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Efficient System Design and Sustainable Finance for China's Village Electrification Program

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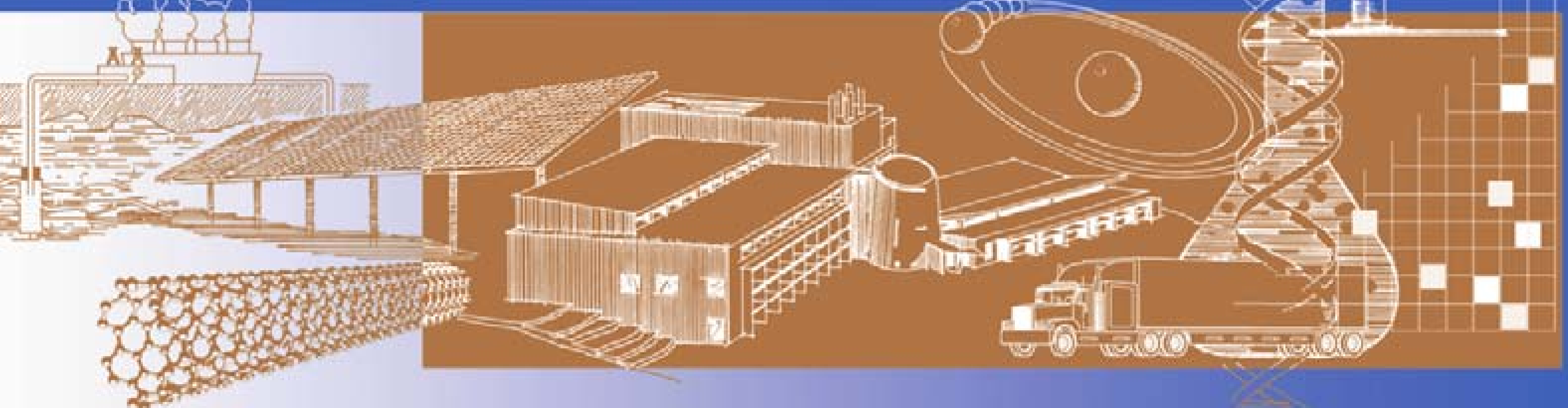

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ABSTRACT

This paper describes a joint effort of the Institute for Electrical Engineering of the Chinese Academy of Sciences (IEE), and the US National Renewable Energy Laboratory (NREL) to support China's rural electrification program. This project developed a design tool that provides guidelines both for off-grid renewable energy system designs and for cost-based tariff and finance schemes to support them. This tool was developed to capitalize on lessons learned from the Township Electrification Program that preceded the Village Electrification Program. We describe the methods used to develop the analysis, some indicative results, and the planned use of the tool in the Village Electrification Program.

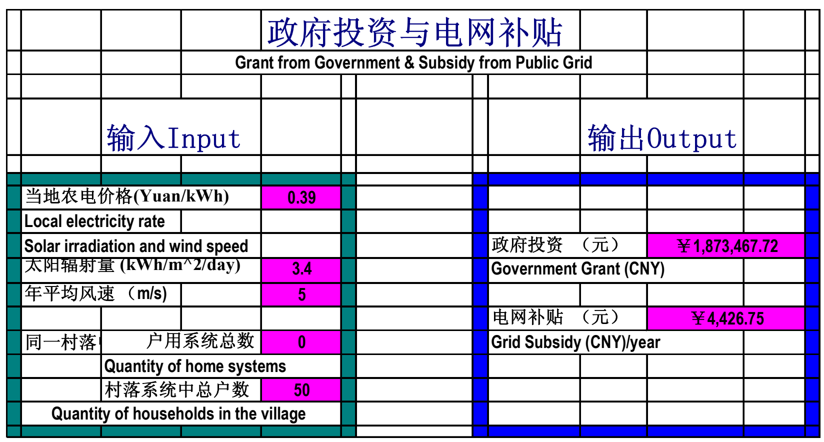

Fig. 1. Initial version of the tool interface

1. INTRODUCTION

China is engaged in a rural electrification program that will provide electricity to 30 million citizens who currently lack access, and has committed several hundred million dollars to this effort. Because of the program's size, and China's standing within the community of developing nations, this program could provide an influential model of best technical and financial practices in rural power systems.

