Toward Universal Electricity Access:

Renewable Energy-Based Geospatial Least-Cost Electrification Planning

SOUTH-EAST ASIA ENERGY BRIEF

Indonesia

A geospatially mapped least-cost electrification plan is an effective and practical tool to underpin a high-level national rollout strategy to anchor a bankable financing plan, aimed at achieving universal electricity access in a systematic and comprehensive manner, by integrating technology choices, including cost-effective renewable energy resources with grid and off-grid power-delivery modalities.

Context

In Indonesia, about 60 million people lack access to electricity (76 percent national electrification rate). Over 50 percent of those without electricity live in islands outside of Java and Bali and away from the main island grids. Committed to scaling up energy access, the Government of Indonesia (GOI) has embarked upon a 1,000 island electrification program. The aim of the program is to improve electricity access in Indonesia's Eastern and Western island regions by utilizing renewable energy-based generation resources. The electrification rollout challenge for Indonesia's islands is posed by the interlinked factors of low access to electricity and a spatially dispersed population combined with the high cost of electricity generation from diesel-based power plants. Under these circumstances, a geospatial least-cost electrification plan integrating on-grid with off-grid complement systems can be particularly effective for arriving at cost-effective measures to electrify Indonesia's islands.

Why Geospatial Planning Can Be Particularly Effective for Electrification in Archipelagos

Meeting electrification targets requires high-level planning on how to expand the system over the medium term at least cost. Geospatial planning is an effective tool for such high-level planning. In densely populated areas, grid-based electrification will likely be the cheapest option for most households. In these areas, planning based on grid extensions alone works well. For example, PLN, the national power utility, has achieved high electrification rates in the large and densely populated Java and Bali islands using grid extensions.

In contrast, in smaller islands with lower and more sparsely distributed populations, the least-cost option depends heavily on two factors: whether the community is close enough to the existing MV grid or to other large load centers to make it cost effective to extend the MV grid, and whether the community will have a large enough demand to warrant centralized supply from either the grid or a communal mini-grid.

Geospatial planning uses information on the location of the existing grid. It identifies how far each settlement is from the grid, and how many households are in each settlement to determine which technological approach can provide electricity to each location most cost effectively. This geospatial approach allows for effective least-cost electrification planning into the more distant future by accounting for growing electricity demand and related network expansion over time.

