Reducing the Cost of Grid Extension for Rural Electrification

NRECA International, Ltd.

February 2000

Joint UNDP/World Bank Energy Sector Management Assistance Programme
(ESMAP)

Contents

Acknowledgments

A number of individuals must be acknowledged for their contributions to this effort. Myk Manon, NRECA's Team Leader for El Salvador, contributed costing data from El Salvador as well as many of the ideas and numerical examples used in this study. Mr. Manon has three decades of experience with rural electrification around the world in El Salvador as well as in Bangladesh, Bolivia, and Nicaragua and other Latin American countries. He has been actively involved in making rural electrification more accessible to rural populations through more appropriate designs and more efficient project implementation.

Ron Mettler, a distribution engineer with broad experience in the United States and Latin America, contributed costing information and furnished a critical review of this document.

An important part of this study was to assess existing experiences around the world that have often not been readily available and documented. A number of individuals helped track down or prepare breakdowns of line costs in the countries in which they were working. These include Ashok Ahuja from New Delhi, India; Stephen Anderson of the Benton Rural Electric Association in the state of Washington; Ricky Bywaters of the Rappahannock Electric Cooperative in the state of Virginia; Cheikhou Cisse of SENELEC of Senegal; Fernando Haderspock of Cooperativa Rural de Electrificación in Santa Cruz, Bolivia; Colin Jack of NRECA in Bangladesh; Mae Soriano of the National Electrification Administration (NEA) in Manila; and Eduardo Villagran from the NRECA office in Guatemala City.

James Taylor, a wood pole specialist from the state of Virginia with broad international experience in the wood pole business, contributed background into the issues on costs and quality of treated wood poles. James Carter of NRECA's Wood Quality Control program shared his knowledge of the workings of that program as an example of how the availability of specifications can help ensure the quality of the materials used for line construction. Pablo Pan III of NEA in the Philippines provided background information on their pole growing program and pole treatment activities.

From the World Bank, Willem Floor provided the resources to undertake this study and assisted in the tedious task of gathering field information. Robert van der Plas also aided in this task. Anthony Sparkes supplied numerous useful comments and suggestions.

And special thanks goes to Gil Medina, the NRECA representative in Manila, who was always prompt, reliable, and efficient in tracking down a range of other information from the field.

Finally, thanks to Mark Hayton, Dale Nafziger, Robert Gibson for providing the photographs in Figures 11, 13, and 31, respectively. All other photos were taken by the author.

Allen R. Inversin
Arlington, VA

Acronyms and Definitions

ACSR	aluminum-conductor, steel-reinforced; currently the most commonly used conductor for power lines
AAAC	all-aluminum alloy conductor
AAC	all-aluminum conductor
BAPA	Barangay Power Association (Philippines)
CCA	chromated copper arsenate
CIF	cost, insurance, and freight (the cost of the commodity, including interest and freight costs incurred in shipping)
GEF	Global Environment Facility
guys	stays
HV	high (transmission) voltage
kV	kilovolt
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt hour
LV	low voltage (also called *secondary voltage*; generally based on 120- or 240-volt single-phase supply)
m	meter
mm	millimeter
MV	medium voltage (also called *primary voltage*; usually in the range of 1 to 35 kV)
NEA	National Electrification Administration (Philippines)
NESC	National Electric Safety Code (United States)
NRECA	National Rural Electric Cooperative Association
PV	photovoltaic (generating electricity through the conversion of light energy)
RE	rural electrification
REA	Rural Electrification Administration, the U.S. government agency under the Department of Agriculture responsible for oversight of the American rural electrification program; now the Rural Utilities Service (RUS)
REB	Rural Electrification Board (Bangladesh)
RUS	Rural Utilities Service (see REA)
SWER	single-wire earth-return (pp. 20, 33)
SHS	solar home system (a PV-based system to provide basic lighting and entertainment needs to an individual home, with a capacity typically in the range of 10 to 100 peak watts)
W	watt(s)
WQC	NRECA's Wood Quality Control program

Glossary

European configuration	A medium-voltage (MV) distribution system characterized by the widespread use of a three-phase, three-wire configuration where consumers are generally served by relatively few transformers of a higher capacity. Single-phase distribution relies on supplying loads with two rather than all three (phase) conductors. Only recently has single-phase distribution been more widely used for supplying rural areas.
ground(ing)	Connecting to the earth, or ground.
North American configuration	A medium-voltage (MV) distribution system characterized by (1) the widespread use of a three-phase, four-wire configuration, with the fourth (neutral) wire solidly grounded at numerous points along the line and (2) the heavy use of smaller, single-phase transformers to serve most consumers. Single-phase distribution relies on supplying loads with the neutral conductor and only one of the three phase-conductors. Single-phase distribution is widely used for supplying rural areas. Vee-phase distribution is also used.
vee-phase	A North American distribution system configuration in which supply is provided by the neutral and only two of the three phase-conductors (p. 33), increasing line capacity when compared to single-phase distribution and permitting low-cost access to three-phase power.

Executive Summary

Meeting the broad development needs of rural areas in developing countries around the world places numerous competing demands on limited financial resources. Because rural electrification is just one of these demands, it is important to ensure that resources devoted to this sector are efficiently used. The focus of this study is to benchmark the cost of medium-voltage (MV) grid extension—of bringing power from a supply at point A to a load center at point B—and to then identify ways to reduce this cost and increase the attractiveness of grid extension as a means of bringing the benefits of electrification to rural populations.

Existing costs were gathered from a variety of countries, and findings are presented. Some of these can be summarized as follows:[*]

- The cost of labor and materials for three-phase line construction typically ranges from $8,000 to $10,000 per kilometer, with costs of materials alone averaging $7,000.
- The cost of poles accounts for roughly 40 percent of the cost of materials, and the use of low-quality poles can quickly double life-cycle pole costs.
- The cost of the conductor (i.e., wire and cable) is usually the second-most-costly component, but its contribution is case-specific because it depends on the load being served and the voltage used.
- Savings of 30 to 40 percent are possible through the increased use of single-phase construction, which can satisfactorily meet all foreseeable needs of most consumers.
- On an annual basis, the operating cost of transformers can be several times their capital cost.
- Because of the non-availability of smaller transformers, the use of oversized transformers can contribute significantly to the per-customer cost of electrifying small rural population centers.

The study presents a variety of options for reducing the cost of grid extension, including the following:

- Using higher voltage,
- Using higher quality poles to reduce life-cycle costs,
- Wider use of single-phase distribution,
- Considering the life-cycle costs of transformers rather than simply the initial capital cost ,
- Properly sizing and placing transformers,
- Considering alternative pole designs,
- Standardizing materials and designs,
- Implementing quality assurance programs,
- Developing manuals and specifications for staking and design, and
- Using small transformers to serve small load centers adjacent to MV lines.

By adopting practices such as these, the cost of three-phase construction (including both materials and labor) over normal terrain in developing countries could typically be $5,000 per kilometer (not including site-specific import duties and transportation costs). Use of single-phase distribution could reduce this cost to roughly $4,000 per kilometer. In countries where labor costs are high, these figures could typically increase by up to $2,000.

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[*] All costs are in U.S. dollars.

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Overview

Demand for electricity in rural areas worldwide has traditionally been met by extending the electricity distribution network out from the cities and towns that were the first areas to be electrified. As the years have passed, however, with the lower consumer density in the new rural areas being served, the cost of bringing power to each new consumer has increased. At the same time, these new consumers have less disposable income and purchase less electricity. In light of increasing construction costs per consumer, low revenues, and the logistical difficulties and associated costs encountered in managing rural systems, electric utilities around the world have found it increasingly difficult to meet demand for electricity in rural areas.

More recently, as the cost of photovoltaic (PV) modules has dropped, interest has focused on harnessing PV technology for rural electrification (RE). Although this can be done using centralized PV battery-charging stations or PV hybrid systems managed by an entrepreneur, the local community, or the government, individually-owned PV solar home systems (SHS) have proved more popular. A niche market exists for this technology, but drawbacks remain, including the following:

- Both capital and recurring costs are and will remain high for some time to come;
- Any subsidies to reduce cost tend to benefit the wealthier segment of the population that can more easily afford these systems; and
- Although the small quantity of electricity generated is welcomed, its use is limited to basic lighting and entertainment.[*]

For such a large per-household investment, it contributes little to the economic development of rural areas or to amenities and services for the general population.

Some see the need to rely on an electric utility—an organization external to the community being served—as another drawback to extending the grid to rural communities. However, reverting to PV generation, even through the use of isolated SHSs, does not preclude this need. Experiences worldwide are

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[*] Even if the PV module were free, the monthly recurring cost of a typical SHS is still significant for many rural households: at least $2-3 for the battery (irrespective of whether it is an automotive or deep-discharge battery), roughly $1 for eventual replacement of the controller, etc., and possibly $1 for periodic technical service calls.

demonstrating that the equivalent of an electric utility is still necessary to provide acceptable financing and ongoing maintenance for SHSs, two key inputs required for affordable and sustainable SHS projects, respectively.

Other alternatives exist, each with advantages and disadvantages. Small hydropower plants can produce power at low cost but need a high capacity factor to be able to capitalize on their low cost. This is often difficult to achieve in rural areas where most of the load is residential and where no grid exists to absorb excess generating capacity. Furthermore, during the dry season, streamflows may be inadequate to generate sufficiently to meet demand.

Diesel plants are generally a low-cost option; however, in remoter areas access to fuel year-around may be difficult and costs high. Sufficient mechanical skills must also be available to maintain the equipment in proper operating condition.

Therefore, no single “best“ option stands out for supplying affordable electricity to those beyond peri-urban areas. Rather, for each situation, the appropriateness of each RE option should be continuously assessed as technologies, costs, demand, and circumstances change. Electrification by grid extension, whether generated from fossil fuels or renewable energy sources, is one such option and is the focus of this study.

Rationale of the Proposed Study

In countries where the quantity and quality of power from the grid is insufficient, alternatives such as PV or diesel generation may be the only electricity-supply options in rural areas. These options may also be advantageous because those desiring electric service are then not subordinate to the whims of a national utility that may not be interested in extending lines into new service areas.

But where adequate capacity exists on the grid and the government is interested in extending service into rural areas, grid extension presents significant advantages over other options from the points of view of both cost-effectiveness and social equity. These advantages include the following:

- When power lines are extended to a village, all rural households—even those who do not have the financial resources to afford electricity in their own homes—can enjoy its benefits, such as pumped or irrigation water, street lighting, improved educational and health services, agro-processing, and employment.
- The grid provides enough electricity to permit broad economic development activities rather than simply lighting and entertainment.
- Extending the grid into often neglected rural areas is perceived by rural households as a permanent community investment and creates a national infrastructure on which to base future socioeconomic development.
- Economies of scale, which accompany the generation of electricity by large, centralized generation plants, result in low-cost electricity.
- For broad electrification programs, cross-subsidies between the generally wealthier urban consumers and the poorer rural population are straightforward to implement and can obviate the need for government subsidies.
- Where electricity is derived from generation based on fossil-fuel, centralized generation facilitates the implementation and monitoring of pollution mitigation measures.

Of course, although the advantages of grid extension are numerous, an important dissuading argument remains its cost. Those promoting other agendas may exaggerate this to their advantage by, for example, alluding to the "huge expense of expanding electric grids into rural areas, at an estimated cost of $20,000–$30,000 per kilometer" or the fact that the solar alternative is "a bargain compared to the $50,000 to $75,000 the local utility charges to extend power lines to a new home that is just one mile from the grid." [1] Nonetheless, cost does indeed remain an obstacle to broader electrification.

It is important to go beyond rhetoric, however, for two reasons: (1) the advantages of grid extension seem overwhelming in cases where sufficient generation capacity exists on the grid and (2) other approaches to RE are competing for the same limited financial resources. The situation calls for both a more accurate estimate of the true costs associated with grid extension and an assessment of the extent to which high costs are intrinsic to it. Only then will national policymakers have the information necessary to decide the best course of action to take to implement RE in each situation, whether by grid extension or by reliance on isolated PV, micro-hydropower, or diesel generation.