To build on the experience of the Township Electrification Program that came before, IEE and NREL set out to develop a tool that could provide reliable, easy-to-use guidance for those implementing the Village Electrification Program.

Such a tool needs to provide two key kinds of information: system design guidance, and estimates of the costs that can be used as the basis for financing for the systems. Figure 1 shows the user interface of the initial version of the tool. The interface is bilingual and costs are expressed in Yuan.

2. OVERVIEW OF THE ANALYSIS EFFORT

This work began with an analysis of several different sized villages under a range of renewable resource regimes. The results have been incorporated into a simple software system (the "tariff tool" or "tool"), which provides design and finance guidance for the situation chosen by the user. The first version of the software was developed as an Excel spreadsheet. At the time of this writing, the same algorithm was being rewritten in Visual Basic.

The tool requires three kinds of inputs: the electricity tariff that customers will pay, renewable resource data, and the configuration of the village. From those user inputs, the tool calculates the grant required from the government to cover the initial capital cost, and the cross-subsidy required to cover the ongoing costs not covered by the specified user tariff. The tool also reports a summary of the design of the system used to develop the cost estimates.

3. ANALYSIS METHODOLOGY

As described above, the tool provides design and finance guidance based on results for a range of conditions that have been developed off-line and incorporated into the tool as static tables. This section describes the analysis used to develop those tables.

3.1 Range of Conditions Considered

Over the range of conditions summarized in Table 1, the analysis developed a least-cost design and estimates of the cost components of that design. There are 189 cases: (9 village sizes) X (3 solar radiation regimes) X (7 wind speed regimes). The "village" with 1 home is a stand-alone single home system; all the others are based on a mini-grid design.

TABLE 1: RANGE OF CASES CONSIDERED

VARIABLE	VALUES CONSIDERED	NOTES
Village size	1, 20, 25, 30,35, 40, 45,50,100,200	Number of households
Average annual solar radiation	3.4, 4.18, 4.95 kWh/m^2-day	See section 3.4 on the development of time profiles for wind and solar
Average annual wind speed	2, 3, 4, 5, 6, 7, 8 m/s	

The analysis for each case begins with three types of inputs: load curves, cost and performance data for system components, and the solar and wind regimes. These data are then used by NREL's HOMER micro-power optimization model to find the least-cost system design that will meet the given load within specified tolerances. The analysis assumes that the systems will be off-grid and assumes that policy will not allow for the use of diesel generators. The elements of the design and cost analysis are described next.

3.2 Data Sources

The data used were developed based on IEE's field surveys and experience, Chinese manufacturer specifications, and in some cases NREL component test data. The data were then adapted to the form required as input to the HOMER model.

3.3 Load Profiles

IEE and NREL developed the load curves based on surveys of some existing village power systems in Qinghai and Gansu provinces in Western China. In those surveys, IEE identified the kinds of end uses included in village homes, schools, and clinics. The end use categories are lights, TVs, VCRs, refrigerators, and other. IEE then estimated the power requirements and usage time profile for each device type. The profile is expressed as the probability that the device will be on during each hour of the day for two seasons. Summer season includes June, July, and August, and the second season includes all other months. The load curves are the result of hourly simulation for a representative year, based on the number of devices of each type connected to the system and their probability of being in use during that hour.[1]

The 8,760-hour annual load curve is part of the data used in the off-line HOMER analysis. In the user interface, the mini-grid size is specified by the number of residences included. Additional loads for nonresidential facilities are included as a function of the number of households. In addition, the village can include remote households that will be served by single-home systems, and the number of those is also specified. In many cases, all the households in the village may be served by single-home systems. The analysis does not explicitly consider the potential expansion of village systems with load growth from added devices or growing population.

3.4 System Components

The system includes generators, batteries, an inverter/ rectifier, and if it is a mini-grid system, distribution lines and a central control system. Generators can be PV, wind turbines, or both. Several different sizes of wind turbines are used depending on the load being served. The analysis did not consider other technologies such as micro-hydro or biomass. Further work could consider those technologies, since the HOMER model can evaluate them as well.

