03-Grid Extension and Enhancement

Off-Grid Electrical Systems in Developing Countries, 2nd Edition

Chapter 3

Preface

- These lectures slides are intended to accompany the textbook *Off-Grid Electrical Systems in Developing Countries, 2nd Edition, 2025* written by Dr. Henry Louie and published by SpringerNature
- Additional content, explanations, derivations, examples, problems, errata, and other materials are found in the book and on www.drhenrylouie.com
- To request solutions, explanations, permissions to use author-supplied images, or if you notice an error, please email the author at hlouie@ieee.org
- Inquiries about guest lectures, seminars, or trainings can be made to hlouie@ieee.org
- If you want to support work in electricity access, consider donating to KiloWatts for Humanity or IEEE Smart Village

Learning Outcomes

At the end of this lecture, you will be able to:

- ✓Identify situations where grid extension would be preferred over off-grid electrification, considering technical and economic factors
- ✓Design and analyze distribution lines to satisfy ampacity, voltage drop, and other constraints
- ✓Calculate the cost of grid extension under a variety of economic and technical scenarios
- ✓Describe methods for rural electrification planning

Introduction

Why aren't more people connected to the grid?

Grid Extension

Grid extension:

- electrification by extending the grid to communities without electricity
- connecting homes and businesses near the existing grid
- enhancing or improving the electricity service provided by the grid (e.g. improving reliability)

To Grid…

Reasons to electrify via grid extension:

- common approach to providing electricity access
- can be fast and least-expensive approach at providing high-tier electricity access for communities

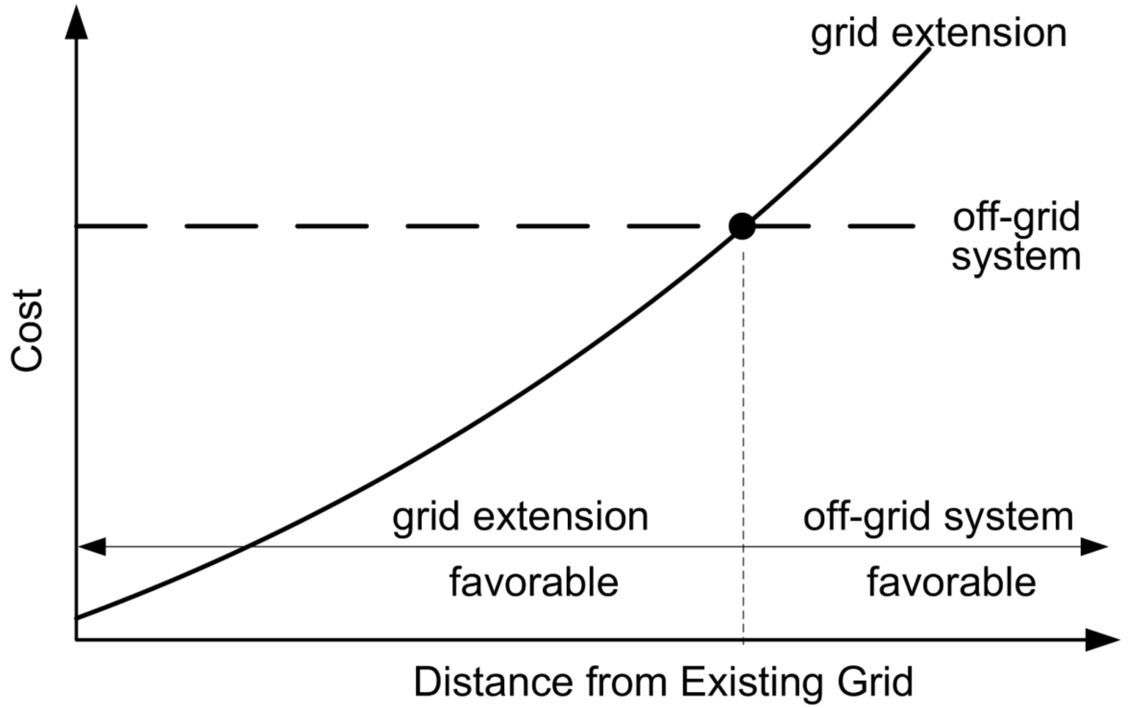
(*courtesy: R. Ngoma*)

…or Not to Grid

Reasons not to electrify via grid extension

- off-grid systems may be less expensive for communities far from the existing grid
- waiting period for grid extension may be very long
- reliability offered by grid may be lower than off-grid systems

