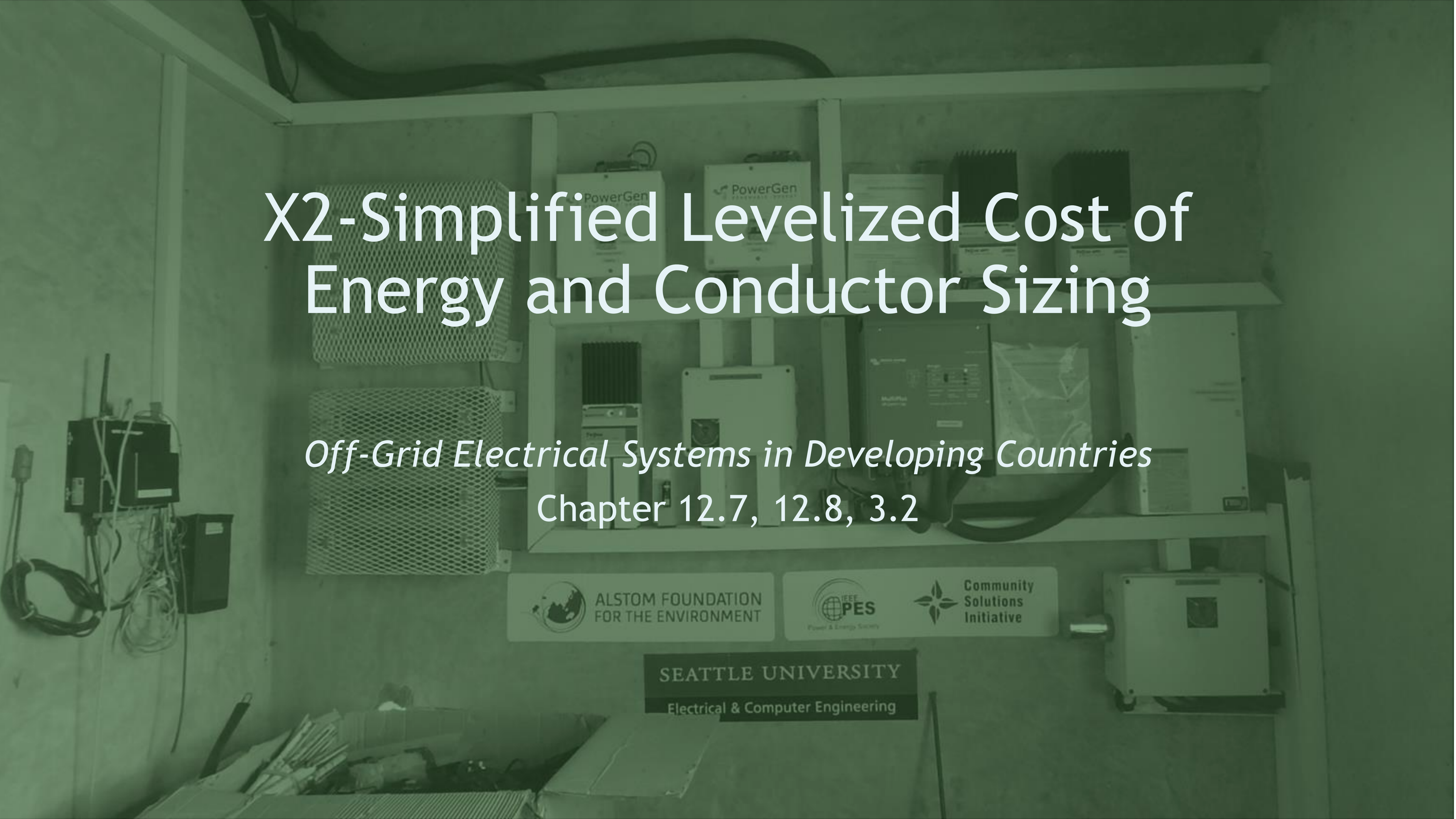
X2-Simplified Levelized Cost of Energy and Conductor Sizing

Off-Grid Electrical Systems in Developing Countries

Chapter 12.7, 12.8, 3.2



Levelized Cost of Energy

- Levelized Cost of Energy (LCOE): the cost of installing and operating a power plant over the course of its lifetime
  - Often 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

The LCOE is the minimum price that can be charged for electricity without losing money.