Indications already exist that grid extension can be much less costly than many currently assume and can be provided at a small fraction of the costs noted above. For example, at the lower end of the scale, efforts in Nepal have shown that total project cost for grid extension and distribution to rural households can cost less than $150 per connection, with minimal recurring costs.[2] This can be compared to the capital cost of at least $600 per household for a typical (i.e., 50-peak-watt) PV SHS, in addition to a recurring cost of at least $4 per month. An initial review of costs even in rural areas of an industrialized nation such as the United States, moreover, reveals that the cost for materials used in line construction can be as low as $3,000 per kilometer, equivalent to the cost of only five typical SHSs.[3]

From an historical perspective, finding ways to reduce the costs of RE is not a new idea. When a major effort at electrifying rural areas in the United States began in the 1930s—when only 11 percent of rural households had access to electricity—the problem of high costs was also at issue. The solution then was to reassess the approach that had been taken in implementing electrification projects. As a consequence, new technical designs (such as 4-wire multi-grounded neutral and single-phase taps) and new institutional approaches (rural electric cooperatives) were developed and adopted. This permitted most of rural America to be electrified over a period of roughly 20 years, in spite of the considerable diversion of resources to war efforts during a portion of this time. Studies of RE in Ireland and Thailand also illustrate approaches to reducing the cost and increasing the effectiveness of RE efforts.[4]

These experiences suggest that, rather than dismissing grid extension as too expensive, efforts should focus on taking a fresh look at the needs of rural populations in developing countries and then to once more adopt and adapt, or develop if necessary, designs to more cost-effectively meet these specific needs.

Study Structure and Purpose

This study first reviews the cost of grid extension in a number of countries. It then identifies ways to reduce these costs by examining how they are affected by a variety of factors.

An electricity supply system may be divided into two discrete components:

1. *Grid extension*: the infrastructure required to transmit power at a medium voltage[*] from the source—the national grid or an isolated power plant—to demand centers where it makes it available at low voltage. This includes both the MV distribution line from the supply at point A to a load center at point B and the distribution transformers at this load center.
2. *Low-voltage (LV) distribution system*: the distribution system within a load center that serves individual consumers.

This study will focus on the first of these two components, the cost of grid extension. Three questions will be asked:

1. What factors give rise to the costs commonly associated with grid extension for RE?
2. Are high costs intrinsic to grid extension? If not, what has been learned from experiences around the world about technical design options that can reduce the capital cost incurred in line construction as well as the recurring costs incurred in operating the system?
3. How low can these costs typically be?

The second component—the LV distribution system within a village—is integral to an electricity supply system and basically can be the same whether the demand center is served by the national network, a village diesel plant, or a hydropower or other renewables-based power plant. Proposing designs to reduce the cost of this second component will be part of a separate effort.[†]

Although data on the capital cost of a line are the easiest to obtain and analyze, it must be kept in mind that, for those making an investment decision, the line's life-cycle cost should be of greater importance. An initially inexpensive line that needs frequent maintenance, overhauling, and upgrading can require considerably greater investment during its lifespan than a line that has been adequately designed from the outset. Consequently, where relevant, the following discussion will also consider the life-cycle cost implications of line design.

This study is not meant to be final or definitive and, for many readers, may include little that is new. Rather, it recognizes the need to reassess designs and construction practices in order to more cost-effectively introduce the benefits of electrification through high-quality, reliable service into rural areas, consistent with their needs. Its overall goal is to raise issues and propose options in order to initiate a discussion on this topic.

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[*] *Medium voltage*, also referred to as a *primary voltage*, is used to transmit power relatively long distances from its source to the load centers. It usually ranges from 1 kV to about 35 kV, well above the consumer voltage of 120 or 240 volts. Use of these higher voltages reduces resistive losses in the line, losses that result in both voltage drop (adversely affecting the quality of the electricity) and energy losses (which add to the recurring cost of operation). It also permits the use of smaller, less-expensive conductors and less-expensive single-phase construction.

[†] NRECA has been contracted by Electricité du Laos, with the financial support of the Japanese Policy and Human Resources Development (PHRD) Fund, to prepare a village mini-grid design manual. The project idea and terms of reference were developed by ESMAP as part of its design of the GEF-financed decentralized rural electrification component of the IDA-financed Southern Provinces Grid Integration Project.

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Case Studies

Data on the “typical“ capital costs of grid extension were solicited from a number of countries and are briefly described and summarized in Appendix A. This chapter analyzes these data to draw lessons from these experiences. In reviewing these figures, several points must be kept in mind:

- Respondents were simply asked to present the complete cost breakdown for a “typical“ kilometer of grid extension line into rural areas. This term was expressly not defined in order to permit respondents to propose what they felt was typical and not to discourage responses by over-specifying the scenario to be costed.
- Although the total cost for designing and constructing the lines was requested for each case presented, it is difficult to ensure that these figures are complete. More difficult costs to quantify, such as administrative, overhead, and maintenance, may have been omitted. Other costs, such as those for the transportation of poles to the field or for right-of-way clearing, are site-specific, difficult to generalize, or cannot accurately be included in a single cost-per-kilometer figure for line extension. Finally, although the quality of materials and construction affects the usable life of a line and therefore its life-cycle cost, this factor is often difficult to quantify.
- An attempt was made to gather costs from a variety of countries worldwide. However, in many cases, no responses were received after repeated requests by various parties. Of those countries for which data was obtained, many had not only adopted the North American configuration[*] but had implemented projects under the guidance of rural electrification engineers and planners associated with the U.S. rural electric cooperative movement. The data obtained can therefore be seen as somewhat biased, but this does not detract from the conclusion that can be drawn for this universe of experience presented. Other field data would, for the most part, only have reinforced the conclusions that were drawn.

In spite of these caveats, useful conclusions can still be drawn; these are presented in the following paragraphs. Note that in most of the accompanying graphs, costs have been grouped according to whether the design used adopted the European or North American configuration. These are the two

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[*] As opposed to the European configuration; see glossary.

principal approaches used for extending three-phase power lines. The first approach, which flourished in Europe, uses three phase-conductors and was designed to serve the more compact settlement patterns found on that continent. The second approach uses four conductors—three phase-conductors and one multi-grounded, neutral conductor. This design evolved in North America to serve the more dispersed settlement pattern of the rural areas.

It should be noted that the grouping of data is only meant to permit a comparison of apples with apples and does *not* imply any advantages of apples over oranges or vice versa.

Figure 1 presents the total (i.e., material and labor) per-kilometer cost in several countries for three-phase MV lines used for extending the grid into rural areas. Cost typically ranges from $8,000 to $10,000 per kilometer, with the cost of materials averaging $7,000. As is clear from Figure 2, the low materials cost from India is primarily attributable to the use of a small conductor and to the extremely low costs for poles and hardware, which are presumably manufactured locally. Furthermore, the cost of labor typically seems to be a small part of construction cost, a fact attributable to the low labor rates in many countries. By contrast, labor in the United States accounts for at least one-half of construction cost. If clearing the right-of-way is also considered, this labor-intensive task adds considerably to line cost in industrialized countries. For example, for the Rappahannock Electric Cooperative in the United States, the cost of line construction nearly doubles when clearing is included (see Appendix A).

Figure 2 illustrates the important contribution of pole cost to the cost of three-phase line construction. Pole cost averages about 40 percent of the total cost of materials, with cost per pole generally varying between $120 and $300 for lengths in the 11- to 12-meter range. An exception ($30) seems to be for the pre-stressed concrete poles used in India, in part due to the short length (8 meters) of the poles quoted for a "typical" grid-extension line. It was not possible to verify either these costs or the quality of the poles. A range of different designs and materials are available for poles, and it is here that some cost savings may be possible in some countries.

Figure 2 also indicates the size (in mm^2) of the phase conductors. The cost of the conductor is much more project-specific than the cost of poles because it is primarily a function of the cross-sectional area of the conductor, and this depends on the actual load it is designed to serve. Figure 15 later in this study shows the variation of cost with size for several types of conductors in a number of countries.

Figure 3 illustrates the difference in total cost between single- and three-phase construction for those countries where both types of construction are found. The percentage cost savings in going to single-phase construction is noted above each set of costs and averages 30 to 40 percent. Typically, the cost of materials and labor for single-phase line construction averages about $6,000 per kilometer. Except for the case of Bangladesh—where the single- and three-phase lines quoted have conductor areas of 34 and 107 mm^2, respectively—the conductor size for both the single- and three-phase lines is roughly the same for each case presented.

In Figure 3, only the cost of single- and three-phase construction within each country should be compared. A cost comparison between different countries may not be valid because different factors may contribute to the cost. For example, the costs incurred by the Rappahannock Electric Co-op are more encompassing because they include the high cost for right-of-way clearance, a figure missing from the data from most other countries. If, on the other hand, only the cost of materials is considered, this electric utility has one of the lowest line-construction costs.

Although expenditures for poles and conductor usually account for most of the cost of grid extension, there are exceptions. In the cases shown in Figure 4, poletop hardware can account for as much as 40 percent of the material cost for a three-phase line. Although the use of pin-type insulators prevails in most cases, the higher cost in Laos stems from the use of more costly post insulators. From the data provided it is also clear that, in the cases of Bolivia and Senegal, increased cost is due to the use of both a higher distribution voltage (roughly 34 kV) and suspension insulators.

Figure 5 illustrates the considerably reduced cost of poletop hardware required for single-phase construction, especially with the North American configuration. This is attributable to the reduction in the number of poletop insulators (for the phase conductors) from three to one and to the elimination of the use of a crossarm. Cost savings for the European configuration are less significant because single-phase (phase-phase) construction still requires two-thirds of the poletop insulators and a crossarm.

In general, a review of costs for grid extension in even the limited selection of countries included within this study confirms that they span a considerable range. It also appears that this range is attributable to more than simple differences in site conditions and that, through a review of existing designs and alternative options, the potential exists for a reduction in the cost of RE in a number of countries.

Insert Figure 1

Insert Figure 2

Insert Figure 3

Insert Figure 4

Insert Figure 5

3

Factors Affecting Cost

Worldwide, the most common design for grid extension is a three-phase configuration. This study will begin with this commonly used configuration as the point of reference and illustrate options for reducing the cost of bringing power to rural areas.

Two factors inflating the cost for grid extension into rural areas are

1. The sub-optimal use of available materials and designs, such as the use of shorter spans than possible and the poor placement and sizing of transformers; and
2. The adoption of designs used to serve urban loads that do not take into consideration the unique design implications of serving rural populations, including the widespread use of three-phase lines and oversizing of transformers and conductors.

This chapter will review variables that affect these costs and illustrate how design modifications might reduce cost.

As noted in Chapter 2, variants of either of two basic configurations—the European and the North American—are used worldwide for electric power distribution. The suggestions for cost-reductions made in this report apply to both configurations.

However, the actual configuration selected can itself also affect cost. For example, by the early 1970s, Tunisia's electric utility had not yet extended its distribution systems far from the urban centers, and it took the occasion to assess the cost and other advantages of converting to the North American system. It concluded that, under circumstances found in that country, savings in the range of 18 to 24 percent would result, at which point it proceeded with the implementation of the North American configuration.[5]

Determining which configuration is the most cost-effective is a site-specific endeavor involving a comparative costing applied to the actual situation, as was done in the case of Tunisia. It should be noted that by now most countries already have well-established designs and trained staff, and conversion at this late date may no longer be cost-effective. Furthermore, it is not clear that cost is the predominant factor in selecting one option over the other. Of greater importance may be more-amorphous issues concerning safety, reliability, versatility, and flexibility.

However, one feature of the North American configuration that has resulted in cost savings is the widespread use of single-phase distribution. The fact that this feature is even being used increasingly by those who use the European configuration seems to confirm that there is some virtue to this feature. The impact of single-phase construction on cost savings is addressed later in this chapter.