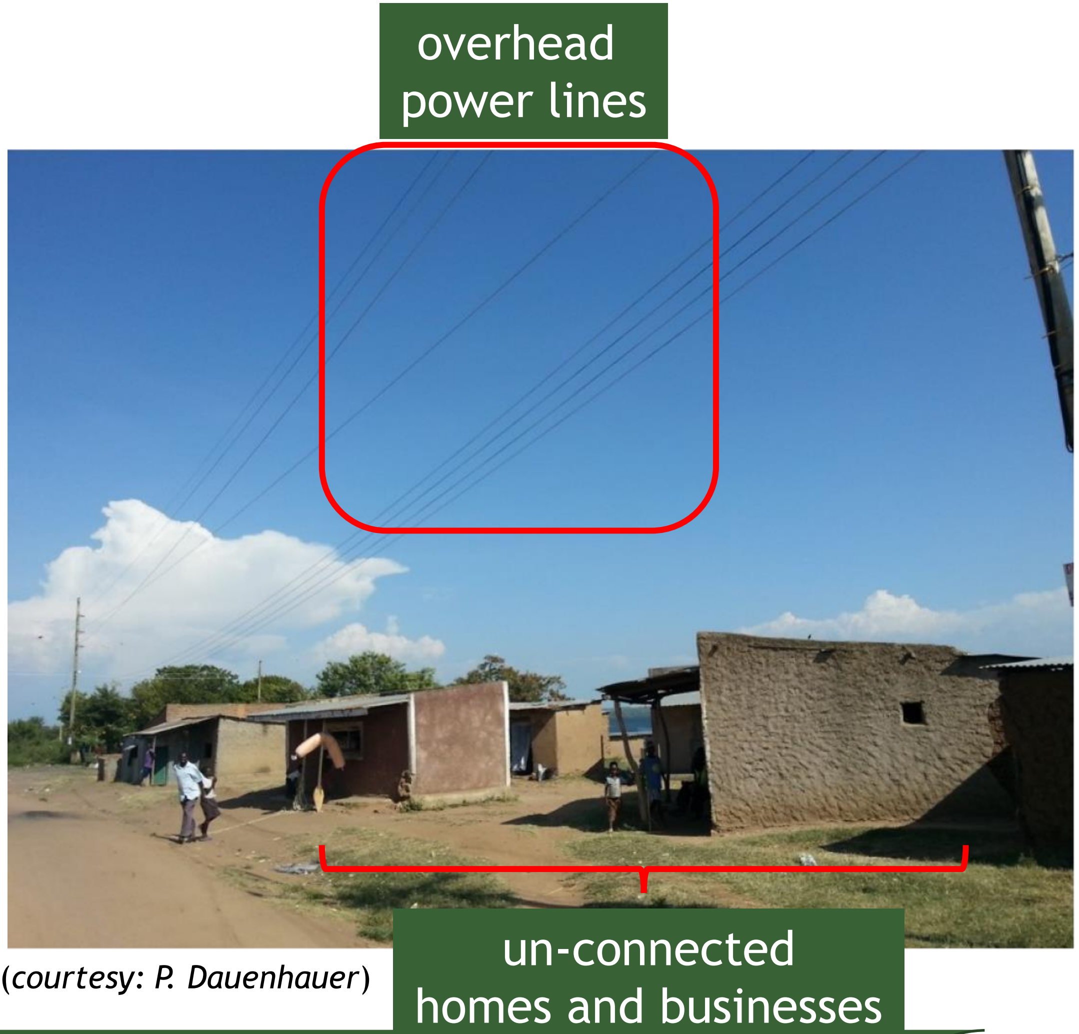
Grid Extension vs Off-Grid



grid extension is preferred for communities close to the existing grid

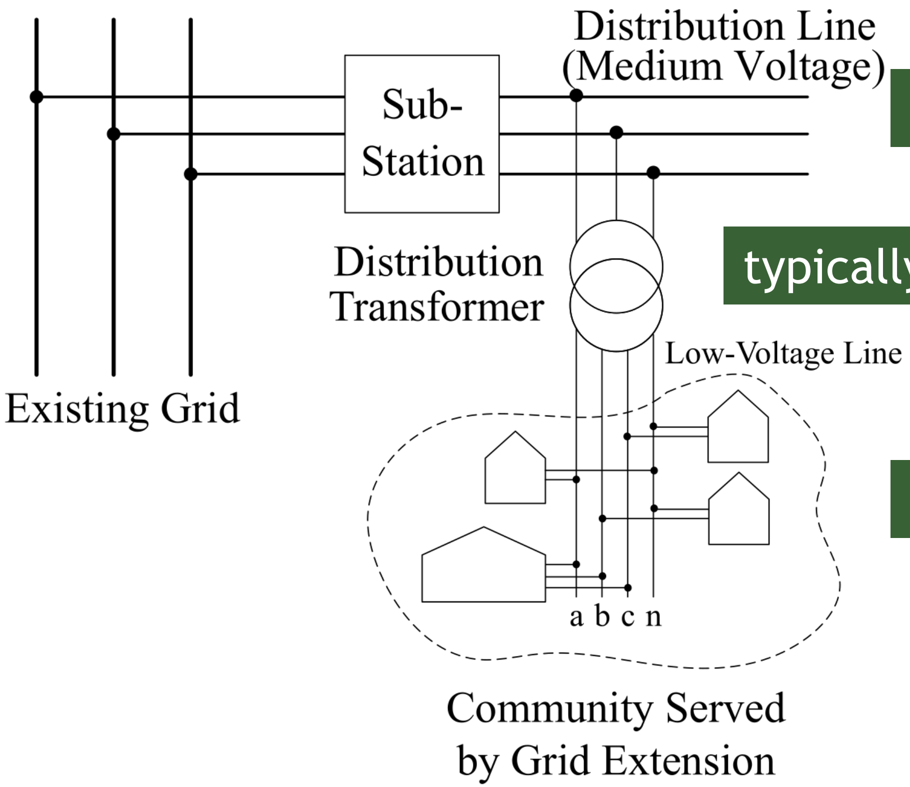
Urban Electrification

- Millions of people without electricity are in urban locations
  - 19% of urban homes in Sub Saharan Africa (SSA)
  - many in refugee and informal settlements
- Many live "under the grid", within 200 m but are not connected



(*courtesy: P. Dauenhauer*)

Basic Components of Grid Extension

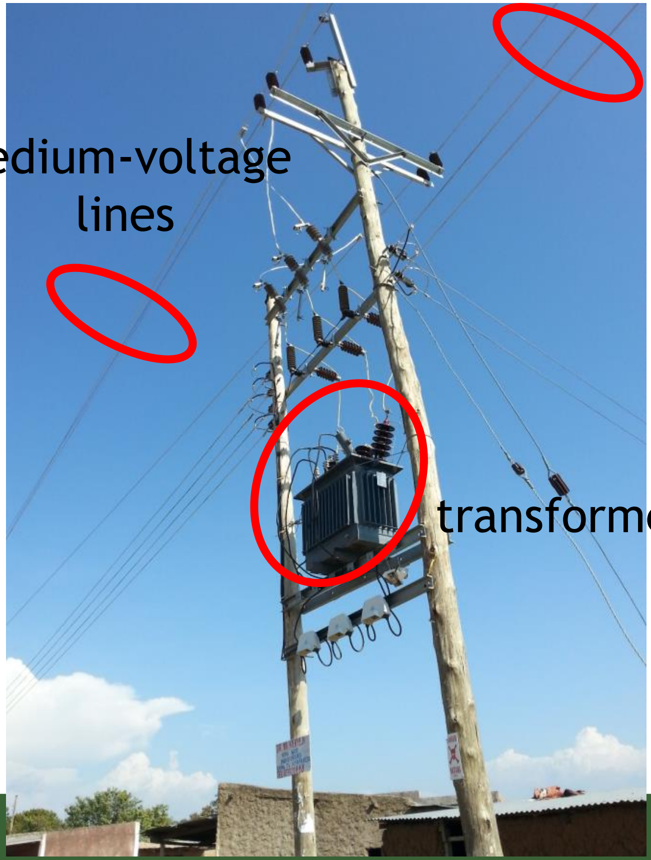


typically 11 to 33 kV

typically 50-200 kVA

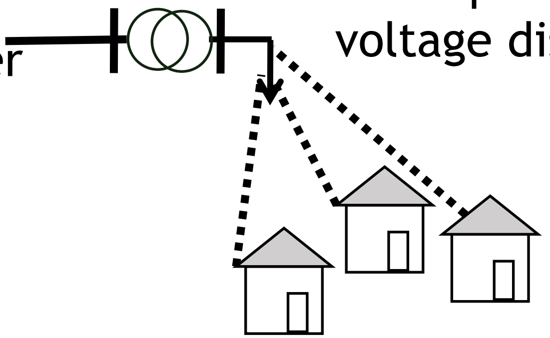
typically 120 or 230 V

Basic Components of Grid Extension



(*courtesy: H. Louie*)

transformer power rating is "shared" by the downstream households

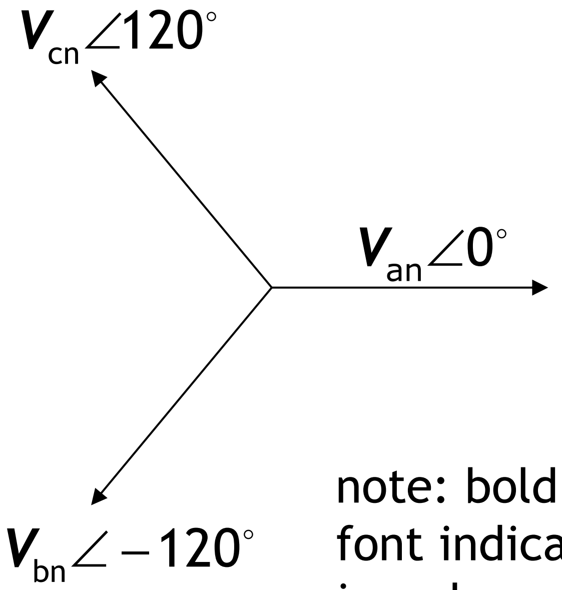


Grid Extension Example

(*courtesy: T. Callsen, Weldy Lamont Associates*)

Distribution Line Design: Three-Phase

- Medium-voltage distribution lines are three phase (a, b, and c)
- Assume balanced conditions
  - voltages have equal magnitude and shifted by 120°
  - currents have equal magnitude and shifted by 120°
  - power (S, P, Q) are shared equally among the three phases