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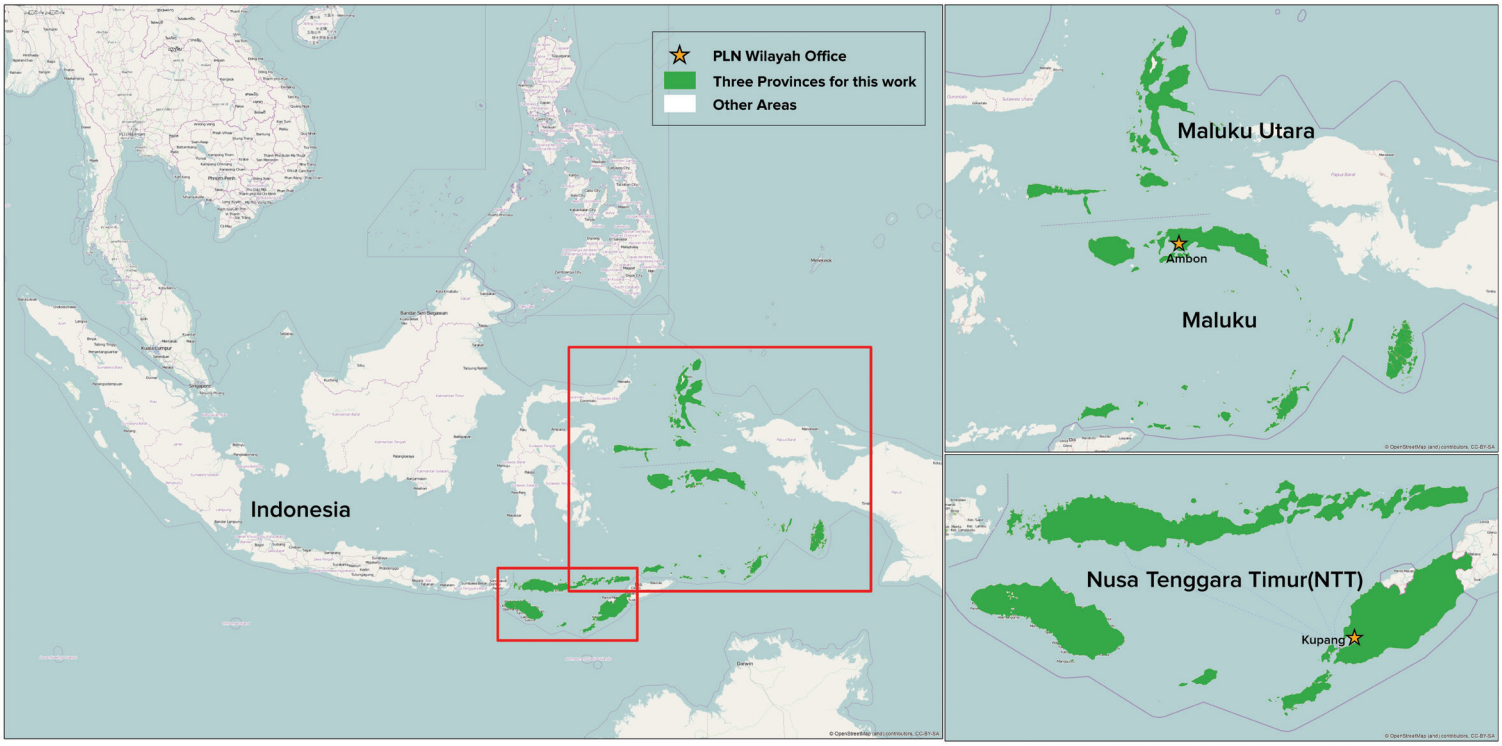
Figure 1. Map of Indonesia, Highlighting Three Provinces for Geospatial Planning



Source: Adapted by the Earth Institute, Columbia University.

Technical Assistance Objective, Scope, and Methodology

In order to support the GOI's access agenda, the World Bank has launched a systematically developed and staged programmatic sector-wide framework as well as an implementation and financing plan for improving electricity access in Indonesia's islands consistent with the targets of GOI's RUKN (National Electrification Plan). A key component of this integrated sector-wide approach is a technical assistance (TA) program that supports the GOI's electrification agenda by arriving at a grid expansion and off-grid complement plan, and by reducing the cost of generation through the use of cost-effective renewable energy technology. The TA that is funded by AusAID, ASTAE, and ESMAP also aims to complement, support, and add value to PLN's current system planning and investment program.

The TA will be used to create a geospatial least-cost electrification plan for three provinces, Nusa Tenggara Timur (NTT), Maluku, and Maluku Utara (figure 1), which have been chosen because of their relatively low electrification rate and their challenging geographical locations. The intention is that PLN will apply this geospatial planning approach in other provinces if it is shown to have benefits for enabling PLN to achieve the GOI's electrification targets.

The geospatial planning process adopted in the TA can be broken down into two main steps:

Step 1: Determining Where Unelectrified Populations Live

The households that currently lack access to electricity are geo-located by:

- Determining how many households in each *desa* (village administration) lack access to electricity by using census data.
- Identifying which areas of each *desa* are actually populated by analyzing BIG (national geospatial agency) land-use maps.
- Using geo-referenced medium-voltage (MV) grid-line data to determine the location of the existing grid and the distance to unconnected communities.
- Estimating the number of households within an unelectrified settlement within each *desa* by linking the population and land-use data results in a geospatial data layer.