Line Design

Before even considering any alternative technical designs to reduce the cost of MV lines, it is necessary to ensure that the poles, conductor, and line hardware incorporated in existing designs are used optimally and that the lines are efficiently designed and constructed. For example, spans should be maximized to take advantage of the strength of conductors while ensuring a generally acceptable degree of safety. Conductors should be optimized to handle realistic demands expected over the life of the system with acceptable losses; they should not be oversized. Pole lengths should not far exceed those necessary to meet established ground clearance requirements. Usable pole strengths should be established using realistic safety factors. Finally, designs should be standardized to minimize the use of specialized engineering expertise, which adds to the time and cost of line design.

Poles

As previously seen in Figure 2, poles are often the costliest single component required for grid extension and are the obvious area in which to focus in attempting to reduce cost. Several options are possible for reducing pole cost, including the use of

- Underground cabling to eliminate the needs for poles altogether,
- Shorter poles to reduce cost of materials,
- Longer spans to reduce the number of poles, and
- Alternative pole designs.

Underground Cabling

An obvious way to reduce pole costs is to do away with the poles altogether and rely on underground cables. In addition to economics, however, aesthetics is a driving force behind the growing use of this option, whether in a new housing development in suburban San Francisco or for the micro-hydropower mini-grid in Namche Bazaar, Nepal, the last village on the trekking route to the Mt. Everest base camp. Another advantage is reduced exposure to the elements—winds, ice, and tree branches—and decreased susceptibility to outages or life-threatening situations.

On the other hand, an overriding deterrent to the use of underground cables is its cost: underground construction costs at least twice as much as using overhead lines. Several other important disadvantages are associated with underground construction when used in areas where a potential future increase in demand or in the physical extent of the system is envisioned:

- Line capacity cannot easily be increased either by adding another phase conductor to a single-phase line or by upgrading the conductor size.

- Making joints along a line or tapping a line to serve new consumers is difficult and costly and requires specialized training.
- Underground lines must be carefully mapped and these maps readily available so that the location of these lines is precisely known when access is required for extensions, taps, or repairs in the future.
- Locating and repairing underground faults requires suitable equipment and training.

Consequently, although underground cabling may eliminate the need for costly poles and have several other positive attributes, these rarely outweigh the significantly higher costs associated with the conductor and its installation as well as with future expansion and repairs. If concern centers on cost, this would generally be an option of last resort.

There are exceptions to this rule, of course. For example, underground construction might be the least-cost approach in areas where overhead lines are susceptible to storms, such as typhoons or cyclones, because of the high cost of replacing poles that fail prematurely (p. 21). Under these conditions, the life-cycle cost of poles and their replacement might exceed the cost of underground construction.

On islands in the Pacific, another circumstance prompting the use of underground cabling is the presence of expansive coconut plantations: in addition to susceptibility to wind damage, overhead distribution lines require the removal of large numbers of trees along the right-of-way, representing lost income to their owners.

Shorter Poles

Countries around the world use poles that are considerably longer than necessary to achieve the required line-to-ground clearance. For example, in Laos, three-phase lines with 80-meter spans over level terrain are frequently constructed using 12-meter poles and aluminum-conductor, steel-reinforced (ACSR) conductor, while in India 8-meter poles are used under similar circumstances.

Smaller girths are possible with shorter poles, and reduced girth and length each lead to reduced cost. Reducing the length of a treated wooden pole 17 percent, from 12 to 10 meters, decreases the cost of a pole by 24 percent (assuming U.S. pole costs; see Figure 6).[*] A further reduction from 10 to 8 meters decreases the cost by another 28 percent, for a total

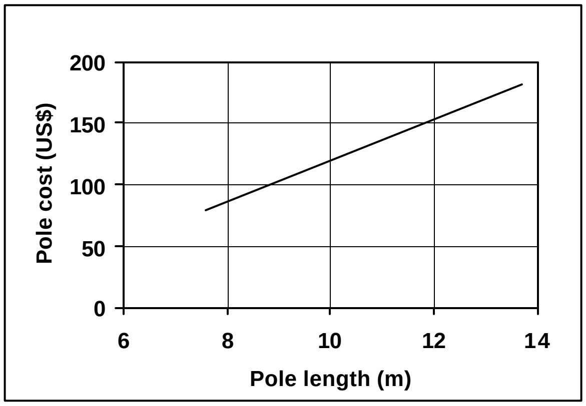

Figure 6. Approximate costs for Class 5, CCA-treated Southern Yellow Pine poles in the United States

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[*] This assumes the need to withstand the same transverse poletop force.

cost reduction of 45 percent. With the pole being a major contributor to the cost of a line, this reduction should have a noticeable impact on the cost of grid extension.

Therefore, although 35-foot (10.6-meter) poles are commonly used in the United States and 12-meter poles are routinely used in a number of countries around the world, neither length need be the norm when extending lines into rural areas. For example, in central Nepal, fabricated steel poles beginning at 8 meters are used in private RE projects. In India, both pre-stressed concrete poles and rectangular hollow steel poles in the range of 7.5 to 9 meters are used for 11-kV lines.

However, the extent by which poles can be shortened is clearly limited. This is established by the minimum acceptable clearance between the lowest conductor and the ground (or any structures found under the line). For example, according to the National Electric Safety Code (NESC) in the United States, the minimum clearance between open supply conductors (rated up to 22 kV) is 5.6 meters when located above roads subject to truck traffic and 4.4 meters above spaces accessible only to people.

In the more densely populated areas, joint use of utility poles by cable TV and telephone companies requires poles of additional height to permit adequate clearances between these various sets of cables and between these cables and the ground. However, in most rural areas in non-industrialized countries, this is not presently of concern. In fact, the evolution of more cost-effective technologies such as direct broadcast television and cellular telephones may mean that joint use of poles may not even be a future concern in rural areas.

Longer Spans

In addition to using shorter poles for a given span to reduce cost, the cost of poles can be further decreased by reducing their number per kilometer of line through the use of longer spans (see Figure 7). Allowable span is set by several factors: the need to maintain adequate line-to-ground clearance for safety purposes, adequate line-to-line clearance to prevent clashing of the conductors and ensuing faults, and strength of poletop insulators. To maintain adequate line-to-ground clearance, longer poles would be required because longer spans imply larger sag if conductor strength is not to be exceeded. So although fewer poles would be needed per kilometer, each pole would be costlier because of both its increased length and diameter.*

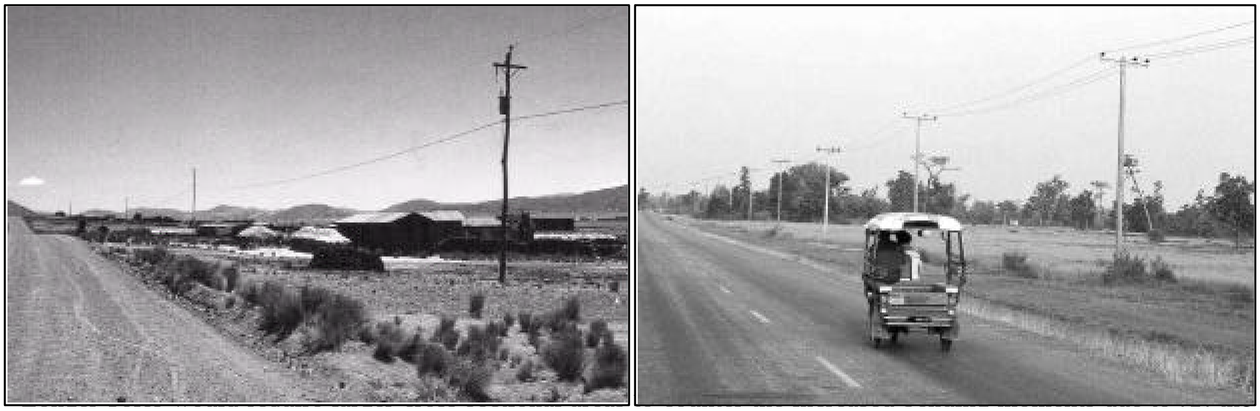

Figure 7. Lines in Bolivia (left) have significantly longer spans than in Laos (right) in similar types of terrain.

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gr r
sp s
along the line) act higher on the pole.

Figure 8 illustrates how the length of poles varies with increasing span in order to maintain the necessary ground clearance—in this case, about 5.6 meters per the NESC—and the resulting effect on line cost, not including labor.

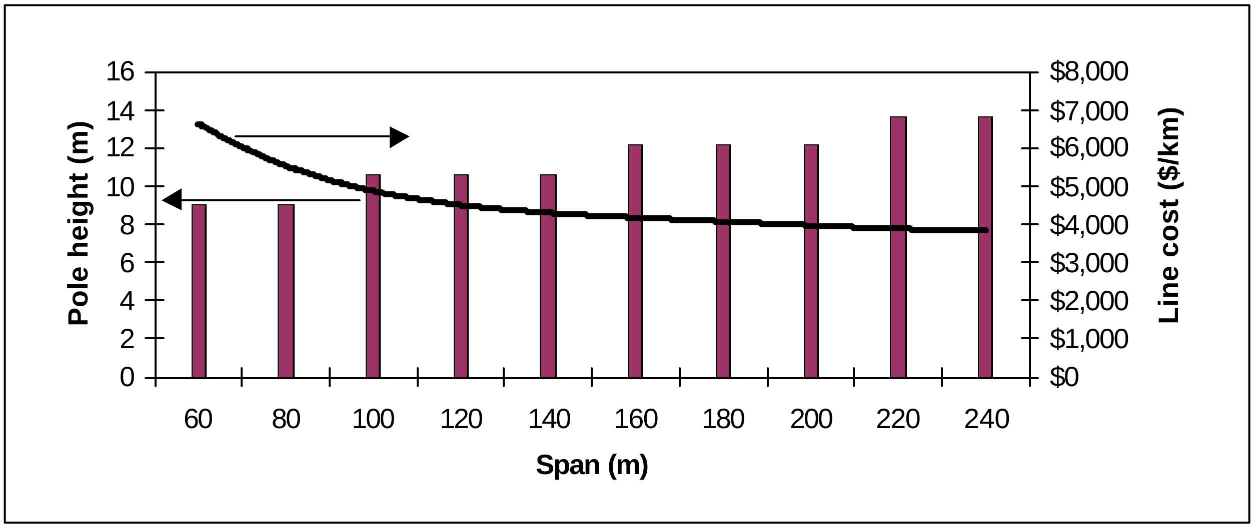

Figure 8. Relationship between span, pole length, and line cost

Note: The bars represent the heights of standardized poles needed to maintain the required ground clearance for different spans. The trend line decreasing to the right indicates the effect of span on the unit cost of construction. In this idealization, a straight #2 ACSR three-phase, three-wire line over level, unobstructed terrain is assumed—i.e., no guys, deviations in direction, or double crossarms. Costs for El Salvador are assumed.

Under these assumptions, line costs decrease with increasing span, but this decrease becomes insignificant for large spans. Actually, beyond a certain point, the difficulty of finding poles of sufficient length prevents a longer span or causes line cost to increase. Using shorter spans results in less sag, and shorter poles can be used to maintain the minimum ground clearance requirements. Shorter poles are less costly, but their increased number per kilometer results in a net increase in cost.

Although spans closer to 200 meters would have the lowest cost for the idealized line considered in this example, significantly shorter spans are commonly used for the following reasons:

- Longer spans may make it difficult to follow a winding road, accommodate the terrain, or clear structures;
- Longer poles are more difficult to find; and
- Minimum clearances considerably in excess of the 5.6 meters are used.

The use of long spans is limited by the paucity of adequately flat terrain. However, this example does illustrate that countries should consider considerably larger spans than are commonly used. In El Salvador, 10.6-meter poles with spans of 130-140 meters are commonly used. This stands in comparison to an average span of 90 meters with poles of similar lengths in the field data gathered (see Appendix A). Because the terrain forces deviations in the direction of the lines, six to seven guys per kilometers are typically used in El Salvador, at an additional cost of about $100 for each guyed pole.