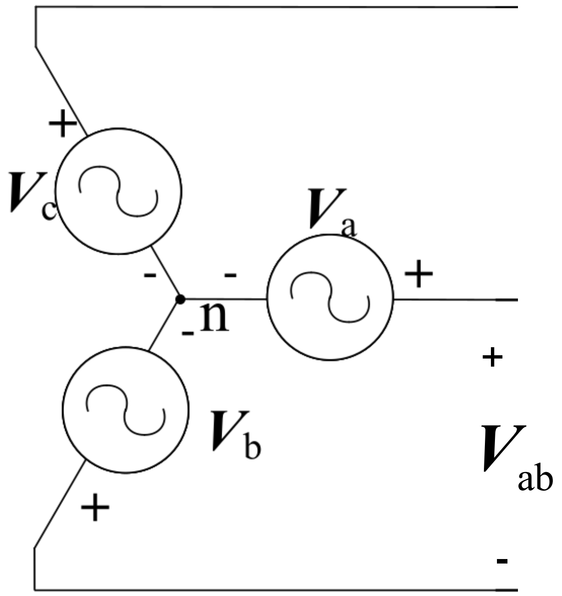


note: bold, italicized font indicate the variable is a phasor (magnitude and angle)

Distribution Line Design: Power, Voltage, and Current Relationships

Relationship between line-line voltage magnitude and line-neutral is

$$V_{\phi} = \frac{V_{\ell\ell}}{\sqrt{3}}$$

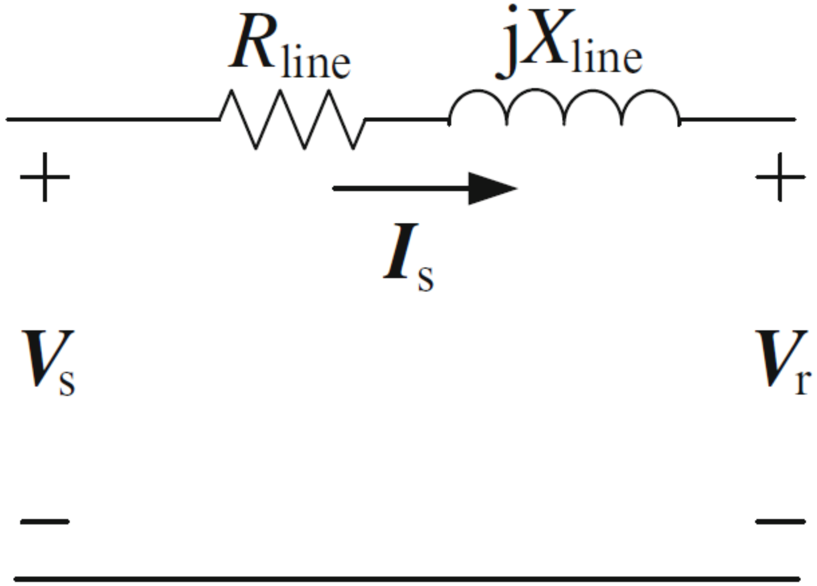


example 3-phase source,
$\boldsymbol{V}_{an}$ is a line-neutral voltage,
$\boldsymbol{V}_{ab}$ is a line-line voltage

Distribution Line Model

- Consider a single phase of the distribution line
- Conductor is modeled as a series impedance between a sending end and a receiving end
  - $\boldsymbol{V}_s$: sending-end voltage, V
  - $\boldsymbol{V}_r$: receiving-end voltage, V
  - $\boldsymbol{I}_s$: conductor current, A
  - R_{line}: conductor resistance, Ω
  - X_{line}: conductor inductive reactance, Ω

$$Z_{\text{line}} = R_{\text{line}} + jX_{\text{line}}$$



Lines longer than ~50 km have shunt capacitance (to ground) that should be included in the model

Distribution Line Design: Power, Voltage, and Current Relationships

- Per-phase power is evenly divided among all three phases
- Sending-end and receiving-end powers may differ due to losses

$$S_s = \frac{S_{\text{total,s}}}{3}$$

$$S_r = \frac{S_{\text{total,r}}}{3}$$

subscript "s" for sending-end quantities
subscript "r" for receiving-end quantities

$$P_s = |S_s| \times PF$$

$$P_r = |S_r| \times PF$$

PF: power factor of load

Distribution Line Design: Power, Voltage, and Current Relationships

- Current at the sending end is the same as the receiving end
- Current in one phase of the distribution line is

$$\boldsymbol{I}_{\mathrm{s}} = \left(\frac{S_{\mathrm{s}}}{\boldsymbol{V}_{\mathrm{s}}}\right)^{*}$$

complex conjugate

$$|\boldsymbol{I}_{\mathrm{s}}| = \frac{|S_{\mathrm{s}}|}{|\boldsymbol{V}_{\mathrm{s}}|}$$

Example 3.1

The sending-end total apparent power on a three-phase distribution line is 900 kVA at a power factor of 0.85. The line-to-line voltage of the distribution line is 22 kV. Determine the real power associated with a-phase on the sending end of the distribution line and the magnitude of the a-phase current.

Example 3.1

The sending-end total apparent power on a three-phase distribution line is 900 kVA at a power factor of 0.85. The line-to-line voltage of the distribution line is 22 kV. Determine the real power associated with a-phase on the sending end of the distribution line and the magnitude of the a-phase current.

The a-phase apparent power will be one-third of the total apparent power

$$S_s = \frac{S_{total,s}}{3} = \frac{900}{3} = 300 \text{ kVA}$$

Example 3.1

The sending-end total apparent power on a three-phase distribution line is 900 kVA at a power factor of 0.85. The line-to-line voltage of the distribution line is 22 kV. Determine the real power associated with a-phase on the sending end of the distribution line and the magnitude of the a-phase current.

Real power:

$$P_s = |S_s| \times PF = 300 \times 0.85 = 255 \text{ kW}$$

Example 3.1

The sending-end total apparent power on a three-phase distribution line is 900 kVA at a power factor of 0.85. The line-to-line voltage of the distribution line is 22 kV. Determine the real power associated with a-phase on the sending end of the distribution line and the magnitude of the a-phase current.

The a-phase line-neutral voltage at the sending end is

$$\boldsymbol{V}_{\phi,s} = \frac{\boldsymbol{V}_{\ell\ell}}{\sqrt{3}} = \frac{22{,}000}{\sqrt{3}} = 12.70 \text{ kV}$$

Example 3.1

The sending-end total apparent power on a three-phase distribution line is 900 kVA at a power factor of 0.85. The line-to-line voltage of the distribution line is 22 kV. Determine the real power associated with a-phase on the sending end of the distribution line and the magnitude of the a-phase current.

