas closest to transmission infrastructure, closest to load centers, and that have the highest human footprint score (lowest ecological impact). We found that this multi-criteria site selection (lower risk and lower impact) is not significantly costly compared to selecting zones just based on levelized cost or minimizing net demand (less than 5% of annual cost of wind capacity) – an important finding for the sustainable scale-up of wind and solar development.

For India, we found that the range of levelized costs of generation of wind and solar PV resources overlap, but CSP resources can be approximately twice as expensive. Further, the levelized costs of generation vary much more across wind zones than those across solar zones because of greater heterogeneity in the quality of wind resources compared to that of solar resources (see Figure 2). Majority of the wind resources (over 80%) are located on agricultural lands, which may either be a constraint or provide opportunities for dual-use and revenue sharing with the agricultural community. Wind and solar PV prices discovered in recent auctions are also comparable across the two technologies, but are lower than the regulated feed-in tariff benchmarks assumed in this study. We find that only 29% of suitable solar PV sites and 15% of CSP sites are within 10 km of a surface water body suggesting water availability as a significant siting constraint for solar plants. About a quarter (28%) of all solar PV potential sites overlap with wind sites, offering opportunities for co-location and reducing transmission expenditures. In a country with severe land and water constraints and large coal reserves, these findings will enable policymakers to aggressively pursue low-impact low-carbon development of its electricity system.

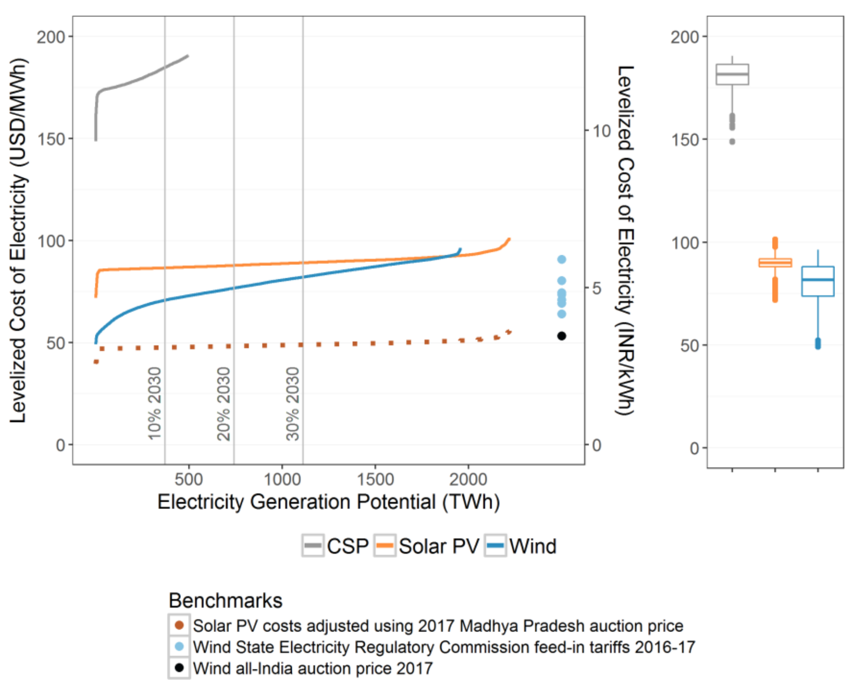

Figure 2: Electricity generation potential sorted by levelized cost of energy (LCOE) for generation (left) and distribution of LCOE's across suitable resource areas (right) for CSP, solar PV and wind. Wind auction price for 2017 and solar PV supply curve adjusted by 2017 auction price shown for comparison.

Significance and impact

Most countries in the Eastern and Southern African Power Pools lacked even the most basic spatially explicit wind and solar assessments. Previous studies on both Africa and India omitted critical cost, interconnection, and socio-environmental impact information. Our studies will enable policymakers and planners to incorporate multiple criteria in renewable energy siting and make wind and solar much more environmentally, socially, and economically sustainable alternatives to conventional fossil and large hydro development. All outputs of our MapRE initiative, including spatial data, maps, and tools are open-source and available for use by any researcher or stakeholder (http://mapre.lbl.gov/). Our recent study in the Proceedings of the National Academy of Sciences was highlighted in several news articles including press releases from Berkeley Lab and the University of California at Berkeley.

Future direction

I, along with my colleagues, will continue development of the MapRE initiative with more tools and data. We intend to expand our analyses to other regions of the world. In partnership with and support from the World Bank, we are also developing a web-based spatial data processing, visualization, and decision-making tool that will use the MapRE methodology and algorithms. This tool aims to significantly lower the barriers in processing renewable energy and other relevant criteria data to enable policymakers, planners, and developers to make quick, informed decisions about siting and scaling up wind and solar energy. The MapRE initiative forms an important part of my larger vision of developing open-source tools and studies using high spatial and temporal resolution data sets to enable the cost-effective, environmentally and socially sustainable scale up and integration of wind and solar resources in large electricity systems.

Papers and Reports published with the support of the Link Foundation Fellowship

Wu, G.C.*, Deshmukh, R.*, Ndhlukula, K., Radojicic, T., Reilly-Moman, J., Phadke, A., Kammen, D.M. and Callaway, D.S., 2017. Strategic siting and regional grid interconnections key to low-carbon futures in African countries. *Proceedings of the National Academy of Sciences*, p.201611845. (*co-lead authors)

Deshmukh, Ranjit*, Wu, Grace C.*, Phadke, Amol, 2017. Renewable energy zones for balancing siting trade-offs in India. *Lawrence Berkeley National Laboratory*, LBNL-1007272. (*co-lead authors)

Deshmukh, R., Ghatikar, G., Yin, R., Das, G.G. and Saha, S.K., 2015. Estimation of potential and value of demand response for industrial and commercial consumers in Delhi. *India Smart Grid Week, Lawrence Berkeley National Laboratory,* LBNL-6987E. (conference paper)

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New articles acknowledging support of the Link Foundation

Lawrence Berkeley National Laboratory News Release. 2017. The economic case for wind and solar energy in Africa. http://newscenter.lbl.gov/2017/03/27/economic-case-wind-solar-energy-africa/

University of California at Berkeley News Release. 2017. Renewable energy has robust future in much of Africa. http://news.berkeley.edu/2017/03/27/renewable-energy-has-robust-future-in-much-of-africa/

How did the fellowship make a difference?

There are limited opportunities for scholarships and financial support for international students in the United States. As an international student, I am incredibly honored and grateful for the crucial support that the Link Foundation Fellowship provided towards my doctoral research. Further, the focus of my research is in developing regions that are data-limited. As such, significant time and travel was required to collect data sets that enabled my research. Without the financial support of the fellowship, I would have been unable to provide the time and patience required to pursue research in my study regions. The fellowship's discretionary funds also supported my travel in India and Africa.