A single-phase European design usually requires crossarms supporting a conductor at each end. The conductors for a single-phase North American design are usually installed in a vertical configuration to save on the cost of crossarms and associated hardware.[6] A vertical configuration would initially seem to imply the need for longer poles to maintain similar ground clearances as with the horizontal, European configuration. However, less ground clearance is required for the lower, neutral conductor used with North American construction than for a phase conductor. For example, in the United States, although the NESC specifies a minimum vertical clearance of 14.5 feet (4.4 m) for a phase conductor in areas only accessible to pedestrians, only 9.5 feet (2.9 meters) is required for the lower, neutral conductor.

Caution should be exercised when considering increasing span by using a single-phase line: If a real possibility exists that the demand along the line will increase to a point that the line must be converted to a two- or three-phase line within its lifetime, span length should anticipate accommodating a larger number of conductors. But this is not as important an argument against the use of single-phase lines as may first appear. Single-phase lines have considerable capacity, and it may be a long time before such a line requires replacement with a line of higher capacity. Even in an industrialized nation like the United States, the widespread single-phase service first introduced about 60 years ago in rural areas continues to provide more than adequate service today. Use of single-phase distribution lines still predominates in many part of the United States, in spite of the large farms and commercial establishments found in these areas. (See page 35 and following for a further discussion of the suitability of single-phase construction.)

Reducing the cost of grid extension by increasing the span and reducing the number of poles can be pursued one step further. When maximum span is limited by the need to avoid clashing of adjacent conductors or by the wind loading on two conductors, restricting the line to the use of only a single conductor removes or reduces this constraint. This configuration, commonly referred to as the SWER (single-wire earth-return), uses a single phase-conductor and relies on the earth as the return path. For a given pole length, the only factors limiting span would then be the tensile strength of the conductor, the strength of poletop insulators, and the required ground clearances.

Nearly 200,000 kilometers of SWER line is used in Australia to serve its dispersed rural population. In the state of New South Wales, use of SWER permitted a saving of at least 10 percent when compared to a conventional single-phase system.[7] If steel conductor is used, spans of 200 to 300 meters are possible, with typical sags of 2.5 meters. In the state of Victoria, the use of SWER is said to result in a saving of 30 percent in comparison to the capital cost for a conventional single-phase system. The distribution system requires only 50 percent of the components necessary to build a conventional single-phase system, but savings are less because more extensive grounding is required. The cost incurred for grounding is approximately 30 percent more than that associated with conventional single-phase systems, and the cost of losses is also greater; however, offsetting these is the reduction in maintenance costs because of the reduction in (1) the number of components used and (2) the width of the right-of-way requiring periodic clearing.[8]

In Laos, the proposed use of a single-phase SWER configuration is expected to halve the number of poles from 12 to 6 per kilometer. Estimated cost of materials (not including labor and transportation) for SWER construction is expected to be $3,100 per kilometer, whereas single-phase (phase-phase) construction costs $4,600, or roughly 30 percent more.

Alternative Pole Materials and Designs

Poles can be made from a variety of materials, most frequently wood, concrete, and steel. None of these has a clear-cut advantage in all situations, and both cost and specific attributes associated with the various options are factors that should be considered in the selection process.

Before reviewing each of these options, however, it is important to note that the quality and strength of the poles selected should not be compromised in the process of reducing cost. Simply having to replace each pole once during the expected life of a system because of poor quality effectively doubles the cost of the pole for that line. The cost of labor adds further to the total because replacing a pole can cost considerably more than its initial installation.

For example, in El Salvador the installed cost for a simple pole structure (i.e., the cost for the pole and poletop assembly and for framing and setting the pole) for single-phase and three-phase lines is $400 and $570, respectively. However, the cost for replacing this structure—including a new pole but assuming a de-energized line and reuse of all the poletop hardware except for armor rod and wire ties—is about $500 and $700, respectively. Replacing the pole while the line is energized increases this cost by 50 percent. And if the pole includes other hardware—such as guys, transformers, or streetlights—that needs to be exchanged between the old to the new pole, costs further increase.

Consequently, rather than costing $570 per simple installed pole for a three-phase line, the total cost for that structure, including a replacement pole, would be about $1,300, effectively resulting in a total undiscounted life-cycle cost that is roughly twice the cost of the original structure. Replacing the pole while the line is energized pushes the total to $1600, about three times the original installation cost.* Because poles are the most costly item of a line, short-lived poles have a significant impact on the life-cycle costs of a line.

Experience in the United States confirms these costs. For example, according to the Benton Rural Electric Cooperative, the cost of replacing a three-phase pole installed in the state of Washington is about 150 percent of the installed cost of the original structure and 200 percent if the pole is replaced while the line is energized.

Consequently, although using less-durable poles can reduce cost, it can considerably increase the discounted life-cycle costs of a line. This is especially true in countries where the cost of labor is high. Even in countries with lower labor rates, however, the need to maintain a poorly designed line diverts resources that should rather be utilized in broadening the reach of RE rather than simply reinforcing what has previously been done.

The remainder of this section discusses the relative merits of wood, concrete, and steel in pole construction.

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* This assumes the pole lasting half of its expected life. Use of inadequately treated wood poles has led to poles with even shorter lives, further increasing the life-cycle cost per pole.

Wood

Treated wood poles have been widely used for electrification worldwide because they exhibit a variety of advantages. These poles

- Can be a produced and treated locally,
- Are lighter than the equivalent cast concrete pole (the common alternative) and easier to handle in the field,
- Are easier to climb,
- Are not susceptible to breakage during transport and handling,
- Rely on a raw material that, unlike cement and steel, is not energy-intensive in production, and

- Permit greater flexibility in the placement of mounting bolts and facilitate later modification in the field.

Properly treated wood poles have been proven to last for decades, even in wet environments (see Figure 9). Any decay is likely to first occur at ground level, where conditions for decay—moisture and air—are most optimum. With a groundline treatment procedure incorporated into a wood pole line inspection and maintenance program, this can be increased considerably. Furthermore, wood poles are not adversely affected in coastal zones where airborne salt can cause corrosion of steel poles or the reinforcing steel in concrete poles.

Figure 9. In some areas, properly treated poles, like the one above treated in 1947, spend most of their lives in water or water-logged soils. (Eastern shore of Maryland, United States)

Other benefits of using wood poles include the following:

- Local plantations permit self-sufficiency in the production of one of the costliest components of an RE program, thus creating employment, reducing the need for foreign exchange, and lowering the cost of RE.
- Properly managed, wood is a renewable resource with wood poles, requiring much less energy for their "manufacture" and contributing no net carbon dioxide or other greenhouse gases in the process, unlike the case with the production of concrete or steel for poles.
- Fuelwood from offcuts and from ongoing right-of-way clearing can serve as a low-cost, easily usable, efficient, and renewable fuel for cooking and space heating, thereby reducing electricity demand and associated construction costs (see Appendix B).
- Increasing forest cover for pole production in marginal areas can produce numerous environmental benefits, including reduced erosion of land and sedimentation that leads to the destruction of riverine habitats, improved ground water quality and quantity, more abundant and diverse wildlife, and opportunities for increased employment opportunities from processing a range of forest products. It also serves as a sink for carbon dioxide, a gas increasingly recognized as contributing to global warming and its adverse implications.

- In a number of countries, rural households have little disposable income, and the problem facing RE programs is the inability of these households to cover the cost of connection as well as the cost of energy. Growing trees for poles may be one option requiring few financial and labor inputs, thus reducing the cost of electrification. It can also provide a regular income to rural households that, in part, can be used to cover the cost of their electric service.

In a growing number of countries, the principal obstacle to the local production of wood poles is the lack of existing forest reserves with suitable trees. It is possible to plant trees specifically for pole production, but adequate lead time is required until newly planted trees can be harvested for this purpose. Tropical pines can produce a 9-meter pole in about 15 years but have limited strength. Faster-growing soft wood species exist, but these tend to be weaker. More commonly found hardwood species, such as eucalyptus, are another option, but these do not offer good preservative penetration and retention.

However, because poles will continue to be in demand for expanding RE as well as for replacing damaged existing poles, the need for poles will continue decades into the future, well after any tree plantation starts yielding trees of adequate dimensions. Furthermore, the advantages of using wood poles should be sufficient incentive for a national commitment to the creation of local tree plantations, possibly in collaboration with other government departments, nongovernmental organizations, or private entrepreneurs (see Box 1).

The quality of, and costs for, treated wood poles available from around the world can vary considerably. Table 1 illustrates the wide range of costs Bangladesh received in response to a single request for bids specifying CCA Type C treatment, kiln-dried 9- and 11-meter poles with no pre-treatment decay, and generally following the specification established by the Rural Electrification Board (REB) of Bangladesh. Incidentally, the effectiveness of these specs has been illustrated by the fact that none of the 1 million U.S. poles the REB has installed throughout that country has shown any signs of decay in spite of the wet tropical environment in which they are used.[9]

Table 1. Average Bid Price from Several Suppliers of Treated Wood Poles

Pole description	Average cost per pole ($)
1. South Africa creosoted radiata pine	111
2. South Africa CCA radiata pine	112
3. Argentina CCA eucalyptus	151
4. South Africa CCA radiata pine	151
5. Norway CCA scotch pine	188
6. Finland creosoted scotch pine	213
7. Chile CCA radiata pine	216
8. Finland CCA scotch pine	228
9. United States CCA southern yellow pine	242

The desire to reduce the cost of RE should not drive pole selection at the expense of quality. A previous example already illustrated how the premature replacement of poles because of unexpected decay can significantly increase their life-cycle cost. Therefore, in selecting the most cost-effective wood pole for a project, the selection, pre-treatment handling, and treatment of poles should be carefully and knowledgeably evaluated.

Box 1. Example: The Philippines

In the Philippines, the National Electrification Administration (NEA) recognized the numerous advantages of using wood poles in rural areas. It also recognized the dwindling source of forest resources in their own country and the high cost in importing poles from overseas. Consequently, the Power Use Development Division of the Cooperative Services Department of the NEA initiated a tree-planting program in 1993. Nearly half of the 119 rural electric cooperatives in the country are now involved in this program.

These rural electric cooperatives raise seedlings that they donate to their consumers (either individuals or users groups) or sell under contract to large landowners. (The largest single area currently under cultivation is 400 hectares.) A condition for membership in some cooperatives is planting a couple of trees on the member's own land. Upon maturity, the co-ops agree to purchase the trees for their eventual chemical treatment and use as wood poles.

Specifically for the Philippines, the NEA recommends planting *Gmelina arborea*, *Eucalyptus deglupta*, and *Acacia mangium*, all of which can adapt to the varied climatic regimes in the country.[*] It is expected that a 35-foot (10.5-meter) pole with a diameter of 8 inches (0.20 meters) will be available after about 8 years following the planting of the seedling. The planting density is at least 500 trees per hectare. It is expected that the co-op will save roughly 50 percent over the current price of imported poles. At an estimated development cost of roughly $1,000 per hectare, NEA projects a 50-fold return on investment after 10 years.

To ensure a long life, poles have to be chemically treated. But the transportation of poles to centralized pole-treatment plants around the country is costly and would, at least in part, negate the advantages of growing trees in the areas served by the cooperatives themselves where they are to be used. For this reason, the Forest Products Research and Development Institute in Laguna has developed a device for the *in situ* treatment of wood poles through high-pressure sap displacement. A cylindrical pressure cap is fitted over the base of a newly felled tree (Figure 10). A water-borne preservative solution is then introduced into this cap and forced up through the bottom of the tree. This forces the sap out, leaving the preservative behind. Up to two poles can be treated simultaneously, with treatment times of up to several hours, depending on a range of variables. The treating equipment costs $5,500 with a 1/3-horsepower electric motor and $8,200 with a 2-horsepower diesel engine.[**]

Currently, about 28 rural electric cooperatives and entrepreneurs are using this treatment plant in the Philippines, with a production rate of about 10 poles daily. *Gmelina arborea*, a light, rapidly growing hardwood, is commonly used and harvested after seven years. By this time, poles have attained a height of about 10 meters and a diameter of 220 millimeters. Treatment is with chromated copper arsenate (CCA), with a retention of 12 to 17 kilograms per cubic meter and full penetration of the sapwood. To minimize environmental problems and ensure quality treatment, the operation should be carefully managed.