The a-phase current

$$|\boldsymbol{I}_s| = \frac{|S_s|}{|\boldsymbol{V}_{\phi,s}|} = \frac{300}{12.70} = 23.6 \ \text{A}$$

Conductor Resistance

- AC resistance of conductor depends on:
  - ℓ: length, m
  - ρ: resistivity, Ohm-m
  - A_{line}: cross-sectional area, m^2
  - s: skin effect (unitless)

$$R_{\text{line}} = s\rho\frac{\ell}{A_{\text{line}}}$$

- Skin effect is frequency dependent, and <u>increases</u> resistance by ~1-3%

Inductive Reactance

- Inductance of a line depends on:
  - length of line
  - physical distance separating the phases (or hot and neutral in single phase)
  - effective radius of the conductors (bundling)
- We will not derive how the inductance is computed, but note:

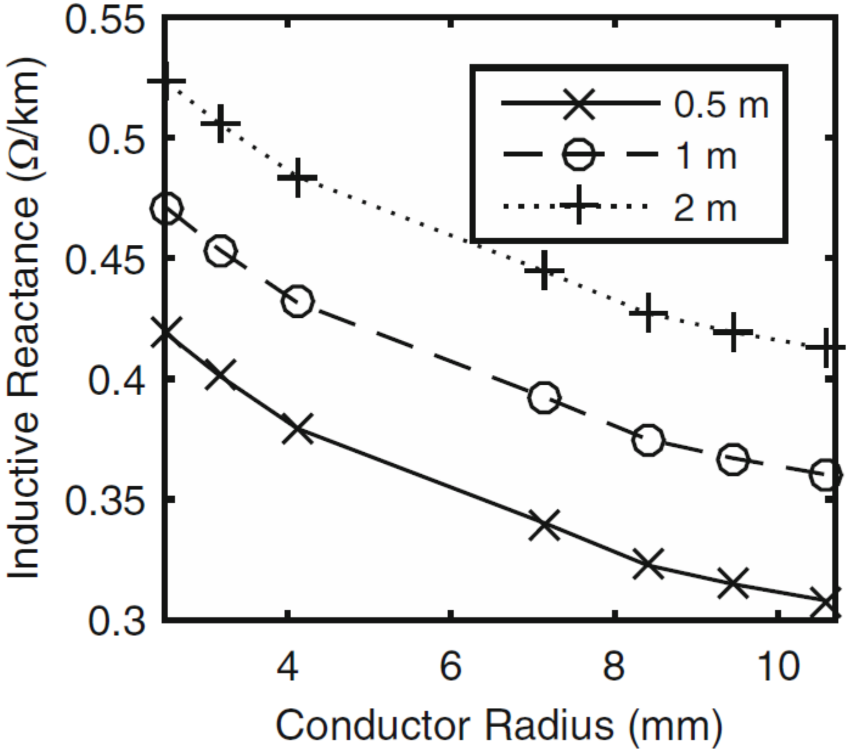
$$X_{\text{line}} = \omega L$$

  - ω: frequency, rad/s
  - L: inductance, H

Inductive Reactance

- As conductors are placed farther apart, the inductive reactance increases (non-linearly)
- As cross-sectional area increases, the inductive reactance decreases

to minimize conductor inductance, place conductors close together and use larger conductors



Conductor Sizing

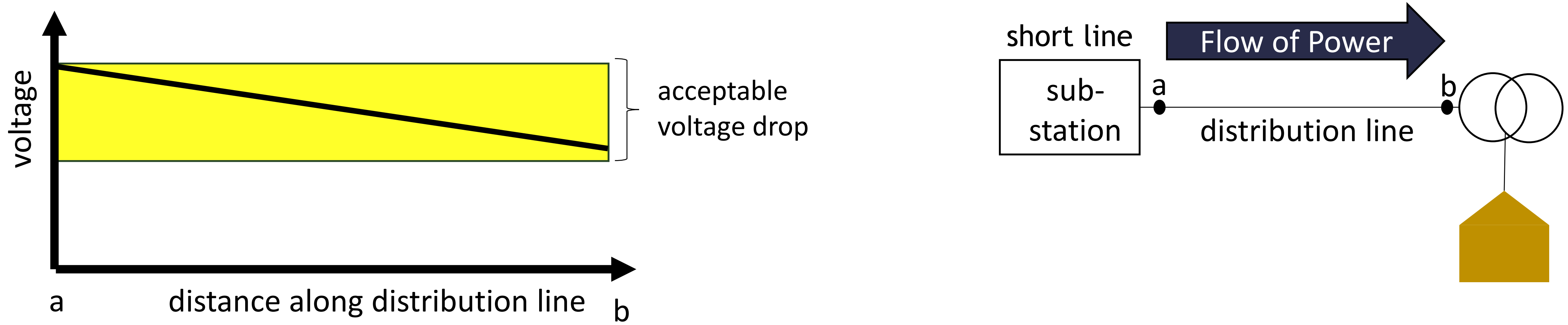
- An important consideration in grid extension design is conductor selection
- Considerations:
  - insulation type
  - appropriate for environment (indoor, outdoor, buried, corrosive, shielded, etc.)
- Conductor cross-sectional area
  - voltage drop
  - heat dissipation (thermal limit)

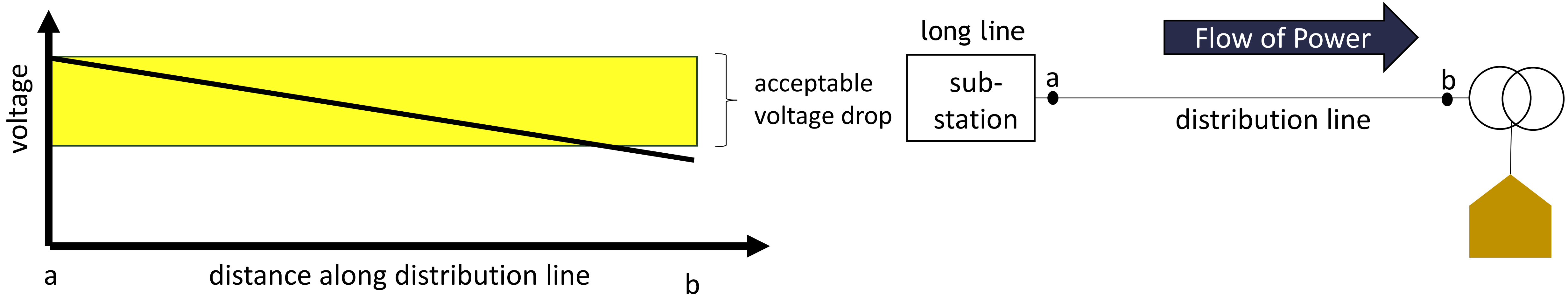
we focus on these aspects

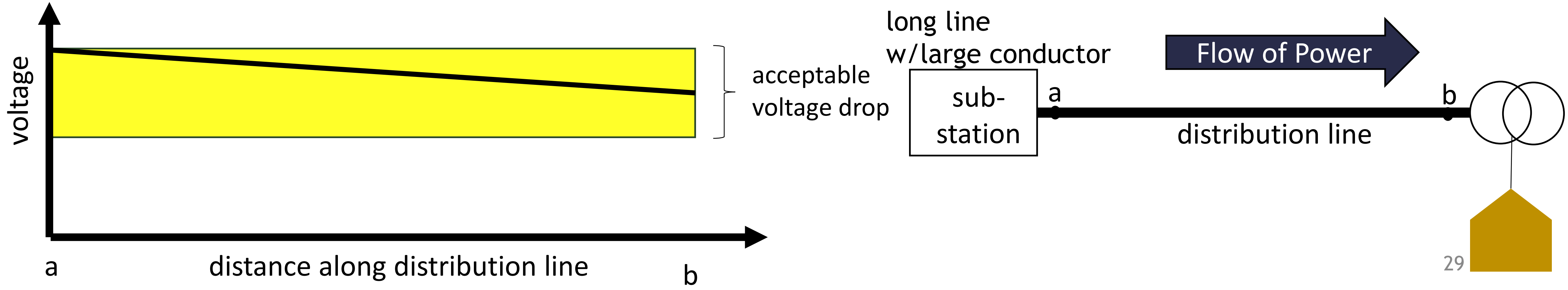
Distribution Line Design Considerations

Voltage Drop Limit

- Impedance causes a reduction in voltage along distribution line
- Voltage drop increases with current (power) flow
- Limit voltage drop to less than 5-10%
- Larger conductors reduce voltage drop


voltage
acceptable
voltage drop
a
distance along distribution line
b
short line
Flow of Power
sub-
station
a
b
distribution line


voltage
acceptable
voltage drop
a
distance along distribution line
b
long line
Flow of Power
sub-
station
a
b
distribution line


voltage
acceptable
voltage drop
a
distance along distribution line
b
long line
w/large conductor
Flow of Power
sub-
station
a
b
distribution line