The design and cost results depend strongly on the cost and performance of the system components and considerable effort went into the development of these data. Each type of component is described in HOMER by a different set of cost and performance parameters [2].

3.5 Solar and Wind Resource Data

As seen above, a single annual average value is used to describe the solar and wind resource levels in kWh/m^2-day and m/s, respectively. Those average values are used as scale factors that multiply 8,760-hour time profiles, developed as described below.

The solar radiation profile is for a single geographical location, relatively central to the area of Western China where most of the Village Electrification Program will be conducted. That location is used to develop the time profile of insolation by applying the Graham algorithm [1] to twelve monthly average values supplied by the NASA web-based data for the representative location [3].

Hourly wind-speed values are developed similarly. A table of monthly average wind speeds for the village of Zhoujiajing, Gansu was used as the basis for seasonal variations. In each month, hourly wind speeds were estimated by sampling from a Weibull distribution with the corresponding average value.

3.6 System Design and Cost Estimation

NREL's HOMER model provides a method for finding the least-cost system design given the load, component, and renewable resource data described in Sections 3.1-3.4. Its methods are reviewed in broad outline here. For additional details, see [2].

HOMER proceeds by simulating each of the 8,760 hours of the representative year. The model performs this annual simulation for each of a number of candidate designs. After examining the entire set of designs, the model selects the one that can meet the load within the specified tolerance at least cost. The model can also perform this optimization across a range of exogenous variables, such as renewable resource levels and system component costs.

The information available from a HOMER analysis includes cost data broken into capital and operation/maintenance costs for each component, as well as tools for comparing the least-cost systems with other potential options. The software also facilitates comparing across ranges of exogenous variables. When results are compared between two different renewable resource regimes, for example, the comparison uses the least-cost system for each of the two resource regimes.

3.7 Tariff Policy

The policies of China's Village Electrification Program combine with the system cost information to determine the tariff structure and the requirements for government support. The results included in the tariff tool incorporate a number of consensus recommendations from two workshops organized by IEE to solicit input on their initial recommendations. (The analysis described here was developed to support IEE's initial recommendations and illustrate their implications for system financing.) The workshop recommendations were as follows:

Basic loads are defined at a level of 200kWh/year per household. In mini-grid systems, loads for public facilities are added, for an average of 247.5 kWh/year per household. The tariff tool estimates finance parameters for systems that will cover basic loads. Users who want higher levels of service will have to make arrangements with their local service provider.

Grants from government will be used to cover the initial capital cost of the system. Costs incurred after that will be covered from two sources: User tariffs equal to the locally prevailing rates for users connected to the grid, and a cross-subsidy collected from ratepayers connected to the national grid. Accordingly, the output of the tool gives the total grant required for the initial capital cost and the recurring annual cost required from the cross subsidy.

The tariff policy recommendations make the calculation of the tariff information straightforward. The spreadsheet contains a static set of tables that are taken from HOMER results across the range of conditions listed in Table 1. The model selects system for the mini-grid, if any, based on the number of connected households and the renewable resource regime specified. For in-between values, the model selects the point from the table with the next largest village size and the next smallest solar and wind resource. This will ensure that the selected design will adequately meet the load for the specified number of homes. The model uses the cost components of the selected system design to compute the elements of the grant and subsidy components of the financing for the system. The model also reports the least-cost system design that is used as the basis for the costs.

4. KEY RESULTS

The analysis described above supports several observations that will apply to the Village Electrification Program generally.

4.1 Cost of Electricity

As with typical off-grid systems, electricity prices are relatively high. For the conditions considered here, levelized cost of electricity varies between \$0.57 and \$1.04/kWh for individual home systems. For a village mini-grid with 100 homes, levelized cost is between $0.87 and $1.09.

Comparing the results for home systems and mini-grids suggests that the minimum economic scale for mini-grids is at least 100 households, and probably higher. The cost of distribution lines and central control facilities are quite high compared to the generating equipment, and they do not increase as fast as village size. So for mini-grid systems, the levelized cost of energy is close to inversely proportional to village size, as shown in Figure 2.