Simple Levelized Cost of Energy

- Consider a simplified LCOE (sLCOE) calculation
- sLCOE consists of three cost elements
  - Capital cost
  - Fuel costs
  - Operations and Maintenance costs

Capital Costs

- Capital costs are the "overnight" capital costs converted into an annuity across *Y* years (the operating lifespan of the project)

$$Cap = \frac{K}{\sum_{y=1}^{Y}\left(1+i\right)^{-y}} = \frac{K}{\frac{(1+i)^{Y}-1}{i(1+i)^{Y}}}$$

Overnight capital cost

- Helpful to express K as $/kW

Fuel Cost

- Fuel cost is the cost per kilowatthour of energy

$$Fuel = \frac{p_f \times s_f}{\eta_{genset}}$$

η_{genset}: efficiency of the gen set
p_f: price of fuel, in \$/liter
s_f: energy density of fuel, liter/kWh

Fuel Cost: Hybrid Renewable System

- If the gen set is expected to provide some fraction of the total energy, with rest supplied by a zero cost fuel (e.g. sunlight, wind), then the fuel cost is:

$$Fuel = \frac{p_{\mathrm{f}} \times s_{\mathrm{f}}}{\eta_{\mathrm{genset}}} \times f$$

f: proportion of total energy supplied by the gen set, [0,1]

Operations and Maintenance (O&M) Costs

- Considers non-fuel operation and maintenance costs, divided as fixed and variable costs
- Fixed (O_f): O&M costs that are incurred regardless of project operation, in \$/kW (related to the capacity of the project)
- Variable (O_v): related to the actual energy production from the project, in \$/kWh

Simplified Levelized Cost of Energy

The simplified levelized cost of energy (sLCOE) is:

$$sLCOE = \frac{Cap + O_f}{E_{\text{annual}}} + Fuel + O_v$$

Must divide Cap and O_f by the energy produced per year per kW of capacity to obtain the proper units of $/kWh

Example

Consider an off-grid system whose overnight capital costs are \$18,000 for the distribution system and \$28,000 for the energy production system. The annual load is 3650 kWh. The system is supplied by a 4 kW PV array with a 1 kW back-up gen set. The gen set is expected to supply 5% of the energy.

Assume the project lifespan is 15 years. The discount rate is 3%.

Example: Capital Cost

- The overnight capital cost is:

$$K = \frac{18{,}000 + 26{,}000}{5} = \$8{,}800\ /\ \mathrm{kW}$$

$$Cap = \frac{K}{\dfrac{(1+i)^Y - 1}{i(1+i)^Y}} = \frac{8{,}800}{\dfrac{(1+0.03)^{15} - 1}{0.03(1+0.03)^{15}}} = \$737.15/\mathrm{kW}$$

Example: Fuel Cost

- Assuming cost of diesel is \$1/liter, gen set efficiency is 25%, and energy density of diesel fuel is 30 MJ/liter:

$$Fuel = \frac{p_{\mathrm{f}} \times s_{\mathrm{f}}}{\eta_{\mathrm{genset}}} \times f = \frac{\$1/\mathrm{liter} \times \dfrac{3.6\ \mathrm{MJ/kWh}}{36\ \mathrm{MJ/liter}}}{0.25} \times 0.05 = \$0.02/\mathrm{kWh}$$

Example: O&M Costs

- Fixed (O_f): assume 1% of project overnight capital costs per year
  - \$88/kW/year
- Variable (O_v): assume to be \$0.01/kWh

Example: sLCOE

The sLCOE is therefore:

$$sLCOE = \frac{Cap + O_f}{E_{\text{annual}}} + Fuel + O_v = \frac{737.15 + 88}{3650 / 5} + 0.02 + 0.01 = \$1.16/\text{kWh}$$

Distribution Line Design Considerations

Thermal Limit

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

Ampacity

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

Thermal Limit: Single Phase Distribution

- The current supplied by a line is found from:

$$|\boldsymbol{I}_s| = \frac{S_{load}}{|\boldsymbol{V}_\phi|}$$

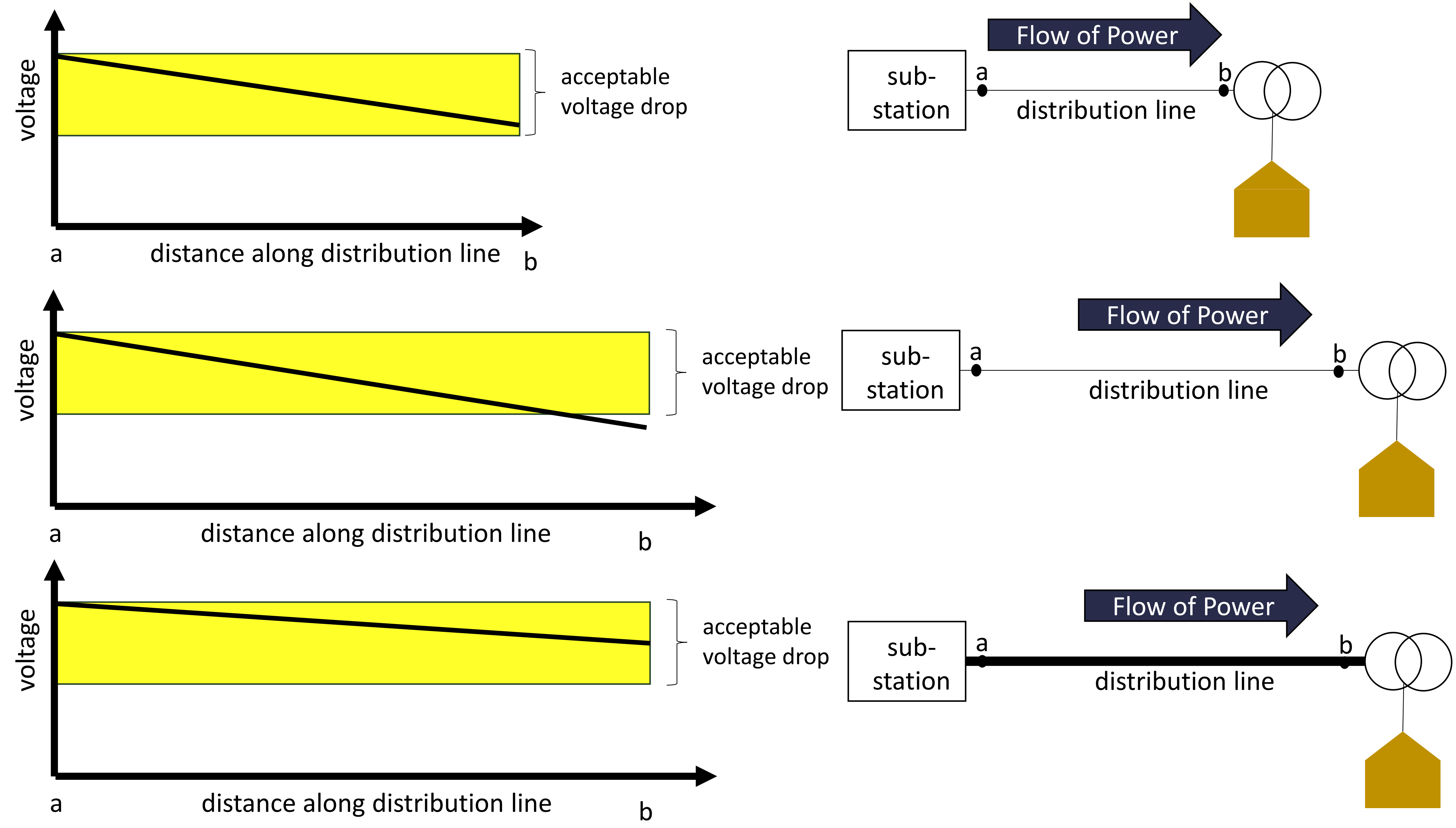
$\boldsymbol{I}_s$: current through line, A
S_{load}: total load supplied by line, VA
$\boldsymbol{V}_\phi$: phase voltage, V

Here we have made the assumption that the voltage at the load is equal to the source voltage