Voltage Drop

- Voltage drop associated with a conductor is

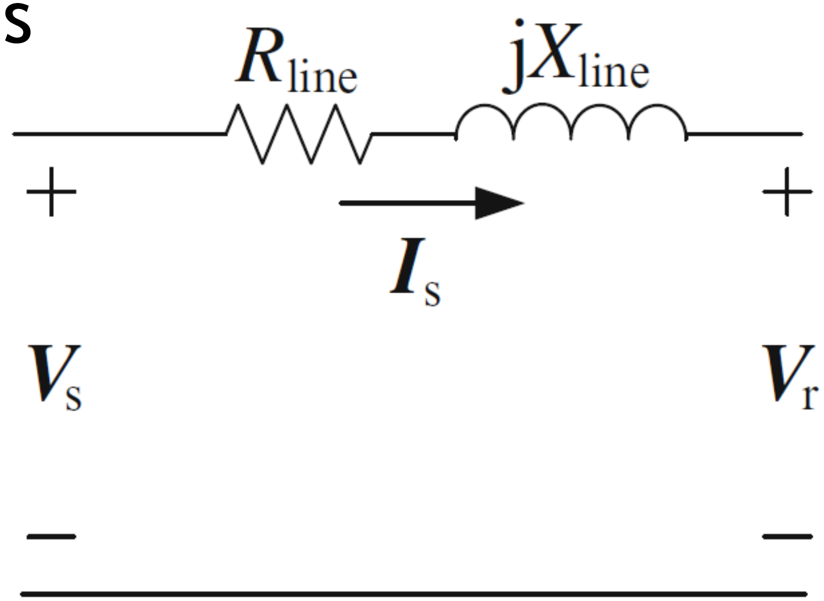
$$V_{\text{drop}} = |\boldsymbol{V}_{\text{s}} - \boldsymbol{V}_{\text{r}}| = |\boldsymbol{I}_{\text{s}}| \times |Z_{\text{line}}|$$

- Expressed as a percentage

$$V_{\text{drop},\%} = \frac{V_{\text{drop}}}{|V_{\text{s}}|} \times 100$$

- Voltage drop is approximated as

$$V_{\text{drop}} \approx |\boldsymbol{V}_{\text{s}}| - |\boldsymbol{V}_{\text{r}}|$$



What if the voltage drop is too large?

- Use conductors with larger cross-sectional area to reduce the resistance and inductive reactance
- Decrease the separation distance between the conductors to reduce the inductive reactance
- Increase the nominal voltage of the distribution line to reduce the current for a given amount of power
- Include voltage boosting equipment such as transformers or capacitor banks

Distribution Line Design Considerations

Thermal Limit

- Resistance causes distribution line to heat due to current in it
- Overheating can cause failure
- Heating is inefficient (losses)
- Larger conductors reduce power loss

Thermal Limit

- Real power loss along a line:

$$P_{\text{loss},\phi} = |I_s|^2 \times R_{\text{line}}$$
$$P_{\text{loss,total}} = 3P_{\text{loss},\phi}$$

Note: real power loss does not depend on inductance of the line

- To reduce real power loss (and heat generated):
  - decrease current (this usually is not an option)
  - reduce resistance (larger cross-sectional area, use less resistive material)

Thermal Limit

- The amount of continuous current in a conductor without overheating it (exceeding its temperature rating) is called the "ampacity" of the conductor
- Ampacity depends on:
  - heat generated by the conductor
  - ambient temperature
  - heat from the sun (if outdoors)
  - cooling from wind (if outdoors)
  - heat from other nearby conductors (especially in conduit and raceways)

Thermal Limit

- Ampacity of a (outdoor) conductor can vary throughout the year as the ambient temperature changes
- Short overloads can be permitted on higher voltage transmission and distribution lines

Exercise

A conductor that satisfies a voltage drop limit will always satisfy the thermal limit

True

False

Exercise

A conductor that satisfies a voltage drop limit will always satisfy the thermal limit

True

False

For example: a short conductor may satisfy the voltage limit, but not the thermal limit

Ampacity Examples

Cross-sectional Area (Copper)	Ampacity (insulated, open-air)	Impedance (Ω/km)
13 mm^2	80 A	2.25 + j0.31
21 mm^2	105 A	1.40 + j0.31
34 mm^2	140 A	0.70 + j0.31

Rated Power of Distribution Line

Rated power of a line is the maximum apparent power (three phase) that can be provided at the nominal voltage without violating the thermal limits of the line

Example 3.4

A cluster of villages is to be supplied by a three-phase distribution line that is 25 km in length. The peak load is predicted to be 4.0 MVA with a power factor of 0.85 lagging. The peak load is expected to grow by 2% per year for the next 10 years. Assume the receiving-end line-to-line voltage is 22 kV, and the voltage drop limit is 10%. The conductors are separated by 2 m. Select the conductor with the smallest cross-sectional area that satisfies the thermal and voltage limits

	Size (mm^2)	Ampacity (A)	Resistance (Ohm/km)	Reactance (0.5 m spacing) (Ohms/km)	Reactance (1 m spacing) (Ohms/km)	Reactance (2 m spacing) (Ohms/km)
A	13.3	95	2.200	0.419	0.471	0.523
B	21.1	125	1.384	0.401	0.453	0.506
C	33.6	165	0.869	0.379	0.432	0.484
D	107.2	325	0.273	0.340	0.392	0.445
E	135.2	415	0.218	0.323	0.375	0.427
F	201.4	525	0.147	0.318	0.367	0.423
G	241.7	590	0.122	0.308	0.360	0.413

Example 3.4

A cluster of villages is to be supplied by a three-phase distribution line that is 25 km in length. The peak load is predicted to be 4.0 MVA with a power factor of 0.85 lagging. The peak load is expected to grow by 2% per year for the next 10 years. Assume the receiving-end line-to-line voltage is 22 kV, and the voltage drop limit is 10%. The conductors are separated by 2 m. Select the conductor with the smallest cross-sectional area that satisfies the thermal and voltage limits

The load after 10 years of 2% of growth per year is

$$S_{total} = 4.0 \times (1+0.02)^{10} = 4.88 \text{ MVA}$$

Example 3.4

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Required per-phase power rating is

$$\theta = \cos^{-1}(PF) = 31.8^\circ$$

$$S_\phi = \frac{S_{\text{total}}}{3}\cos(\theta) + j\frac{S_{\text{total}}}{3}\sin(\theta) = 1.38 + j0.86 \text{ MVA}$$