[*] *Primer on Woodpole Production Program* (brochure prepared by the Power Use Development Division, Cooperative Services Department, National Electrification Administration, Manila, Philippines).

[**] “Series 4, High Pressure Sap Displacement Treatment,” second revision (Laguna, Philippines: Forest Products Research and Development

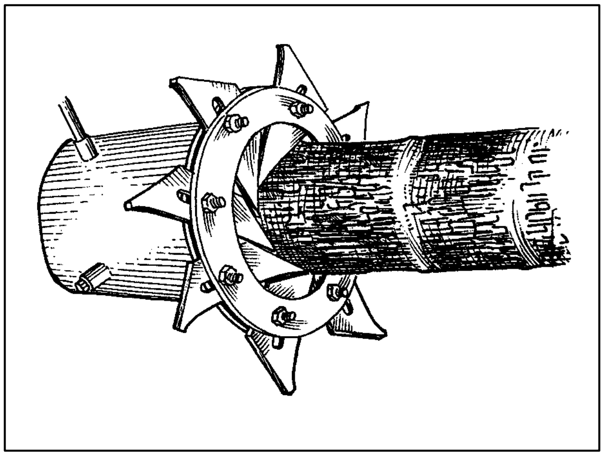

Fig. 10. Adjustable steel fingers mounted on the pressure cap restrain the rubber seal when the preservative within the cap is pressurized.

In the case of the bids in Table 1, some were found to be non-responsive because of the use of other preservatives (bids 1 and 6) or other specifications (bids 1-4). Some (1, 2, 4, and 7) were from plants operating under conditions that encouraged pre-treatment decay of poles (which quickly reduces pole bending strength and can prevent proper loading of preservative). Bid 5 was finally accepted, and although the initial cost may be high, this choice may well lead to lower life-cycle costs. In fact, the most expensive pole on this list also carried with it a 40-year "replacement or money-back" guarantee in writing, backed by a major U.S. bank. This essentially guarantees the life-cycle cost of the pole.

Concrete

Where wood poles are not an option because suitable poles are not grown locally or the cost of importing them is too high, steel-reinforced concrete is a common alternative. This permits local manufacture with relatively inexpensive, readily available materials: cement and reinforcing steel. Disadvantages can include the increased cost of transport and difficulty of handling due to their weight, increased breakage during transport and handling, and susceptibility to failure due to corrosion of the reinforcing steel because of either the environment or contamination within the concrete.

Because concrete has little strength in tension, steel is embedded in the concrete to provide this strength. Forces imposed by external loads are transferred from the concrete to the steel through a bond between the two. This bond is formed by the chemical adhesion that develops at the concrete-steel interface, by the natural roughness of the surface of hot-rolled reinforcing bars, and by the closely spaced, rib-shaped surface deformations on the bars, which provide a high degree of interlocking of the two materials.

The several pole designs that are commonly used include

- Cast reinforced concrete
- Cast pre-stressed concrete
- Spun concrete.

Although **cast reinforced concrete** is the easiest and least costly design, it yields the poorest strength characteristics. Reinforcing steel or "rebar" is simply placed in the forms prior to pouring the concrete (Figure 11). Reinforcing steel has no initial stresses; these stresses only develop as the structure is placed under load. As the structure begins to deflect, a portion of the concrete is placed under tension and can begin to develop hairline cracks *before* the steel begins to provide the necessary tension to counteract the imposed load. This design may also be subject to voids or variations in density, depending on the actual manufacturing process used.

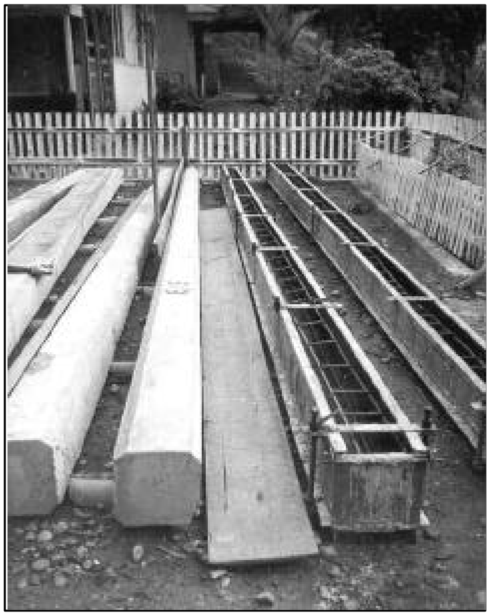

Fig. 11. Steel reinforcement placed in a mold ready for casting at an isolated site in Indonesia. Completed poles at the left are curing.

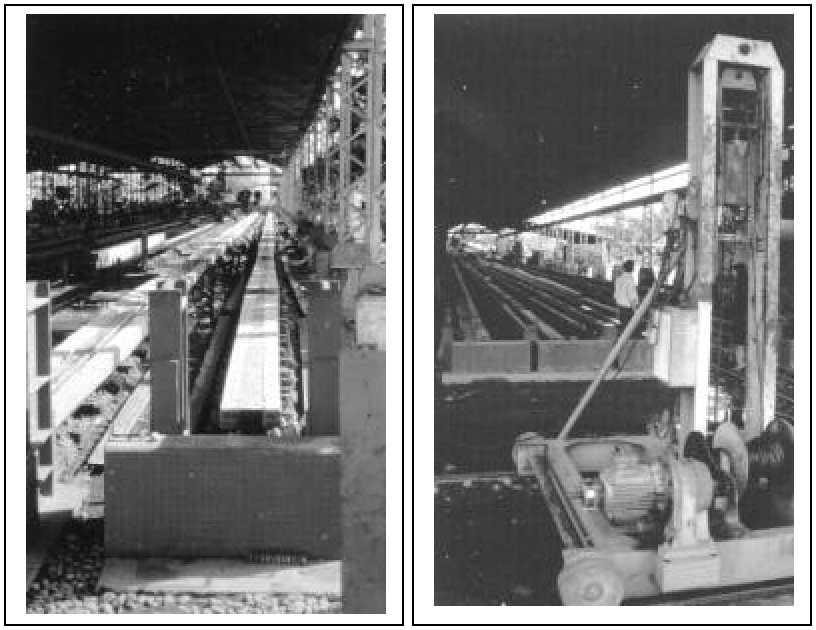

Figure 12. Reinforcing steel is stretched between two anchors by the winch (right, in the foreground) and secured in that position. On the left, poles poured nearly end to end for the length of the factory are left to cure (Thadeua, Laos).

In **cast pre-stressed concrete**, the reinforcing steel is pre-stressed and is under tension even before the structure is placed in use. Furthermore, special pre-stressing steel with several times the tensile strength of reinforcing steel —in the form of either wires, cable, or bars—is used. Pre-tensioning and post-tensioning represent two alternatives for pre-stressing the steel. However, only pre-tensioning reinforcement is used in the production of poles. In this case, the pre-stressing strands are tensioned between massive abutments in the casting yard prior to placing concrete in the beam forms (Figure 12). The concrete is then poured around the tensioned strands. After the concrete has attained sufficient strength, the strands are cut. As they try to collapse back to their original length, the pre-stressing forces are transferred to the concrete through the bond and friction along the strands, chiefly at the outer ends.

Spun concrete begins with a "cage" of reinforcing rods placed into a mold into which concrete is added and rotated for up to half an hour. The pole is then steam-cured for several days before being removed from the mold and left to cure for a month. The centrifuging of the mold permits making the center of the pole hollow, reducing its weight without significantly reducing its strength, and leaving a shell of denser concrete. As with the ordinary cast concrete poles described above, spun poles can be made of unstressed or pre-stressed reinforcing steel.

Steel

Where a grid must be extended to areas without vehicular access, wood and concrete poles have the disadvantage of being too heavy and bulky if they have to be carried. Some efforts have been made for small, isolated projects to cast poles either on-site or even in-place. But these poles, which are made simply of reinforced rather than pre-stressed concrete, have limited strength.

An alternative has been to use steel poles. Their construction permits a pole to be fabricated of smaller sections that can be easily transported, by porter if necessary, and assembled on-site. The strength of steel is predictable and steel poles can be designed and manufactured to more exacting tolerance. Because steel is susceptible to corrosion (rusting), appropriate precautions must be taken, including galvanizing or painting.

One design for such poles originated from the work of Nepal Hydro & Electric Pvt. Ltd. of Butwal (Figure 13). Slightly tapered tubular poles comprise sections made of 1.5- and 2-millimeter plates, each with a length of 1.25 or 2.5 meters, and galvanized with a zinc coating at about 600 grams per square meter. For transport and storage, sections are placed inside each other. Each section weights from 4 to 60 kilograms, permitting one and sometimes more pole sections to be carried by a single individual. Assembled, these become poles with lengths of 5 to 17 meters. Cost is about $1.30 per kilogram. For example, a lighter-weight (i.e., 1.5-millimeter construction except for the base section) 10-meter pole costing $130 can handle a maximum transverse poletop load of 130 kilograms without guys. A heavier-weight and slightly longer 10.6-meter pole costing $310 can handle a maximum load of 540 kilograms.

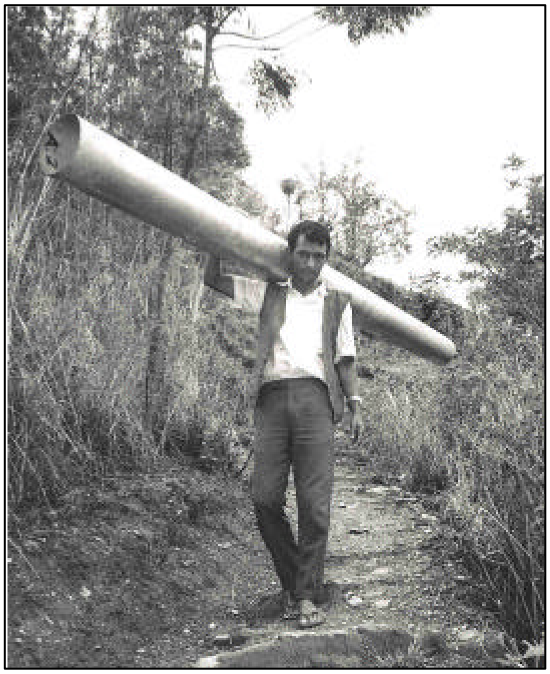

Figure 13. Sections of a steel pole fabricated in Nepal easily can be carried by porters to isolated villages.

Another approach to design is utilized for 11-kV and LV lines in India.[10] Poles with a length of 7.5 or 8.0 meters are assembled from two rectangular steel sections of different diameter, one being inserted about 0.2 meter into the other. They are joined by bolts as shown in Figure 14. The larger section weighs no more than 60 kilograms. These poles are designed for a maximum working poletop load of up to 200 kilograms and are painted with red oxide primer to prevent rusting.

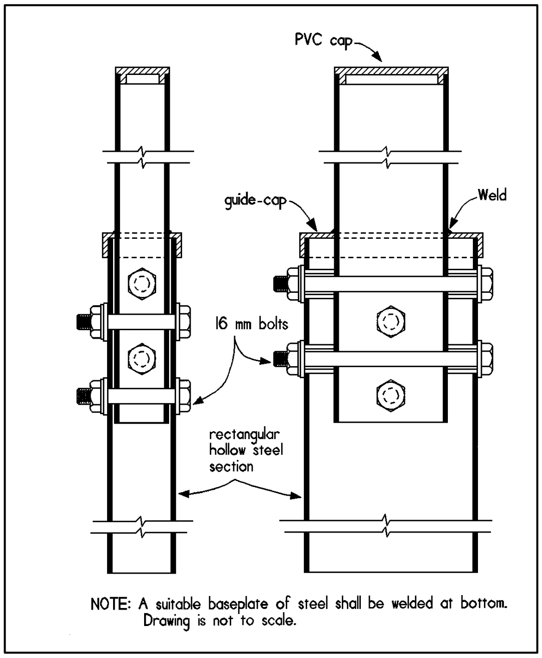

Figure 14. A steel pole design prepared by the Rural Electrification Corporation of India.