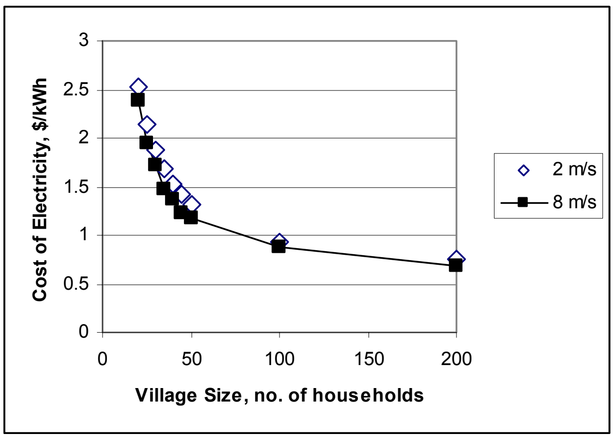

Fig. 2: Cost of energy as a function of village size

4.2 System Design

Table 2 illustrates how the cost of electricity depends on the system design for a single-home system.

TABLE 2: ALTERNATIVE SYSTEM DESIGNS

PV (kW)	Wind (kW)	Number of Batteries	Cost of Energy ($/kWh)
0	1	3	$0.63
.05	1	2	$0.71
.2	0	5	$0.85

The addition of a small wind turbine reduces the cost by 26% compared to the system using PV only. These estimates are based on performance tests of 50 peak watt wind turbines available in China, suggest that those turbines could be useful in remote applications in many areas of rural China. However, the increased complexity of systems that include wind turbines will also have to be considered in the design decision. The results in Table 2 are for wind speed 6 m/s and insolation 3.33 kWh/m^2-day

Table 2 illustrates how the three components complement each other. Adding 50 Watts of PV eliminates 1 battery, but the PV panel costs more. Adding 200 Watts of PV and 2 batteries to the least-cost system shown in the first row eliminates the need for the wind turbine, but increases total cost.

4.3 Renewable Resource Availability

Figure 3 shows how the least-cost single-home system configuration changes as a function of the renewable resource availability, showing the transition from PV-battery to wind-PV-battery to wind-battery as wind speeds increase. For mini-grid systems, wind turbines begin to be economic at higher wind speeds, because the larger wind turbines used in those systems have higher cut-in speeds.

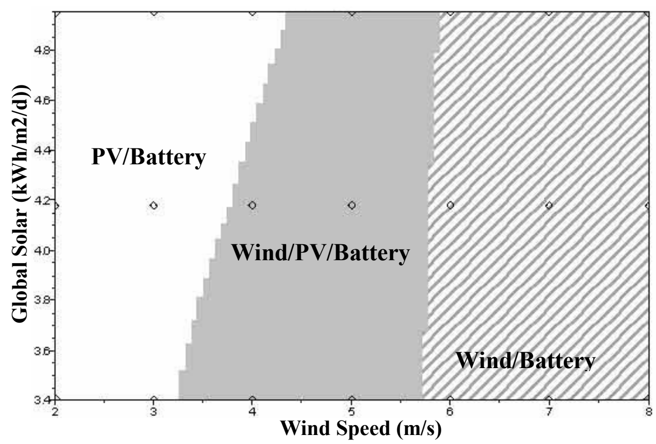

Fig. 3: Influence of renewable resource regime on system configuration

Figure 4 shows how the wind and solar regimes affect the levelized cost of energy for single-home systems. Starting from nominal values of 4 m/s annual average wind speed and 4.18 kWh/m^2-day average insolation, the wind speed has a much greater potential impact on the levelized cost.

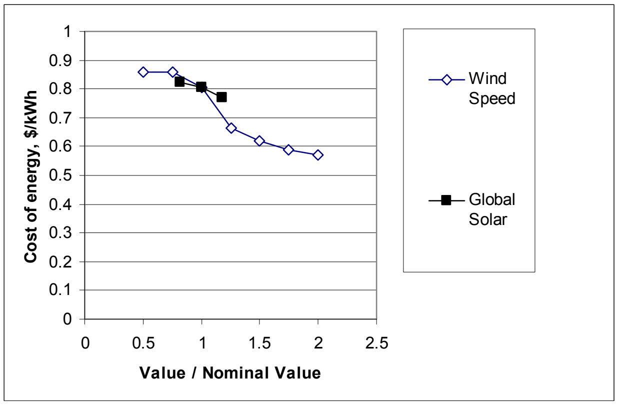

Fig. 4: Influence of renewable resource regime on cost

4.4 Component Cost

Figure 5 shows how the initial capital cost of the PV panels, wind turbines, and batteries influences the levelized cost of energy for home systems. The influence of PV cost decreases markedly at higher values.