Example 3.4

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Current based on the receiving-end line-neutral voltage

$$S_\phi = \boldsymbol{V}_r \boldsymbol{I}_s^*$$

$$\boldsymbol{V}_r = \frac{22\,\text{kV}}{\sqrt{3}} = 12.702\angle 0^\circ \text{ kV}$$

$$\boldsymbol{I}_s = \left(\frac{S_\phi}{\boldsymbol{V}_r}\right)^* = \left(\frac{1.38 + j0.86 \text{ MVA}}{12.702\,\text{kV}}\right)^* = 127.96\angle -31.8^\circ \text{A}$$

Example 3.4

A cluster of villages is to be supplied by a three-phase distribution line that is 25~km in length. The peak load is predicted to be 4.0 MVA with a power factor of 0.85 lagging. The peak load is expected to grow by 2% per year for the next 10 years. Assume the receiving-end line-to-line voltage is 22 kV, and the voltage drop limit is 10%. The conductors are separated by 2 m. Select the conductor with the smallest cross-sectional area that satisfies the thermal and voltage limits

Conductors A and B do not meet ampacity requirement

$$I_s = 127.96\angle -31.8^\circ \text{ A}$$

	Size (mm^2)	Ampacity (A)	Resistance (Ohm/km)	Reactance (0.5 m spacing) (Ohms/km)	Reactance (1 m spacing) (Ohms/km)	Reactance (2 m spacing) (Ohms/km)
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Example 3.4

Checking Conductor C

$$Z_{\text{line}} = (0.869 + j0.484) \times 25 = 21.73 + j12.10\,\Omega$$

$$\mathbf{V}_{\text{drop}} = |\mathbf{I}_{\text{s}}| \times |Z_{\text{line}}| = 127.961 \times |21.73 + j12.10| = 3.182\ \text{kV}$$

$$\mathbf{V}_{\text{s}} = \mathbf{V}_{\text{r}} + \mathbf{I}_{\text{s}} Z_{\text{line}} = 12{,}704 + 127.96\angle -31.8^\circ \times (21.73 + j12.10) = 15.88\angle -0.54^\circ\,\text{kV}$$

$$V_{\text{drop},\%} = \frac{V_{\text{drop}}}{|\mathbf{V}_{\text{s}}|} \times 100 = \frac{3.182\,\text{kV}}{15.88\,\text{kV}} \times 100 = 20.03\%$$

Voltage drop is too large!

	Size (mm^2)	Ampacity (A)	Resistance (Ohm/km)	Reactance (0.5 m spacing) (Ohms/km)	Reactance (1 m spacing) (Ohms/km)	Reactance (2 m spacing) (Ohms/km)
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Example 3.4

Process is repeated to find that Conductor G satisfies all constraints

	Size (mm^2)	Ampacity (A)	Resistance (Ohm/km)	Reactance (0.5 m spacing) (Ohms/km)	Reactance (1 m spacing) (Ohms/km)	Reactance (2 m spacing) (Ohms/km)
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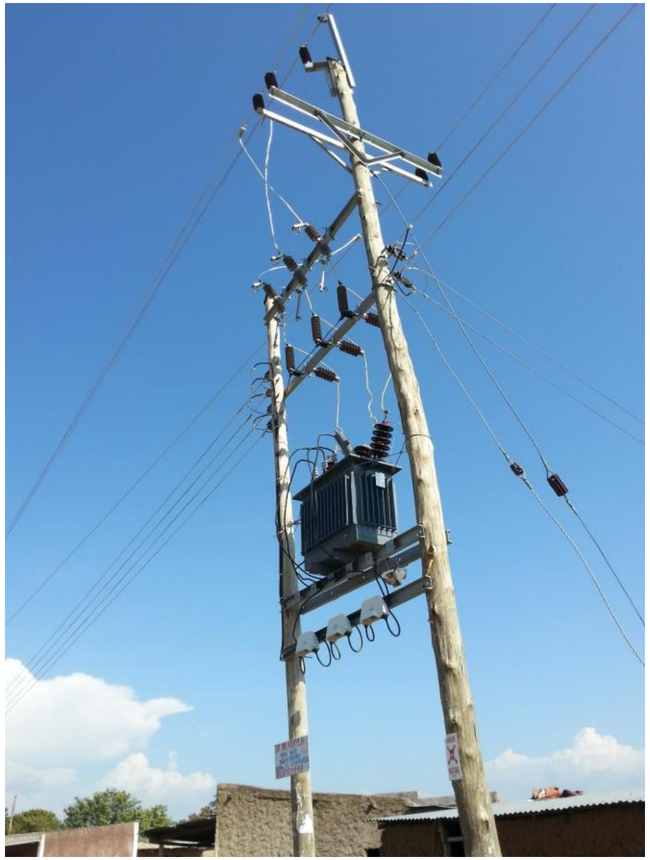
Transformer Ratings

- Transformers described by their power and primary/secondary voltages
- Typical rural electrification ratings:
  - power: 25, 50, 100 kVA
  - voltage: 11 kV/400V, 22 kV/400 V, 33 kV/400 V
- Exceeding power rating can cause the transformer to overheat and shorten its lifespan



(*courtesy: H. Louie*)

Low-Voltage Connections

- Connection from secondary of the transformer to the user
- Homes usually supplied single-phase 230 V (or 120 V)
- Different configurations possible
  - single phase, two wire
  - split-phase
  - three phase wye and delta

see chapter 17 for details

- Voltage drop limits low voltage length to ~1 km or less

Economic Model of Grid Extension

- General "truths"
  - grid extension is costly and requires significant upfront capital
  - grid power (energy) is less expensive than off-grid power (energy)
- The question becomes "under what conditions are the upfront costs worth it?"
- We consider a simple economic model

Grid Expansion Cost

Cost to extend the grid to the village

- widely variable in developing countries, often +US$20,000 per km
- cost dependent not only on distance, but also voltage level and capacity

Construction Costs

1. Distribution line (medium-voltage)
2. Low-voltage line
3. Transformer
4. Substation
5. User premise equipment (UPE) such as meters, wiring, sockets, switches, etc.

Example Costs

Ghana (2010)

Item	Description	Cost
33 kV line	wood pole, 120 mm^2 conductors	US$26,222/km
11 kV line	wood pole, 120 mm^2 conductors	US$24,690/km
200 kVA transformer	33/0.4 kV w/accessories	US$16,253
100 kVA transformer	33/0.4 kV w/accessories	US$13,815
50 kVA transformer	33/0.4 kV w/accessories	US$11,851
200 kVA transformer	11/0.4 kV w/accessories	US$13,344
100 kVA transformer	11/0.4 kV w/accessories	US$11,529
50 kVA transformer	11/0.4 kV w/accessories	US$10,243
Low-voltage line	3-phase, 4-wire, wood pole	US$16,597/km
Low-voltage line	1-phase, 3-wire, wood pole	US$14,869/km
Low-voltage line	1-phase, 2-wire, wood pole	US$12,958/km
3-phase user connection	meter, 25 mm^2 conductor	US$531
1-phase user connection	meter, 16 mm^2 conductor	US$275

Tanzania (2022)

Item	Cost
Low-voltage line	US$14,890/km
Medium-voltage line	US$21,270/km
Low-capacity electricity meter	US$100
High-capacity electricity meter	US$250

Medium-Voltage Line Cost Model

- Medium-voltage construction cost depends on length and rated power

$$c_{\text{line}} = \beta_{\text{line}} \times l_{\text{line}} \times S_{\text{rated,total}}$$

typically US$1200 to US$6600 per MVA km

- Alternate cost model based only on line length

$$c_{\text{line}} = \beta_{\text{line,km}} \times l$$

typically US$3000 to US$3000 per km

Low-Voltage Line Cost Model

- Low-voltage line cost model

$$c_{\mathrm{LV}} = \beta_{\mathrm{LV}} \times l_{\mathrm{LV}}$$

typically US$10,000 to US$18,000 per km

- Depends on type of insulation (if any), conductor size, bundling, overhead/underground