Step 2: Identifying the Least-Cost Option to Bring Electricity to Unelectrified Populations

Three different electrification options[1] are evaluated and compared for each population cluster identified in Step 1. The model assumes, for capacity and cost calculations, that each of these options deliver an equal end-use of electricity:

1. Solar PV technology has been chosen to illustrate the results of geospatial planning in this note. However, a comprehensive geospatial least-cost electrification plan would be integrated with an extensive renewable energy resource mapping effort that would look at all available renewable energy generation resources to arrive at a grid expansion and off grid complement plan and funding prospectus.

- **Grid connection:** extending the existing medium voltage (MV) grid to the population cluster to connect to existing grid-based electricity generation and networks.
- **Communal solar mini-grids:** installing a solar-diesel battery system that serves between 10–250 households—LV lines link each household to a centralized generation and storage facility.
- **Solar home systems:** using a distributed model by installing individual solar panels at each home along with a battery bank on the premises.

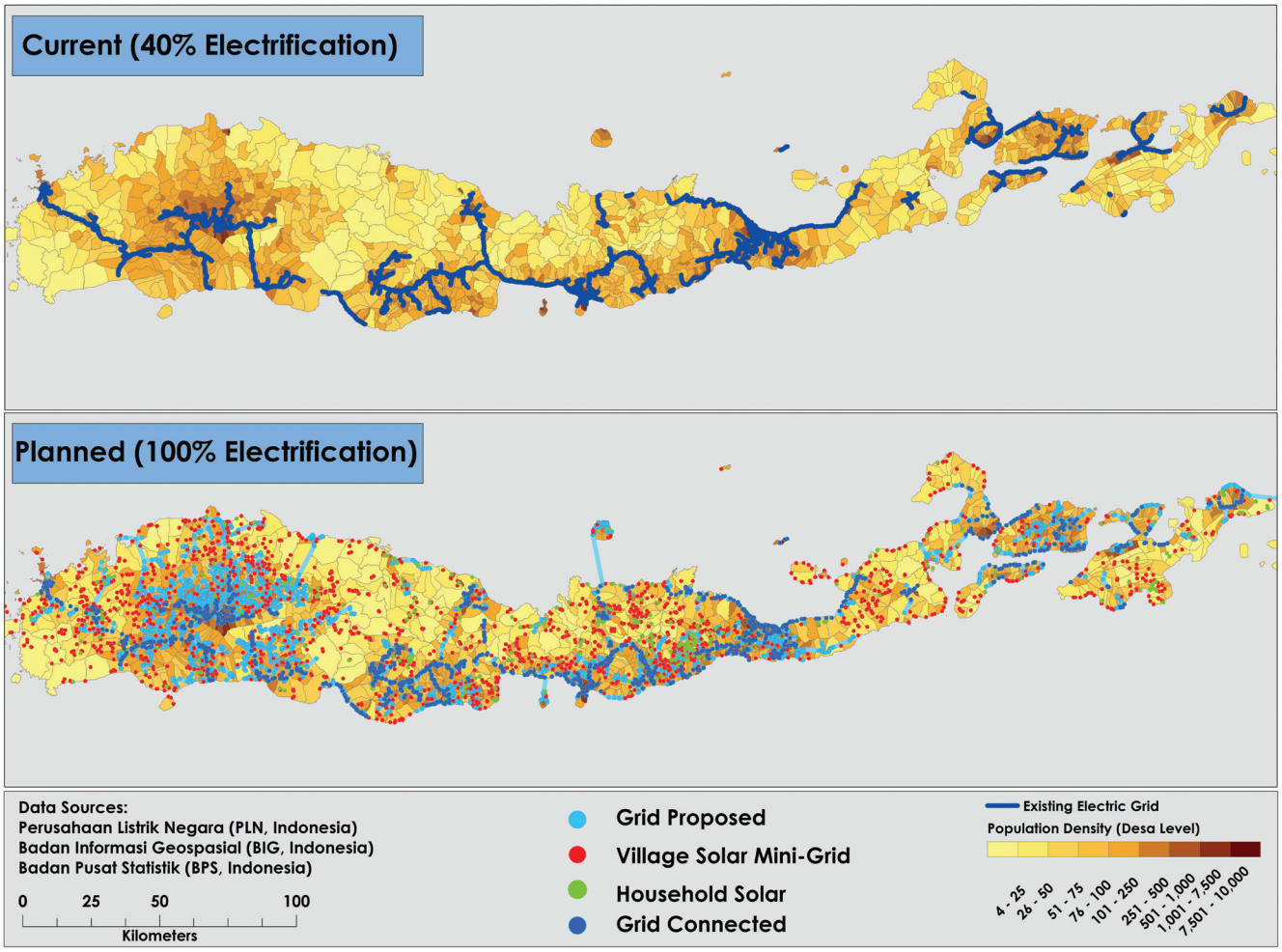
A least-cost technology option is selected for each settlement, leading to the creation of an electrification plan. A key output is a map indicating which communities are recommended for grid connectivity, for whom an estimated route is identified for grid interconnection, and which communities are designated for mini-grid power connection or for electrification using solar home systems. Other outputs include detailed quantitative information on the number of new connections; total and average costs per connection; and various technical details, including estimated MV line length needed for each technology and for each phase of the electrification roll-out plan. From these outputs, a multiphase energy access scale-up plan is developed. The effectiveness of this approach is illustrated in figure 2 with the example of Flores Island, NTT.