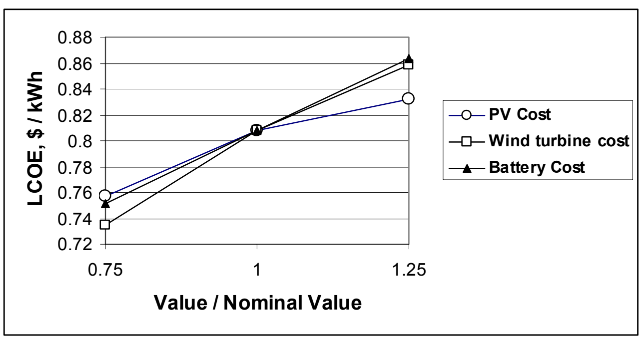

Fig. 5: Relative influence of component costs

4.5 Allocation of Total Cost

Figure 6 illustrates how the system costs of a home system are financed, using the recommendations of the workshop study group discussed in Section 3.6. The grant and cross-subsidy pay most of the costs because the cost of electricity from the small home system is an order of magnitude larger than the local grid-connected rate.

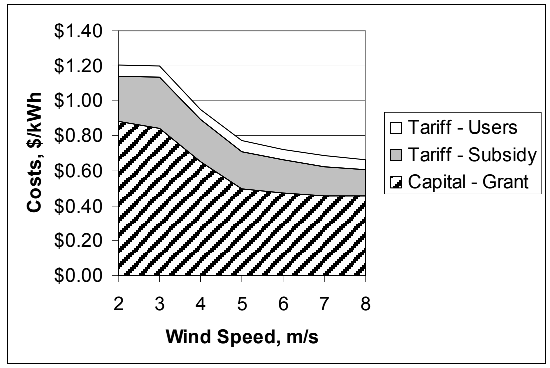

Fig. 6: System Finance Components

Figure 6 also illustrates how the allocations shift with changing system designs. Here the system design changes with the average annual wind speed, shown on the x-axis. Customer tariffs remain constant at $0.06/kWh (0.5 Yuan/kWh), the nominal value for the local grid electricity rate. As the wind speed increases, the total cost decreases. Customer tariffs cover a slightly larger fraction of total costs. Between 2 and 3 meters per second, the cross-subsidy component actually increases slightly in absolute terms, even though total cost is decreasing. This happens because as wind turbines enter the system, the overhead and maintenance component increases while the initial capital cost decreases more than enough to compensate. Since the operating and maintenance costs are part of the subsidy, that component increases.

5. USE OF THIS WORK IN THE VILLAGE ELECTRIFICATION PROGRAM

One of the most important and potentially influential features of this work is the way that it is proposed to be integrated into the Village Electrification Program in China. The workshop organized by IEE proposed that the tool based on this analysis be used as a mandatory standard for system design and finance throughout the program. At the time of this writing, that recommendation is under consideration by the National Reform and Development Commission. The simple interface and conceptual framework of the tool make it useable by system integrators and provincial utility staff independent of outside technical assistance. This ease of use will promote efficient system designs and sustainable finance through a decentralized organizational framework that can meet China's ambitious timetable for rural electrification.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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(2) T. Lambert, P. Gilman, P. Lilienthal, "Micropower System Modeling with HOMER," in F. Farret, M. Simoes, *Integration of Alternative Energy Sources of Energy,* John Wiley and Sons, 2006. Available online at http://www.mistaya.ca/products/homer.htm

(3) NASA, online solar radiation database, http://eosweb.larc.nasa.gov/sse/

[1] For any given hour, the assumption that all the devices of a given type have the same probability of being on implies that the number of devices on has a binomial distribution. In each hour, simulations are made by sampling from this distribution for each device type and adding the loads across device types.

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