Transformer Cost Model

- Transformer line cost model

$$c_{\text{xmfr}} = \beta_{\text{xfmr}} \times S_{\text{rated,xmfr}}$$

typically US$100 to US$500 per kVA

Substation Cost

- A substation might need to be constructed or modified for grid extension
- Costs may include
  - switches
  - land
  - civil works
- Cost model

$$c_{\text{sub}} = \alpha_{\text{sub}} + \beta_{\text{sub}} S_{\text{sub}}$$

Wide range in cost coefficients depending on modifications needed

User Premise Equipment

- Users include: homes, businesses, and other structures receiving electricity
  - do not confuse “users” with number of people served
  - a single user is can serve multiple people
- User equipment: meters, wires, circuit breakers, outlets, etc.
- Most homes will not already be wired, so utility may have to also wire homes or provided “ready boards”

$$c_{\text{UPE}} = \beta_{\text{UPE}} \times N_{\text{con}}$$

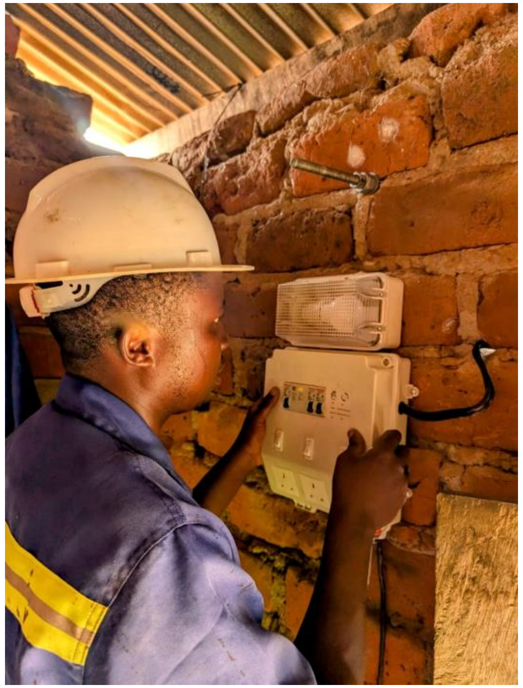
User Premise Equipment Cost

UPE cost model

$$c_{\text{UPE}} = \beta_{\text{UPE}} \times N_{\text{con}}$$

typically US$90 to US$500 per connection

“Ready Board”



(*courtesy: B. Simons*)

Total Infrastructure Cost

- Total infrastructure cost of grid extension

$$c_{\text{grid}} = c_{\text{line}} + c_{\text{LV}} + c_{\text{xmfr}} + c_{\text{sub}} + c_{\text{UPE}}$$

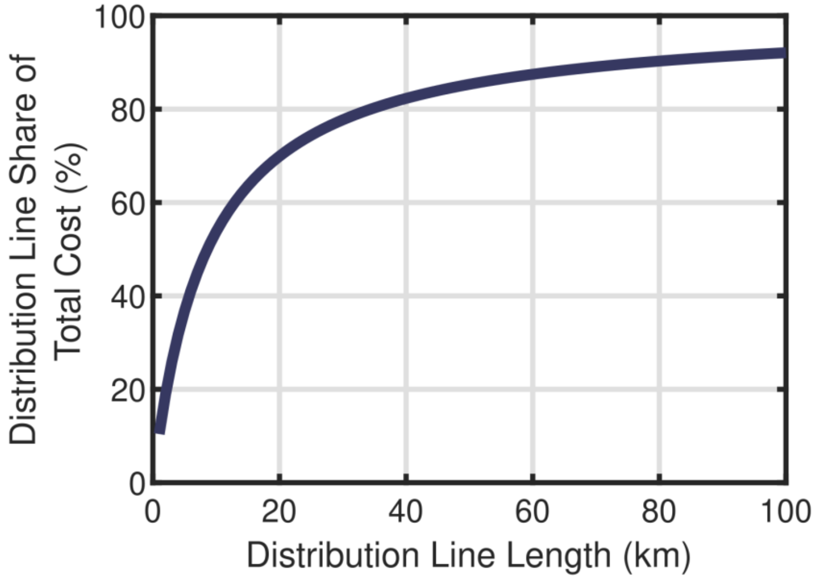
- Often expressed in cost per connection

$$c_{\text{con}} = \frac{c_{\text{grid}}}{N_{\text{con}}}$$

- Wide variety in cost per connection, typically US$500 to US$5000

Total Infrastructure Cost

- Total infrastructure cost depends heavily on the length of the distribution line
- Distribution line share of total costs can easily exceed 50% of total costs
- Common to consider grid extension not economically viable for communities >20 km from existing grid



Lifetime Cost of Grid Expansion

- Distribution lines and grid connections have finite lifespans
- Maintenance is also required
- What is the present annual cost of the grid expansion?

Lifetime Cost of Grid Expansion

Lifetime cost of grid extension

$$c_{\text{grid,life}} = c_{\text{grid}} + \left(t_{\text{grid}} \times m_{\text{grid}} \times c_{\text{grid}}\right)$$

annual maintenance cost in percentage of capital cost per year

lifespan of project, in years

Lifetime Cost of Grid Expansion

- Convert the future costs into *present dollars* with discount rate i
- Value of today's money after 1 year is

$$V_1 = V_0(1 + i)$$

- After Y years

$$V_Y = V_0(1+i)^Y$$

can be rearranged to find the present value of a cost that is Y years in the future

Lifetime Cost of Grid Expansion

- Fixed expenses or payments over *Y* years has a present value of

$$V_0 = V_{\text{annual}} \frac{(1+i)^Y - 1}{i(1+i)^Y}$$

annual expense or income

- Useful in understanding how costs are spread across the lifespan of the grid extension project

Example 3.8

The present cost of a grid extension project is US$100,000. Compute the fixed annual payment equivalent of this cost over a 20-year period at a discount rate of 5%.

Example 3.8

The present cost of a grid extension project is US$100,000. Compute the fixed annual payment equivalent of this cost over a 20-year period at a discount rate of 5%.

$$V_{\text{annual}} = V_0 \frac{i(1+i)^Y}{(1+i)^Y - 1} = 100,000 \frac{0.05(1+0.05)^{20}}{(1+0.05)^{20} - 1} = \text{US\$}8024.26$$

The total sum paid over 20 years is 20 x 8024.26 = US$160,485.20.