Preliminary Results for Flores Island

To date, the geospatial planning approach has been applied to Flores Island, one of the main islands in NTT. Flores has a population of over one million people, 170,000 electricity connections, and an electrification rate of 40 percent. The current status and proposed electrification plan are shown in figure 2. The upper image shows the existing grid line (in dark blue), while the lower panel shows the model results for the proposed, least-cost electricity access program.

The model estimates that the least-cost option for achieving full electrification on Flores consists of making roughly 165,000 new grid connections (blue dots), 84,000 new communal solar mini-grid connections (red dots), and 3,000 new solar home systems (green dots). In total, making the 250,000 new connections will cost US$267 million, or US$1,055 per connection on average (table 1). It will also require PLN to invest in 22 MW of installed capacity.

Figure 2. Results of Geospatial Electrification Planning for Flores Island, NTT



Source: Authors.

Table 1. Summary of New Connections and Total Cost of Electrification Program in Flores

	Number of New Connections	Total Cost (US$ millions)	Average Cost per Connection (US$)
Grid connection	166,000	168	1,012
Communal solar mini-grid	84,400	94	1,114
Solar home systems*	2,650	5	1,887
Total	**253,050**	**267**	**1,055**

*The cost figures presented in table 1 assume that all system types—grid, mini-grid, and solar home systems—must meet the same minimum annual household demand, as specified by PLN. This assumption results in a solar home system peak capacity of approximately 350 watts.