Conductors

In terms of cost per kilometer of line, the conductor generally represents the second costliest component. Materials used in the manufacture of conductors are usually limited to a combination of copper, aluminum, and, occasionally, steel. Figure 15 presents an idea of the cost for conductors made of these materials. Factors that affect the life-cycle cost of the conductor are the following:

- Size
- Required number of conductors
- Materials used in construction.

Proper Sizing

Higher costs than necessary can arise from oversizing the conductor. In addition to the increased cost of using heavier conductors, greater structural requirements for poletop hardware and poles and increased labor inputs also increase cost.

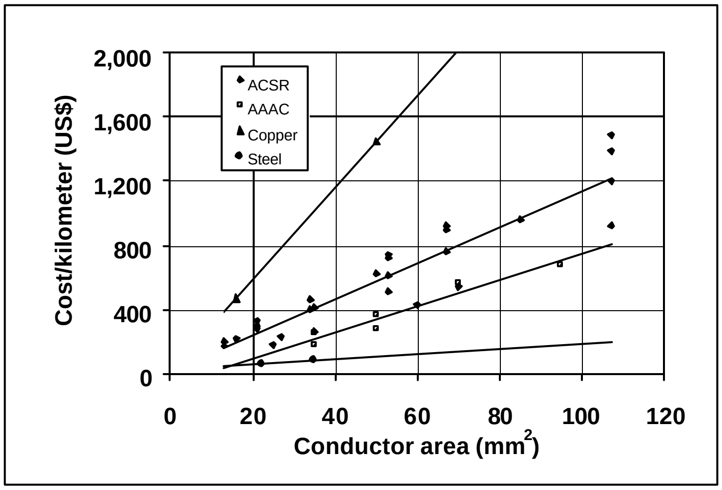

Figure 15. Some indicative conductor costs from around the world (Bangladesh, Bolivia, Indonesia, Laos, Nepal, Philippines, United States).

The first step toward minimizing life-cycle costs for the conductor is to realistically assess the loads to be met by the line during its life. Similar geographical regions that have already been electrified, with similar economic potential, should be surveyed to serve as a basis for assessing average initial loads as well as the growth of load in new regions. The already electrified regions surveyed should preferably have 24-hour, grid-connected service to ensure that the documented loads and load growth are not constrained by limited generation capacity. However, these regions could be supplied by a diesel or other isolated generation source as long as it is clear that the demands served by these isolated generators have not been suppressed because of either limited hours of operation or limited generation capacity. Projections of loads in areas to be electrified made on the basis of loads in areas with suppressed demand would tend to understate the actual demand to be met in the new areas. Consumers in the surveyed regions should also be paying tariffs similar to those projected in the new areas to be electrified.

In projecting existing electricity demand for a new area to be electrified, one must be alert to the impact on load and load growth in the area caused by such factors as the level of disposable income, the presence of raw materials or industry, the potential for tourism, and access to the market for goods that might be grown or produced locally.

In the interests of minimizing the cost of grid extension, although it is necessary not to underestimate the load over the foreseeable future, it could be equally important to consider making most effective use of line capacity. This would be achieved through demand-side management, i.e., managing electrical demand on the system in order to maintain as constant a load as possible. Examples include the following:

- In the villages around Aserdi in central Nepal, a MV line serves three types of loads: lighting (mostly in the evening), hulling of rice and milling of grain (during the day), and a water pump at the end of the line. If demand increases to the point that it affects the performance of the line, the pump at the end of the line could be operated whenever excess line capacity is available, because water is stored in a reservoir supplying a gravity-fed water-distribution system.

  Also, a capacity-based tariff is used for small domestic consumers in the area.* This is less costly

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* With a capacity- or demand-based tariff, the consumer pays for using up to a pre-selected level of power (e.g., 25, 50, or 250 W) but can use this power for an indefinite period of time. Rather than paying a tariff based on the actual energy (in kWh) consumed—which is measured by an energy meter that periodically must be read and billed by the

to administer because no meter, meter reading, or billing is required. It also tends to increase the load factor (leveling the power demand) if the appropriate electrical end-use equipment is readily available. For example, to encourage people to cook using electricity rather than firewood—increasingly difficult to find—without the peaks usually associated with electric cooking, various designs for low-wattage heat-storage cookers have been developed and are being promoted. These are designed to be plugged in most of the day when excess capacity is available in the home, storing heat that can later be used for cooking or heating when needed. In the Aserdi region, the 250-W limit on consumption was specifically set with this use in mind; it permitted the simultaneous use of the cooker and one light.

Although daily load factors of 20 to 30 percent are commonly associated with isolated plants in Nepal and elsewhere, the 60 to 80 percent load factors at this site illustrate their success in making effective use of line capacity by smoothing the load profile.[11]

- Large peaks caused by cooking with cheap, commonly available hotplates can easily more than quadruple the demand placed on a distribution system and increase construction and operations costs accordingly. Appendix B suggests that incorporating community woodlots as an integral part of an RE program could be an effective means of reducing these costs. Electricity would then be used to meet specialized needs where electricity is most efficient (especially for motors, lighting, and entertainment) and cheap, readily available fuelwood would meet heating requirements for domestic and industrial uses.

Once the nature of the loading has been determined, minimum cost can be assured by following the standard approach for properly sizing the conductor to meet the expected load and load growth. In this process, both the voltage drop at the end of the line as well as energy (kWh) losses along the line—both of which depend on conductor size—can be kept within acceptable bounds.

Number of Conductors

Probably the most significant approach to reducing conductor cost is to use less conductor, either by using higher distribution voltages or by using single-phase line extensions with adequate capacity to meet the projected load in the service area. As is described in the next section, use of single-phase lines requires only one or two conductors rather than three (European design) or four (North American system). Reduction in the length of the conductor can range between 33 percent (from three- to single-phase in the European configuration) to 75 percent (from three-phase with the North American configuration to SWER). Cost-savings due to a change in line configuration and in the number and size of conductors is covered later in this chapter (p. 31).

Materials Used

Materials used in conductor construction include copper, aluminum, and steel.

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utility—the consumer pays a fixed monthly tariff. To ensure that the household's consumption does not exceed its pre-selected level of power, any of several types of current limiter is used to restrict demand.

The argument can be made that a capacity-based tariff results in inefficient use of electricity, with villagers, for example, leaving lights on all day. Although this is possible, villagers quickly realize that leaving lights on all day results in the need to frequently replace lightbulbs, adding unnecessarily to their domestic expenses. Furthermore, a capacity-based tariff should not be used with larger consumers, as they can easily cover the cost of the meter and meter-reading.

Copper

Copper has the lowest resistivity of the three materials commonly used for distribution lines and is the costliest of the three. However, it is heavy relative to its strength. Consequently, forms of copper conductor have been developed to address this. One form is Copperweld, a conductor with a steel core (to impart strength) and covered with a thickness of copper (to reduce its resistance). Although it is a costly conductor, it may prove the most economical life-cycle solution in cases where the local environment could lead to corrosion of the line. For example, on a system on the east side of the island of San Andreas in the Caribbean, ACSR lasted only about four years and has since been converted to copper.

Aluminum

Because aluminum is a relatively good and inexpensive conductor, it is the most widely used. Its conductivity-to-weight ratio is twice that of copper and its strength-to-weight ratio is 30 percent greater. It comes in a variety of forms, including

- Aluminum-conductor, steel-reinforced (ACSR), the dominant conductor;
- All-aluminum alloy conductor (AAAC); and
- All-aluminum conductor (AAC).

The ACSR conductor is composed of a number of strands of aluminum wire wrapped around a core of one or more strands of galvanized steel to provide its strength. To avoid the use of galvanized steel, which tends to corrode when used in conjunction with aluminum, AAAC is sometimes used. It retains the strength and current-carrying capacity of ACSR but is lighter and resistant to corrosion. AAC is soft and is the least expensive of the aluminum conductors but has a lower tensile strength; it is more commonly used with LV spans.

It may be difficult to decrease the capital cost of the conductor beyond that obtained by (1) properly sizing the conductor over the design life of the installation or (2) using fewer conductors, as with single-phase distribution. However, because corrosion of the line reduces its service life, the improper choice of conductor can increase its life-cycle cost.

Therefore, the preferred option among the conductor options available is in part dictated by its compatibility with the environment in which the line is to be built. Because of its cost-effectiveness, ACSR conductor is one of the most commonly used. However, in an environment containing industrial pollution, the galvanizing that was applied to the steel strands acts as a sacrificial anode and is eventually consumed. The steel then deteriorates, diminishing in strength and lifespan.

However, industrial pollution is usually not a concern in rural areas. In a salt environment, a different corrosion mechanism occurs. The salt forms an electrolyte between the steel and aluminum conductors and the galvanizing corrodes, exposing small areas of steel. Then a galvanic reaction is set up between the steel and the aluminum, with the aluminum becoming the sacrificial anode. This results in the rapid loss of aluminum, followed by a steadily increasing resistance to current flow at the affected location. This failure mode leads to a shorter life than if only industrial pollution were present. In these circumstances, AAC or AAAC could be used–and the latter is generally preferred because of its higher strength.

However, depending on the precise environment and extent of the pollution, this conductor may not be the best solution. For example, in Barranquilla on Colombia's Caribbean coast, AAAC lasts as little as 10 years because of industrial pollution and salt spray.

Steel

Low-cost steel conductor has considerable tensile strength for its weight. When used for line extension, it permits an increase in the permissible span, thereby reducing cost through the use of fewer poles per kilometer. Although the greater resistance of steel compared to that of either copper or aluminum often discourages its use, a higher voltage can partially make up for the increased resistance. Corrosion is also a problem, but this can usually be addressed by using galvanized conductor. Steel conductor has been used with SWER systems where spans are limited only by conductor strength and not by proximity to other conductors.

Poletop Assembly

Although the cost of poletop assemblies (including crossarms and braces, insulators, and associated bolts) is generally relatively small, Figure 4 does illustrate that it can occasionally be significant. Relying on pin insulators rather than on post or suspension insulators wherever possible can reduce insulator costs. Not only are suspension insulators, the required shoe support for the conductor, and the hardware required to attach this assembly to the crossarm more expensive than pin insulators, but it takes two and sometimes three suspension insulators to replace each pin insulator on a crossarm.

For the North American configuration, costs for the crossarms is eliminated when a single-phase configuration is used (see Figure 16; also see Figure 30 on p. **Error! Bookmark not defined.**). For all three-phase configurations, crossarms can be eliminated if post insulators are mounted horizontally off the pole in a vertical configuration. However, in this case, the saving from not using the crossarm will be exceeded by the increased cost of the insulators (as well as possibly the increased pole length or reduced span required to maintain the required ground clearance).

Figure 16. The simplicity of the poletop assembly associated with single-phase (phase-neutral) distribution is readily apparent.

Line Configuration

As noted earlier, MV lines into rural areas of non-industrialized countries have typically consisted of three-phase lines, an extension of the practice found in urban and peri-urban areas that were the first electrified. This is especially the case in countries influenced by the European colonizing powers, where the distribution systems are based primarily on a three-wire, three-phase configuration.