Maintenance Costs

- Model maintenance costs as fixed yearly cost over the life of the grid extension project

$$c_{\text{grid},0} = c_{\text{grid}} + \left(m_{\text{grid}} \times c_{\text{grid}} \frac{(1+i)^{Y} - 1}{i(1+i)^{Y}} \right)$$

- Convert this to equal (fixed) annual payments:

$$c_{\text{grid,annual}} = \frac{c_{\text{grid},0}}{\frac{(1+i)^{Y} - 1}{i(1+i)^{Y}}}$$

Energy Cost

- In addition to grid expansion costs, there is a cost incurred in generating electricity
- Generation cost is a variable cost, which is a function of consumption by the end-user

Generation Cost

- Cost of energy largely depends on power plant specifics (fuel source, capacity, age, etc.) and transmission/distribution losses
- Generation costs in developing countries tend to be greater than the average in the rest of world
- Africa average: US$0.18/kWh (in 2013) but can vary widely

Levelized Cost of Energy

- Levelized Cost of Energy (LCOE): the cost of installing and operating a power plant over the course of its lifetime
  - expressed as $/kWh
- Convenient for comparing different energy sources
- Discount rate applied to future costs
- Typically accounts for:
  - installation
  - financing
  - operation and maintenance costs, including fuel
  - salvage value
  - total energy production

LCOE is discussed further in Chapter 19

Total Grid Extension Electrification Cost

- Total annual cost: energy cost + annual lifetime infrastructure cost
- Computed as $c_{\text{total,annual}} = \left(LCOE \times E_{\text{annual}}\right) + c_{\text{grid,annual}}$

Example 3.10

Compute the cost of electrifying a village with 203 homes assuming the total annual infrastructure cost is US$31,846 annual consumption is 365 kWh per user (home) per year and the losses are equal to 10% of the load. Assume the LCOE is US$0.15/kWh.

Example 3.10

Compute the cost of electrifying a village with 203 homes assuming the total annual infrastructure cost is US$31,846 annual consumption is 365 kWh per user (home) per year and the losses are equal to 10% of the load. Assume the LCOE is US$0.15/kWh.

Annual energy consumption + losses: $E_{\text{annual}} = 365 \times 203 \times (1 + 0.10) = 81{,}504.50\,\text{kWh/yr}$

Total annual cost:

$$c_{\text{total,annual}} = (\text{US\$}0.15/\text{kWh} \times 81{,}504.50\,\text{kWh}) + \text{US\$}31{,}846 = \text{US\$}44{,}072$$

Discussion

It is almost always more expensive to serve rural customers.

Do you think that rural customers should be charged a “cost reflective” price or should all customers be charged the same rate?

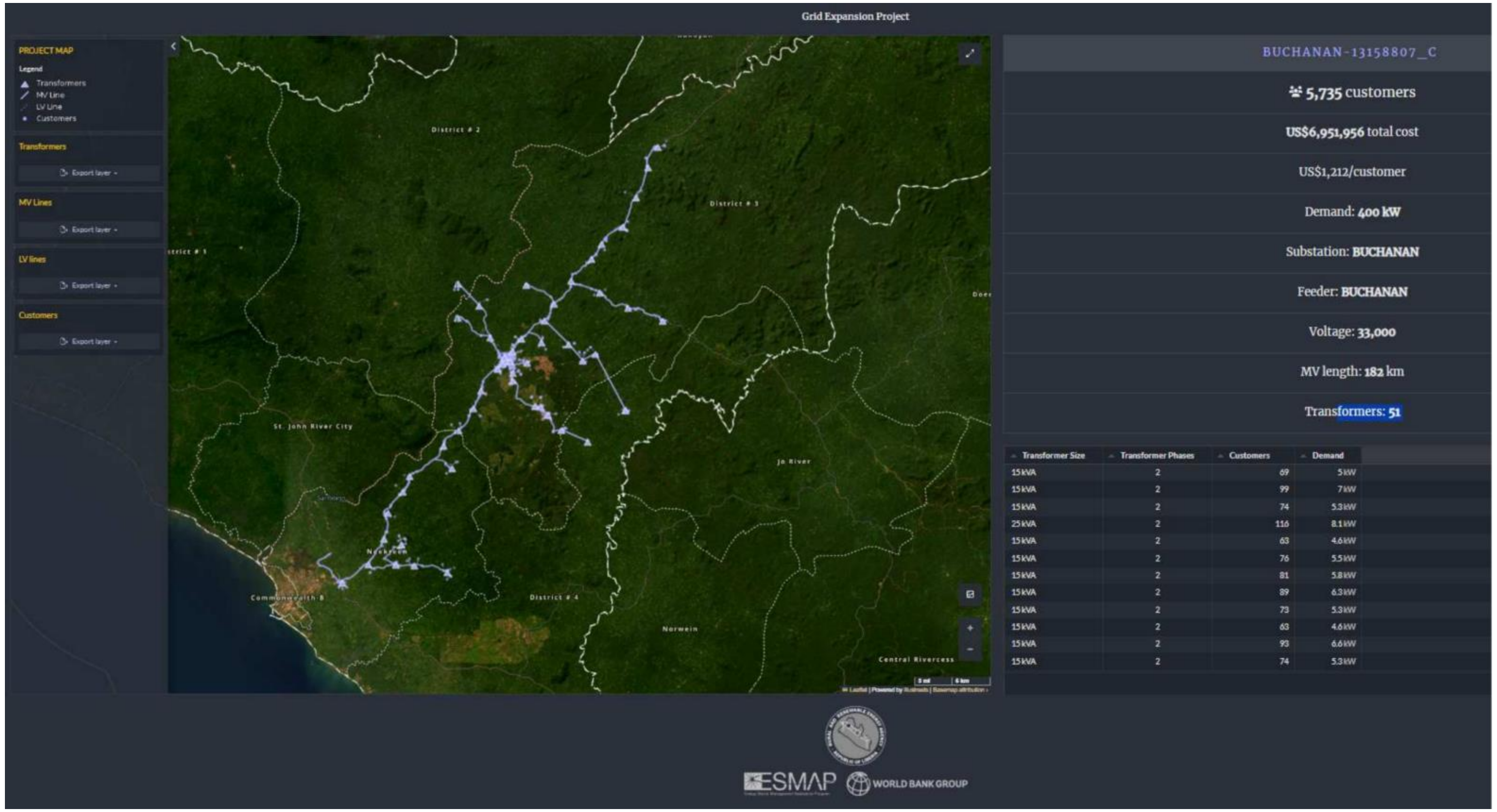
Rural Electrification Authorities (REA)

- Develops and coordinates a country's electrification efforts
- Sets electrification priorities and targets
- Develops Rural Electrification Master Plan (REMP)
  - identifies a <u>least-cost electrification plan</u> for the country

Least-Cost Electrification Plans

1. Analyze existing infrastructure
2. Define electrification modalities to consider
3. Create geospatial model
4. Estimate load
5. Cluster buildings to be electrified
6. Develop cost model for modalities
7. Apply line routing and economic optimization
8. Adjust plan according to priorities

Least-Cost Electrification Plans



(*courtesy NRECA International*)

The Liberia National Electrification Analysis project platform shows the least-cost electrification modality throughout the whole country. The project is funded by the World Bank and developed by NRECA International in partnership with Rural and Renewable Energy Agency and the Ministry of Mines & Energy

Electrification Modalities

Favorable Community Characteristics

Modality	Proximity to Grid	Load	Population Density
Connection to Existing Grid	under	low-high	dense
Grid Extension	near	medium-high	dense
Mini-Grid	far	low-medium	dense
Solar Home System	very far	low	sparse

Prioritizing Electricity Access

Grid extension priorities favor communities that

- ✓have high potential for electricity use
- ✓are close to the existing grid
- ✓are densely populated
- ✓have industrial, commercial, or tourism potential
- ✓have medical, educational or other social institutions
- ✓have political or cultural significance

Summary

- Grid extension is often the preferred approach to increasing electricity access
- Grid extension components: substation, medium-voltage line, transformer, user premise equipment
- Costs typically +US$20,000/km with per connection costs over US$1000
- Total costs include infrastructure, maintenance, and energy costs
- Rural Electrification Authorities often develop least-cost electrification plans