Table 2. Summary of Each Phase of the Rollout

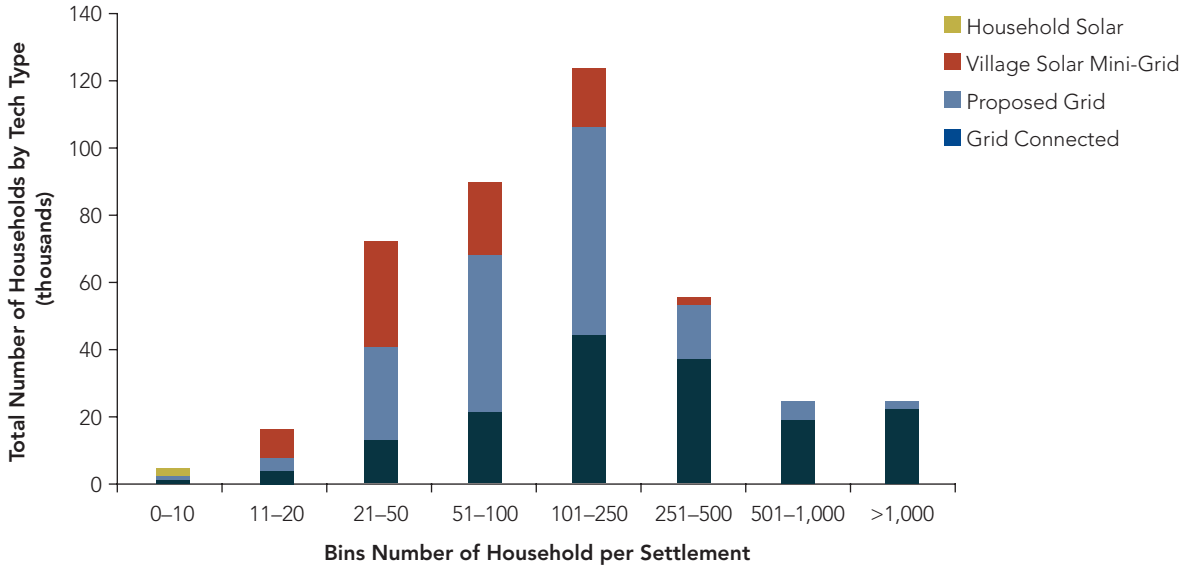
Phase	Number of Households Connected	Total Cost of Phase (US$ millions)	Total new MV lines (kilometers)	Average Cost per Household (US$)
1	19,918	15.85	98	796
2	40,239	41.51	496	1,032
3	40,087	41.48	492	1,035
4	40,017	42.31	526	1,057
5	25,880	26.72	321	1,032
Total	**166,141**	**167.87**	**1,934**	**1,010**

The least-cost electrification option is driven by the number of households per settlement. For settlements with less than 10 households, solar home systems are normally the most cost-effective option. At the other extreme, most settlements with more than 1,000 households are already connected to the grid. Communal solar mini-grids are the least-cost electrification option for half of all settlements with between 11–50 households, and they are still viable for approximately one in five settlements with between 50–250 households (see figure 3).

Assuming a five-phase electrification program, the model optimizes the roll-out plan considering both cost and geographic information, as summarized in table 2. It shows that grid extension ramps up each year as the grid reaches houses that are further from the grid. In addition, the average cost per connection initially increases from phase 1 to phase 2 to reach more remote communities. The main difference in the average cost per connection between the five phases comes from the increase in MV line length required to electrify communities as the grid extends into increasingly remote and less densely populated areas. Households connected during phase 1 require an average of 5 meters of MV line, whereas households connected during phase 2 require an average of 12 meters of MV line. The average cost per connection across all phases is roughly US$1,000 per household.

To further illustrate the grid extension pattern resulting from the geospatial planning approach, West Flores is taken as an example. Figure 4 shows the existing grid (in dark blue) and the proposed grid extension (in light blue) against a

Figure 3. Impact of Number of Households per Settlement on Which Electrification Option is Least Cost



Source: Authors.

Table 3. Highlighted Strengths of the Geospatial Planning Approach

Feature	Existing PLN Roadmaps	Geospatial Planning Approach	Strengths of Geospatial Planning Approach
Purpose of planning tool	Planning how to achieve electrification targets by selecting the best electrification option for each community		Achieves the same purpose as roadmaps, but with additional value at larger spatial scales.
Data inputs	Detailed local surveys	Centralized datasets	Using centralized data sets allows the model to be updated quickly and at low cost. The geospatial model can easily test different scenarios such as changes to the cost of solar panels or limitations in project budgets. It is possible to refine the centralized population dataset per realities reflected in detailed local surveys by Rayon (administrative units), Area, and Wilayah (PLN branch) offices.
Process of using data	Multi-criteria analysis + professional judgments	Optimized model to select least-cost electrification option	The geospatial approach looks beyond the scope of typical planning to anticipate future needs farther from the existing grid. By comparing grid, mini-grid, and off-grid options, the model produces a quantitative, least-cost electrification plan for each settlement.
Presentation of outputs	"Scorecards" for every *desa* showing multicriteria analysis	Maps showing least-cost electrification option; tables summarizing the number of connections and total cost by region	Spatially specific maps are a clear and compelling way to show what full electrification will look like. The maps can be used to communicate electrification plans to governments and donors. They can also be used internally by PLN to inform local electrification planning projects. Results can also be easily broken down into different planning levels, such as by *desa* (village), kabupaten (regency), or kecamatan (district).