The driving forces behind the adoption of a three-phase line rather than a single-phase configuration is its increased efficiency for transmitting power. Although the conductor for a single-phase line of "European" design would cost 67 percent of the cost of the conductor required for a three-phase line, only 50 percent of the original power could be transmitted for the same conductor size, line voltage, and voltage regulation (i.e., voltage drop). For the North American configuration, the decreased efficiency is even greater: for a conductor savings of 50 percent (by going from four to two conductors), only about 17 percent of the power can be supplied (assuming the same phase-phase voltage as above).[*]

Although the rationale of using three-phase lines for increased transmission efficiency is valid, this applies more to high-voltage, alternating-current transmission lines as well as to MV lines serving larger load centers. In these cases, the larger current-carrying capacity associated with three-phase lines is essential.

However, for RE, lines are frequently needed to serve small load centers at some distance from the main line. In these cases, even with the smallest acceptable conductor, the capacity of a conventional three-phase line is still too great. For example, an 11-kV, single-phase line constructed with a very small, #6 (13-mm^2) ACSR conductor could be used to serve a load of 1,000 kW-km, with voltage regulation still within 4 percent. Such a line could serve two remote communities of 100 to 200 households each, located 20 kilometers from the main line, each with a coincident peak demand of 25 kW. (This reflects a typical demand for grid-connect rural consumers in countries around the world.) If single-phase capacity is adequate to serve the expected load, there is no use in going to more expensive, three-phase construction.

Even if more capacity were required than is possible using a single-phase line of given design, converting from single- to three-phase construction is not the only solution. Simply increasing conductor size can still be less expensive than reverting to three-phase construction.[12] Using a higher operating voltage is another possibility (see p. 37).

In summary, a two-wire, single-phase configuration—either the European or North American variant—provides several ways of reducing the cost of grid extension to serve rural loads:

- A smaller length of conductor is required (even though a somewhat larger conductor or a higher voltage might be needed, depending on the projected demand).
- Fewer poletop assemblies are required (furthermore, a crossarm and braces or equivalent are not required if the North American configuration is used).
- In cases where crossarms are used, wider spacing of the poletop insulators permits longer spans and therefore fewer poles before being limited by clearances required between conductors (unless, as mentioned earlier, provision must be made to later convert to a three-phase line; in this case using mid-span line spacers is another option sometimes used for increasing span: see Figure 17).

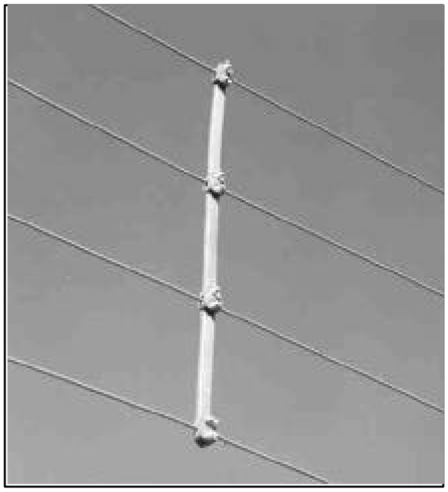

Figure 17. To reduce clashing of conductors for long spans, use of spacers of lightweight composite materials is becoming a popular option in some countries for both LV and MV lines.

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[*] In fact, because a portion of the return current loop in a North American system is through the ground, practice indicates that more power than this can be supplied when using small conductors. For example, with a 35-mm^2 ACSR conductor, the percentage of power that can be supplied for the same voltage drop increases from 17 to 28 percent because of the portion of the return current typically passing through the ground.

- Fewer conductors would mean less transverse wind-loading (which must be counteracted by the pole) and may allow the use of smaller diameter poles. They also imply less transverse force due to conductor tension at poles where the line changes in direction, and this may permit the use of lighter guys and anchors, or both.
- The stringing of lines, installation of poletop hardware, and mounting of transformers are easier and do not require the use of any heavy equipment, and consequently involve reduced cost.

As shown previously in Figure 3, data from a number of countries that have some experience with both single- and three-phase construction confirm that substantial cost savings in line construction are possible by relying on single-phase lines.

If a single-phase line is constructed, and if an eventual increase in load beyond the capacity of that line is envisioned, adding another length or two of conductor to the existing line at some later time would increase its capacity. A single length of conductor can be added to a single-phase (phase-phase) line designed after the European configuration to convert it from single- to three-phase. In the case of the North American configuration, either a single length of conductor can be added to a single-phase (phase-neutral) line to convert it to "vee"-phase or two lengths of conductors can be added to convert it to a three-phase line. Not only does a vee-phase line have increased capacity over a single-phase line, but two transformers connected in an open-delta configuration can also be used to provide three-phase power (see Figure 18).

Figure 18. A two- or "vee"-phase line with two single-phase transformers providing three-phase power to workshop in eastern Maryland (United States).

However, in the case where future conversion is likely, the original line design should incorporate the more stringent design requirements of a three-phase line, such as shorter spans, with its somewhat higher cost. Although the argument might be made that nothing is gained by beginning with a single-phase line if the line will eventually revert to a three-phase design anyway, there are still at least two advantages to adopting this approach:

- Accurately predicting future load is frequently a difficult task that is subject to a variety of factors, and it is best to delay a commitment to three-phase distribution until it is clearly needed..
- Any delay in covering the cost of increasing line capacity reduces the life-cycle cost of the investment by decreasing its present value.

Another variant of single-phase lines that can further reduce costs is the use of SWER, which is similar to the North American system but with the neutral conductor replaced by a return current loop entirely through the ground. This is widely used in portions of Australia and to a lesser extent in a number of other countries, including Brazil, Canada, New Zealand, and Tunisia. In this case, only a single conductor is used and, by using high-tensile-strength steel conductor, spans of considerable length are possible (p. 20).

Good grounding is an essential condition for the effective and safe application of this configuration. For example, SWER lines are usually restricted to lines handling no more than 100 kVA at 12.7 kV in order to that the voltage drop between the grounding lead and ground does not exceed 20 volts (requiring a ground resistance of no more than 2 to 3 ohms). For this reason, grounding at SWER distribution transformers is more complex, time-consuming, and costly than with conventional single-phase systems. Because of the increased safety risk with SWER systems, such systems are often left off the repertoire of options in a number of countries, especially in industrialized countries where the risk is not felt to be worth the cost savings. However, the widespread application of this configuration in the semi-arid areas of Australia seems to imply that safety concerns can be adequately addressed through proper design and construction.

With the application of this configuration, a redundant, extensive, and therefore more costly grounding system is commonly used at each transformer location. In areas such as Australia or Canada, where the population is dispersed and consumer loads can be significant (i.e., farms), a separate transformer with its own grounding system is necessary for each individual consumer, significantly adding to the cost of an installation. However, where consumers are not scattered but located in communities, a single, properly designed grounding system can be installed at a suitable point in the community. The ground conductor would be carried around the community, as is usually the case with secondary distribution systems. Additionally, this conductor can be grounded at guy locations, at service entrances, etc., as is already common practice with conventional LV lines in a number of countries, further decreasing risk.

In rural areas of less industrialized nations, it is not uncommon to see communities located in the vicinity of high-voltage transmission lines but lacking access to electricity because HV/LV substations are too costly to construct for such small loads. To address this problem and reduce the cost of rural electrification, a variant of SWER was first introduced in Ghana and, more recently, in Laos.[13] In this case, low-cost grid extension is achieved by using the shield wire above the transmission line as the conductor for a SWER line. This wire is insulated from the tower to sustain the medium distribution voltage that is imposed on it at the nearest major substation along the transmission line. The wire is tapped at the point on the transmission line nearest the village and brought to a distribution transformer in the village center (see Figure 19). A second conductor connected to a dedicated ground as well as to the transmission tower

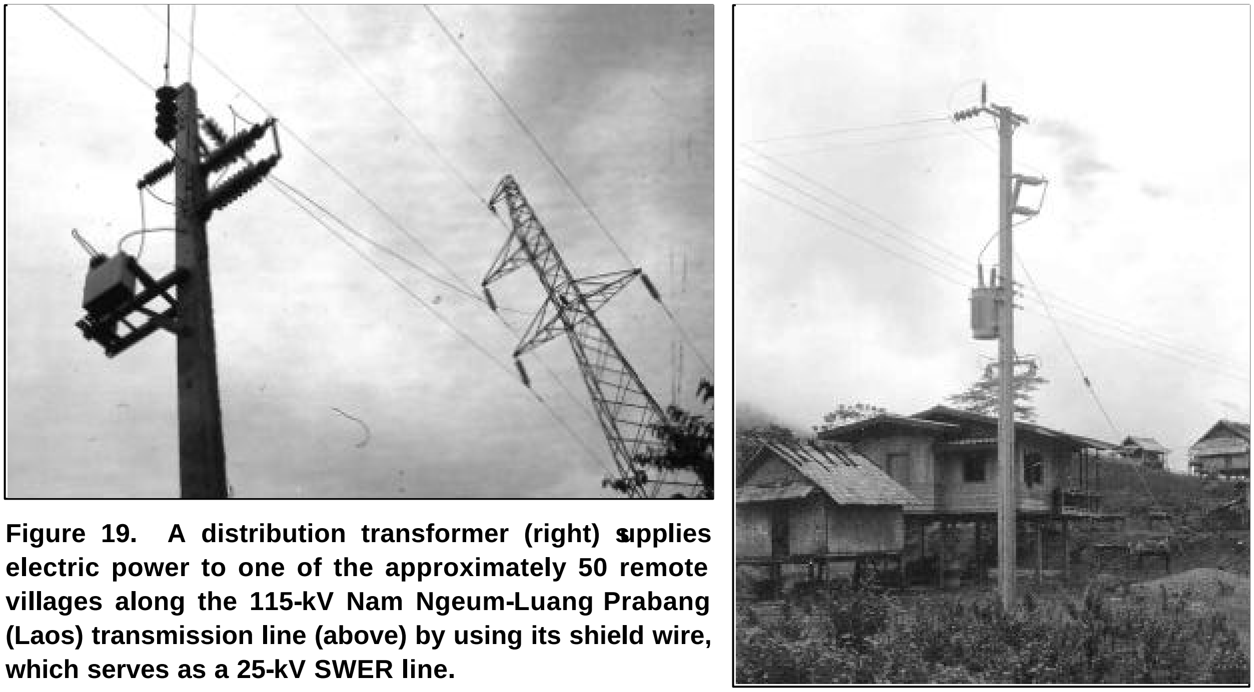

Figure 19. A distribution transformer (right) supplies electric power to one of the approximately 50 remote villages along the 115-kV Nam Ngeum-Luang Prabang (Laos) transmission line (above) by using its shield wire, which serves as a 25-kV SWER line.

ground is carried to the village. Some ancillary hardware is also used to ensure proper operation of the system. From the distribution transformer, a typical LV system supplies the villagers. Efforts are presently being undertaken in Laos to use the two shield wires in conjunction with the ground to supply three-phase power to load centers along their new transmission lines.

In storms during which lightning strikes the shield wire, the closest protective gaps mounted on the shield wire insulators will spark over and ground the wire through the arc. Because the shield wire is energized at the substation, this will initiate a short circuit to ground and the protection relay at the sending-end substation will trip the circuit breaker and have to be reset. To avoid repeatedly resetting the breaker, operators wait until the storm has passed.

If single-phase lines are clearly less costly under some circumstances, why is their use not more widespread? The reason is probably attributable to the fact that extending single-phase lines consisting of two phase-conductors may not have been a cost-effective approach to serving much of Europe, with its fairly concentrated populations centers and high demand. Similarly, when the European colonizing nations introduced electricity into what are now considered "developing countries," they continued with the practice of electrifying the more densely populated, urban areas where three-phase lines are more appropriate. Simply continuing with this same practice as lines are slowly being extended into rural areas is the path of least resistance.

More recently, the cost-advantage of using single-phase grid extension to serve smaller, more dispersed loads is being increasingly recognized, even in countries that had adopted the European design and its emphasis on three-phase distribution.

The European configuration was also initially used in the United States. However, as noted in the introduction, this configuration changed after the Rural Electrification Administration (REA) developed a new, cheaper approach to RE in the early 1930s to serve areas with low population density. This approach relied heavily on single-phase lines composed of one phase-conductor and one neutral-conductor to serve dispersed loads.