background of *desas* shaded from dark to light according to decreasing population density. Phase 1 involves a small number of new connections to reach the most dense (i.e., darkest) but unelectrified *desas* around the main settled area of Ruteng. The subsequent panels for phases 2–5 show incremental grid extensions into relatively densely populated *desas*, with occasional large "leaps" to reach more distant, highly populated areas.[2]

The off-grid space. For those areas where grid extensions are not cost-effective, off-grid alternatives exist, including communal mini-grids and solar home systems. A number of options exist for designing communal mini-grids, including generation technology choice based on available renewable resources and potential integration under a grid expansion program. Communal solar mini-grids are likely to be the least-cost electrification option for communities that are relatively remote and have lower demand that does not justify the capital required for an MV-grid interconnection.

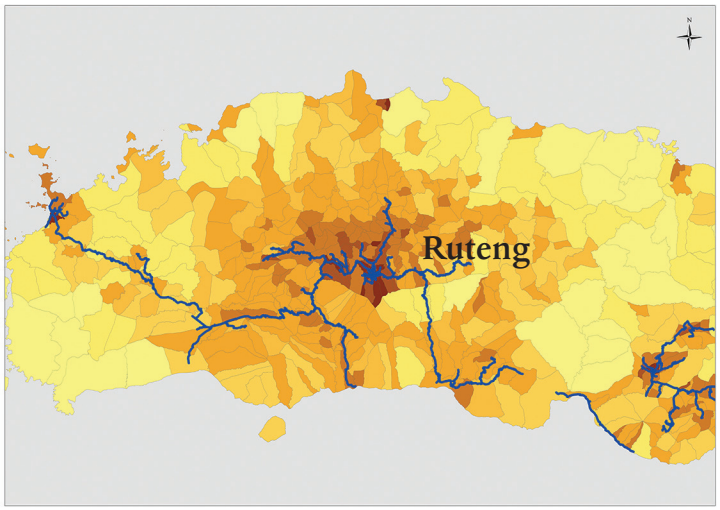
PLN is evaluating a design standard for solar home systems based on a service standard that is equivalent to a PLN customer in the lowest tariff class served by one of its grid network systems. This would require a 350-watt peak solar panel per household. Assuming 1,825 sun-hours per year and 75 percent efficiency, these systems can supply 40 kWh equivalent per household per month, which provides sufficient energy to light a small house, charge a cell phone, and run a radio. At costs of approximately US$5–6 per watt peak installed, such a system would cost about US$2,000 per household, which is roughly consistent with the estimate used for this modeling effort, as summarized in table 1.

Benefits of the Geospatial Planning Approach

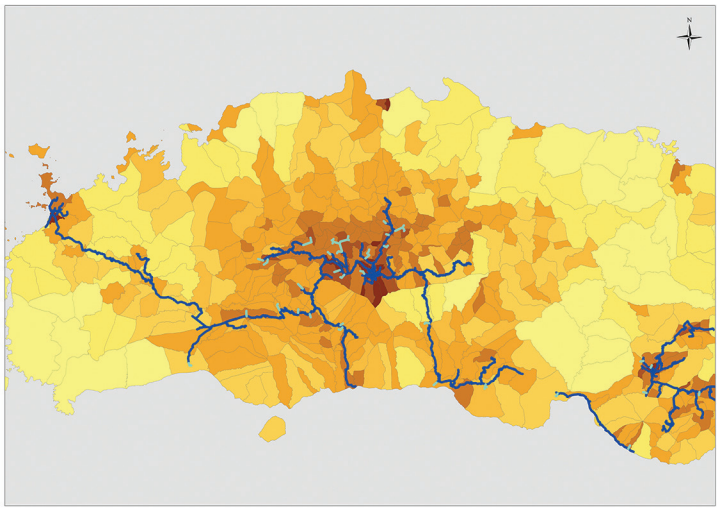
Complementing the current electrification roadmap process at PLN, this geospatial planning approach is useful for rapidly creating a credible least-cost electrification plan that is relatively easy to replicate and can be used as an effective communication tool both internally and externally (table 3). It provides results that support high-level budgetary planning—both for PLN internally and for PLN to communicate to external stakeholders like the Ministry of Finance, the Ministry of Energy and Mineral Resources, and international donors.

2. Note that due to the high level nature of the planning process, this illustrates a grid plan, meant to convey an estimated pattern for inter-connecting settlements in order to create a least-cost network; it does not indicate a proposed grid design, which would specify precise routing and reticulation of transmission and distribution lines in a manner much more responsive to the specifics of topography, road networks, and other features and to detailed electrical engineering considerations.

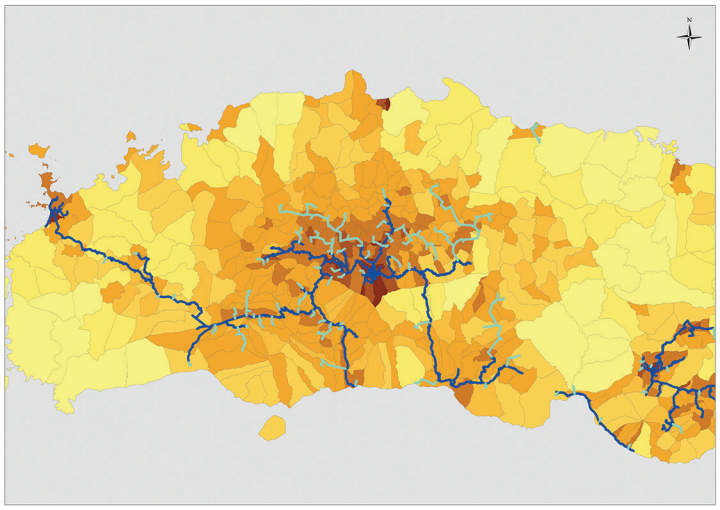
Figure 4. Proposed Grid Expansion in West Flores (light blue)