In the initial stages of development in the United States, commonly used substation sizes were 750, 1,000, and 1,500 kVA, providing three-phase power at 12.5 kV. These were located near the load center of the areas served and provided power within a radius of roughly 100 kilometers. Except for three-phase lines within several kilometers of the substation, single-phase construction was mostly used. When 24.0 kV was later adopted as a distribution voltage, distributed loads totaling 5,000 kVA were often served from one substation. In extreme instances, single-phase lines in excess of 200 kilometers in length were operated satisfactorily.

To this day, most rural electric utilities in the United States still average only 2 to 7 customers for every kilometer of line, and most residences and farms outside village agglomerations and towns continue to be served only with single-phase power. By permitting the electrification of rural America in a couple of decades and continuing to provide the power necessary to serve the very productive rural areas of the country, single-phase power has clearly proved its effectiveness.[*]

Another perceived drawback of single-phase grid extension is that it does not provide the power requirements to drive larger motors. This idea is often reinforced by engineers more familiar with utilities that serve urban areas. For example, although recognizing the cost savings implicit in single-phase construction, a recent European publication on reducing the costs of electrification observed that "a MV, single-phase network is a deterrent to connection by commercial consumers because it is not adaptable for use with motors."[14]

As evidence to the contrary, it should be noted that after 60 years of electrification, much of rural America still has access only to single-phase power but that this fully meets the needs of even large farms and commercial establishments (see Figure 20). Single-phase motors of up to 10-horsepower capacity are readily available. If larger motors are required, three-phase motors up to 100-horsepower capacity can be run off a single-phase supply through the use of static or rotary phase converters. Newly developed written-pole motors are available up to 60 horsepower and electronic, single-phase, adjustable-speed drives are available to power three-phase motors in excess of 100 horsepower using a single-phase supply.[15]

Figure 20. A 100-kVA single-phase pole-mounted transformer is adequate to serve the needs of this rural farm in the United States.

If larger motors are essential, a disadvantage of using single-phase motors is that they are somewhat costlier than their three-phase counterparts, especially above the fractional horsepower sizes. Using a phase converter to drive large motors of 10- to 100-horsepower capacity from a single-phase source may add a further $2,000–15,000 to the cost, respectively. However, it must be kept in mind that bringing three-phase power to rural areas simply to serve a few three-phase motors can itself be costly. The additional cost associated with the use of a few single-phase motors or the use of phase converters is usually small in comparison to the considerable cost of the alternative: stringing kilometers of three-phase lines in rural areas simply to serve a few three-phase motors, when the predominant loads are for lighting, entertainment, and small motors. Figure 3 illustrated that three-phase construction averages $3,000–4,000 more per kilometer than single-phase construction. It is not difficult to determine the number of large-motor loads necessary to justify the construction of a three-phase line.

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[*] It is interesting to note that the REA was placed not under the aegis of the government ministry or department associated with electricity, energy, industry, or mines but rather under the Department of Agriculture. This represents a *de facto* recognition that, in the United States, the desired impact of rural electrification was on developing agriculture in particular and rural areas in general rather than on simply increasing access to electricity. In this manner, the priority given to rural electrification is probably considerably greater than if it were lumped with some national utility or ministry of energy, whose primary obligations to urban areas would distract it from effectively dealing with the needs of rural electrification.

Consequently, although some observers may express concern that single-phase power constrains development, this notion has little substance. One drawback is that single-phase motors, beyond the fractional horsepower size, are difficult to find on the local market. But this is only because there is no demand for single-phase motors in countries promoting the use of three-phase power. Create the market and motors will appear.

Contrary to accepted wisdom, moreover, three-phase distribution can result in increased motor costs. Although main three-phase feeders may be adequately built and maintained, experience in a number of countries has shown that this is often not the case with LV circuits. Subsequent occurrences of temporary fault conditions cause the opening of commonly used single-phase protection devices along three-phase lines. This results in single-phasing and eventual burning out of three-phase motors. It has been observed that one of the most prolific small industries on the Asian subcontinent is the rewinding of small three-phase motors.[16] So for small-motor customers, selecting single-phase over three-phase motors, even if a three-phase supply is available, may result in life-cycle financial benefits even if the initial cost per motor is higher.

Line Voltage

Another important option for reducing the cost of grid extension is to reduce the size of the conductor. However, reducing its size results in increased resistance. Reducing conductor size beyond the optimum limit has two adverse impacts: (1) it increases recurring costs for operating the line because of increased energy losses caused by resistive heating, and (2) it increases the voltage drop along the line, adversely affecting the quality of power for consumers, especially those toward the end of the line. Both of these impacts also depend on the magnitude of the current transmitted by the line.

However, increasing line voltage decreases the current required to meet the same power demand. Doubling line voltage halves line current, which reduces percentage voltage drop and energy losses to one-quarter their previous levels. The higher the line voltage, the lower the line current required to serve a given load. A smaller current means that a smaller, less costly conductor can be used to meet the same load under the same conditions.

As an example, Table 2 illustrates the impact on the cost of grid extension caused by increasing working voltage. In this example, the cost of constructing an illustrative three-phase, 11-kV line is first compared to that of a three-phase line operating at twice the voltage, i.e., 22 kV. As noted previously, a smaller conductor can be used because of the higher voltage and still result in the same voltage drop and power loss. In this example, construction costs per kilometer are reduced by about 20 percent (from $9,100 to $7,100). This saving from converting to a higher voltage of 22 kV is due to the possibility of now using smaller, less costly conductor and, also, lighter guying and poletop assemblies.

This example is then extended to illustrate the savings possible in using single-phase rather than three-phase construction. For this purpose, a single-phase (phase-phase) line operating at 22 kV is designed to replace the three-phase line operating at the same voltage. Because single-phase transmission is less efficient, a larger and costlier conductor is now necessary to maintain the same voltage loss and power drop. However, a total cost reduction of about 15 percent (from $7,100 to $6,000) still results from the conversion to single-phase construction. This saving is due to the need for two rather than three lengths of conductor, less poletop hardware, and somewhat lighter construction.

Table 2. Cost Savings Through Increased Working Voltage and Use of Single Phase

	Three-phase, 11 kV		Three-phase, 22 kV		Single-phase, 22 kV	
Component	**Description**	**Cost ($)**	**Description**	**Cost ($)**	**Description**	**Cost ($)**
Poles	10.6 and 12 m	70,900	10.6 and 12 m	69,800	10.6 and 12 m	62,100
Conductor	1/0 (53 mm^2) ACSR	76,900	#6 (13 mm^2) ACSR	32,900	#4 (21 mm^2) ACSR	24,100
Poletop assembly	Pin insulators, crossarms, etc.	50,000	Pin insulators, crossarms, etc.	49,000	Pin insulators, crossarms, etc.	40,500
Guys	cable, attachments	8,300	cable, attachments	7,800	cable, attachments	6,000
Labor		65,500		53,400		46,300
Total		271,600		212,900		179,000
Total/km		9,100		7,100		6,000

Note: In this example, the base case is a 1/0 (53-mm^2) ACSR three-wire, three-phase line operating at 11 kV and serving several remote villages with a total maximum load of the equivalent of 150 kW at the end of a 30-kilometer line. This would result in a voltage drop of nearly 3 percent and an energy loss of about 4 kW. Costs incurred in line construction in El Salvador are assumed here.

Although reverting to a higher distribution voltage reduces the size and cost of the conductor, the higher voltage may also require increased insulation value for the insulators, transformers, capacitors, lightning arrestors, and so on, as well as greater line-line and line-ground clearances. However, for the voltages noted in Table 2, this is not significant. Where there is a considerable jump in design, construction, and operating costs is from 22 to 33 kV. At this point the additional clearances, safety factors, and insulation have to be reviewed. Operating at a higher voltage also results in higher maintenance costs if the utility is involved in a program of insulator washing and cleaning. And in areas near the ocean, industrial estates, and volcanic areas, voltages above 6.6 kV usually require special design considerations.

Present worldwide practice limits distribution voltages to about 35 kV (1) to ensure the safety of the public and of utility workers and (2) to avoid increased costs of fault coordination. Above this voltage, the trend is to move toward large post insulators or suspension insulators similar to transmission line design. Small transformers at these higher voltages are also more expensive and not as readily available.

Distribution Transformer

Typically, the cost of distribution transformers is a small part of the construction cost of most lines serving rural areas. However, although the cost for constructing a line is generally borne by hundreds or thousands of consumers served by that line, the capital cost of each transformer is usually borne by the much smaller number of consumers it serves. Depending on design, its cost can be important.

Moreover, given that transformers consume power 24 hours per day independent of imposed load, recurring costs incurred in operating transformers can even be more significant. Therefore, in considering the cost of transformers, their life-cycle cost—in this case, the sum of both their initial capital cost and their operating cost—must be considered. The relative importance of various costs is illustrated in Box 2. Only after these components are understood can approaches to reducing cost be better designed.

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[1] Gadi Kaplan, "Appropriate Technologies," *IEEE Spectrum*, October 1994; and Christopher Flavin and Molly O'Meara, "Solar Power Markets Boom," *World Watch*, September/October 1998, respectively.

[2] Allen R. Inversin, "New Designs for Rural Electrification: Private-Sector Experiences in Nepal" (Arlington, Virginia: NRECA, 1994).

[3] Allen R. Inversin, "Off-grid Rural Electrification: Summary, Analysis, and Recommendations Following Field Visits to Lao P.D.R., February-March 1997," prepared for the World Bank, March 25, 1997, Annex A. Although the high cost of manpower in the United States can significantly increase the cost of line construction, these labor costs do not reflect the cost of construction encountered in many developing countries.

[4] Michael J. Shiel, "Rural Electrification in Ireland" (U.K.: The Panos Institute, 1988); and Voravate Tig Tuntivate and Douglas Barnes, "Rural Electrification in Thailand: Lessons from a Successful Program," draft copy (Washington, D.C.: Industry and Energy Department, World Bank, 1995).

[5] R. Masmoudi, "Rural Electrification in Tunisia" (proceedings of the World Bank Electric Power Distribution Design Workshop held on May 27, 1993, in Washington, D.C.).

[6] See Figure 30 on p. **Error! Bookmark not defined.**.

[7] *High-Voltage Earth Return Distribution for Rural Areas*, fourth edition (Electricity Authority of New South Wales, revised June 1978).

[8] N.P. Drew and D.J. Postlethwaite, "Single Wire Earth Return Distribution Systems: Economic Rural Electrification" (paper presented to the 7th CEPSI Conference, Brisbane, October 1988).

[9] Correspondence with James A. Taylor, wood pole specialist.

[10] *REC Specifications and Construction Standards* (New Delhi: Rural Electrification Corporation, Ltd., 1994).

[11] Allen R. Inversin, "New Designs for Rural Electrification: Private-Sector Experiences in Nepal" (Arlington, Virginia: NRECA, 1994).

[12] This is illustrated in Table 2 (p.37).

[13] Promoted by Prof. F. Iliceto of the University of Rome. See F. Iliceto *et al*., "MV distribution from insulated shield wires of HV lines, Experimental applications in Ghana" (Symposium 11-85, CIGRÉ/UPDEA Symposium, Dakar, 1985) (112, boulevard Haussmann, 75006 Paris).

[14] René Massé and Hervé Conan, "Distribution de l'électricité en zone periurbaine dans les pays en dévéloppement: Note de synthèse" (France: GRET, APAVE, and BURGEAP, January 1997).

[15] The manufacturer of written-pole motors is Precise Power Corporation, P.O. Box 9547, Bradenton FL 34206-9547, USA (http://www.precisepwr.com). Electronic drive technology is available from Unico, Inc., 3725 Nicholson Road, Franksville, WI 53126-0505, USA (http://www.unicous.com).

[16] Glen R. Benjamin, Paul J. Stary, and J. Mike Deans, "A Comparative Analysis: Three-Phase 400/230 V vs. Single-Phase 230 V LV systems" (Arlington, Virginia: NRECA International, Ltd., circa 1979).