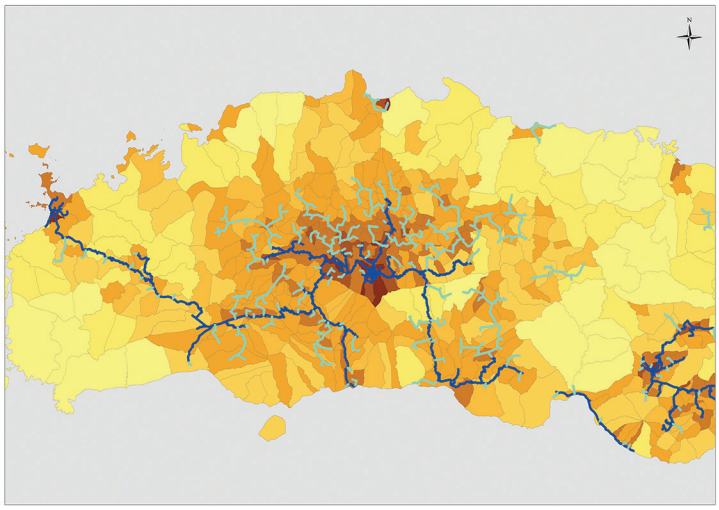
Baseline



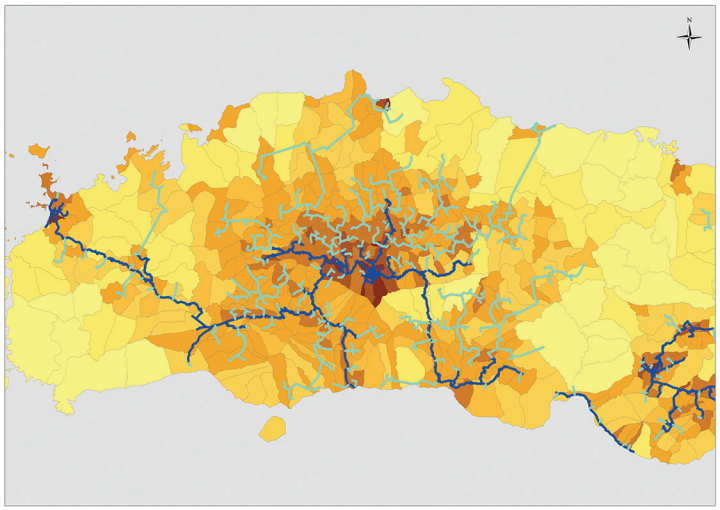
Phase 1 (98 km)



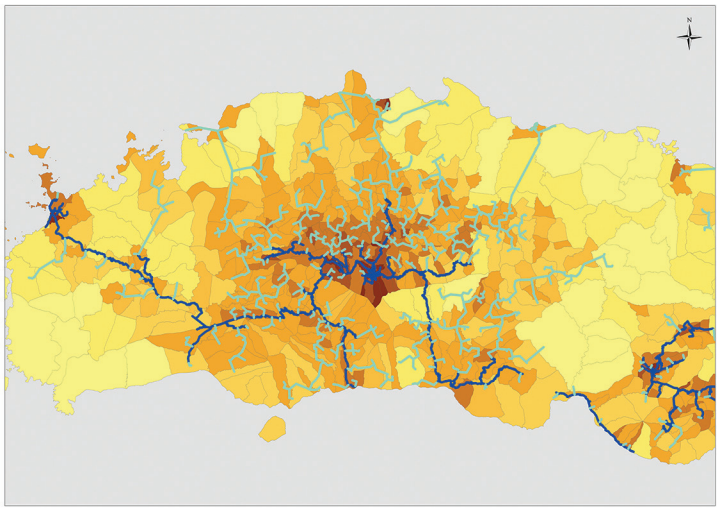
Phase 2 (496 km)



Phase 3 (492 km)



Phase 4 (526 km)



Phase 5 (321 km)

Source: Authors.

The Way Forward

The results of the geospatial least-cost electrification network planning approach as illustrated in this progress brief for the island of Flores, NTT have demonstrated the added value of this planning framework. Specifically, PLN has endorsed the methodology as an effective tool for preparing a holistic, credible, and spatially explicit electrification rollout plan that complements the current system planning process at PLN. In addition, this planning approach can provide a strong analytical foundation to anchor the preparation of a sector-wide investment funding prospectus for the plan's focus areas. Scaled-up application of the methodology to the rest of Indonesia shall be forthcoming to assist and anchor the GOI and PLN's high-level budgetary planning and financing framework for an electrification rollout to be organized within a programmatic sector-wide approach. Moreover, this geospatial planning approach will be used as the basis for rallying donor participation and syndication of the projected financing gap for a least-cost electrification planning rollout that is directly aligned with national priorities and access targets.

Acknowledgments

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Suggested Readings

ESMAP 2012. "Rwanda: Extending Access to Energy, Lessons from a Sector-Wide Approach (SWAp)." World Bank, Washington, DC. http://www.esmap.org/sites/esmap.org/files/ESMAP_Energy_Access_RwandaSWAp_KS013-12_Optimized.pdf.

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Parshall, Lily, Dana Pillai, Shashank Mohan, Aly Sanhoh, and Vijay Modi. 2009. "National electricity planning in settings with low pre-existing grid coverage: Development of a spatial model and case study of Kenya." *Energy Policy*. http://modi.mech.columbia.edu/wp-content/uploads/2013/04/Kenya-Paper-Energy-Policy-journal-version.pdf.

Above: PLN's island-based grid-connected Solar PV facility at Gili Trawangan

Left: Improving electricity access through renewable energy generation resources

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