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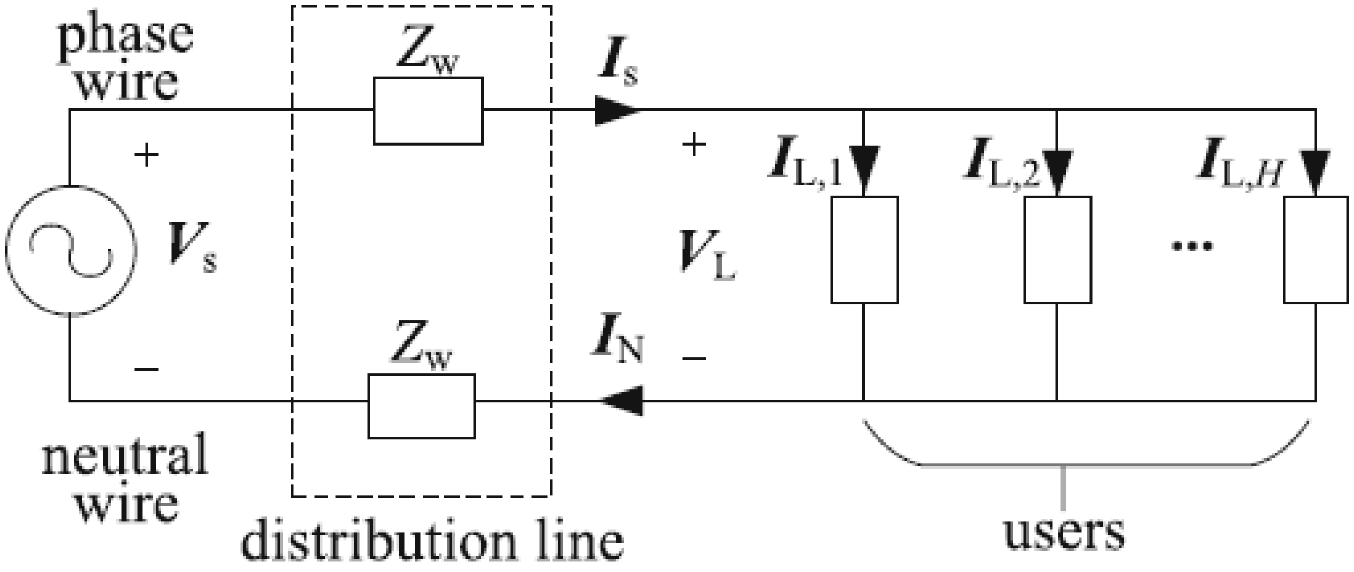
Flow of Power
sub-station
a
b
distribution line
voltage
acceptable voltage drop
a
distance along distribution line
b
Flow of Power
sub-station
a
b
distribution line

Voltage Drop: Single Phase Distribution

- Consider a line serving *H* users
- All users consume the same power at the same power factor
- Users are located at the end of the line

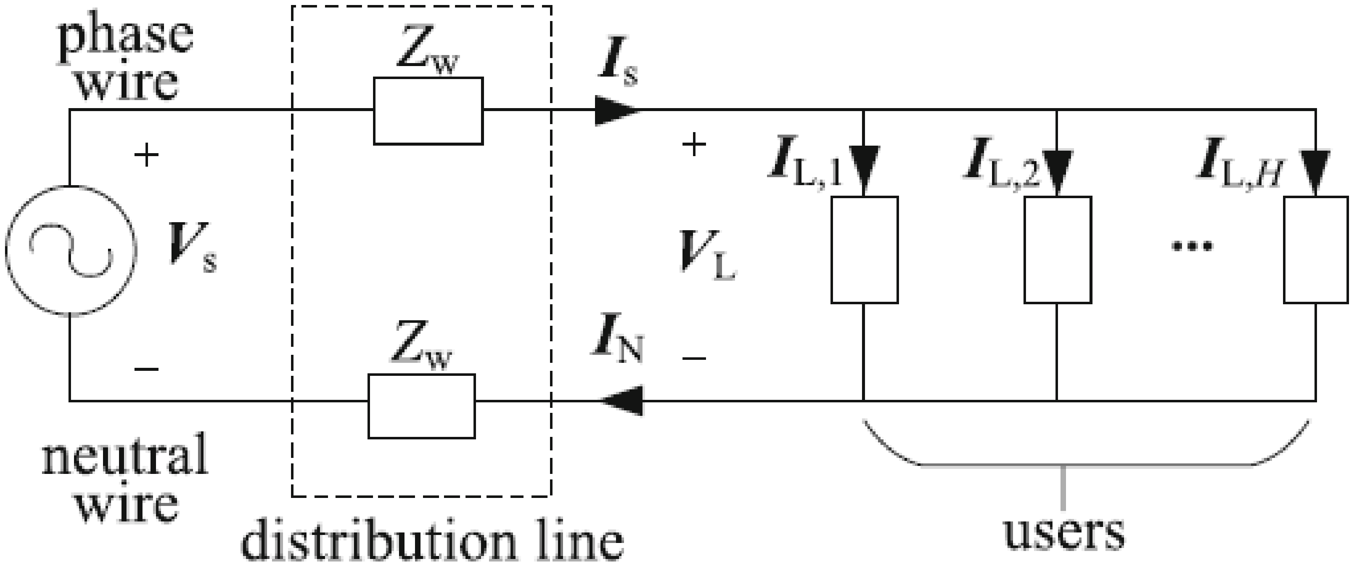


Voltage Drop: Single Phase Distribution

- By KCL:

$$\boldsymbol{I}_{\mathrm{s}} = \sum_{h=1}^{H} \boldsymbol{I}_{\mathrm{L},h} = \boldsymbol{I}_{\mathrm{L}} H = \boldsymbol{I}_{\mathrm{N}}$$

- The current on the neutral is equal to the current on the phase wire



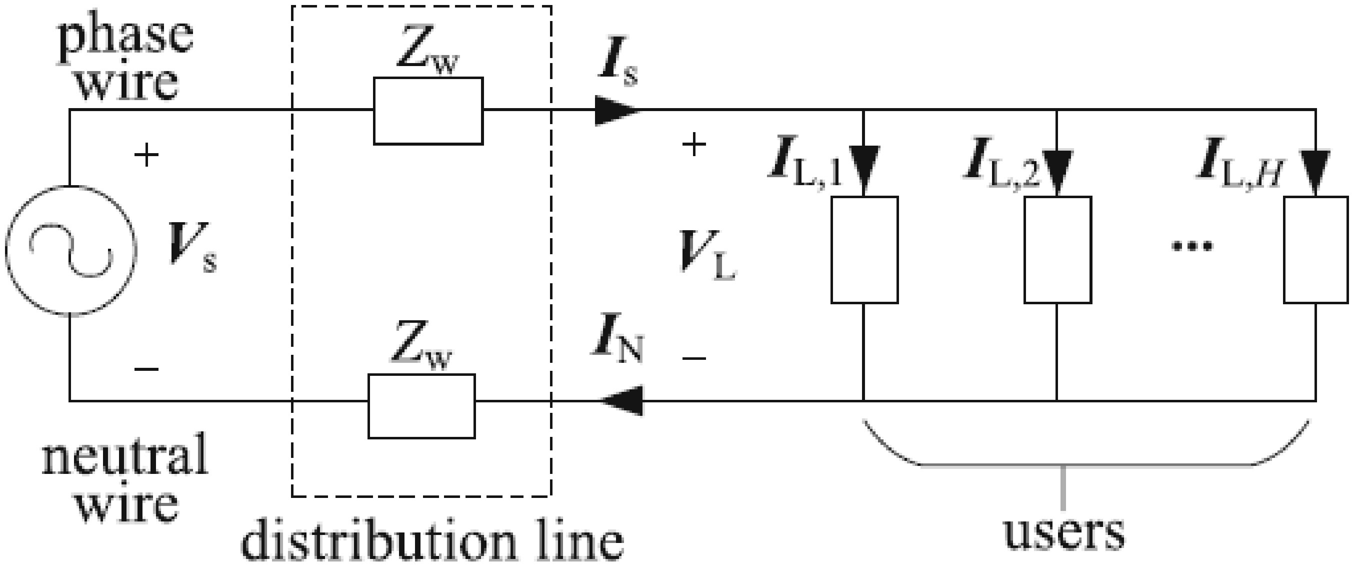
Voltage Drop: Single Phase Distribution

- By KVL:

$$\boldsymbol{V}_s = \boldsymbol{I}_s Z_w + \boldsymbol{V}_L + \boldsymbol{I}_N Z_w = 2\boldsymbol{I}_s Z_w + \boldsymbol{V}_L$$

- The voltage drop is:

$$V_{drop} = |\boldsymbol{V}_s - \boldsymbol{V}_L| = 2|\boldsymbol{I}_s Z_w| = 2|\boldsymbol{I}_L||H||Z_w|$$



Example

Consider a distribution line serving 20 houses. The aggregate peak load is expected to be 2000 W with a power factor of 0.85. The houses are supplied by a low-voltage line at 230 V, with an impedance of

$$Z_W = 0.75 + j0.31\ \Omega$$

Determine the voltage drop along the line.

Example

- The line current is:

$$|\boldsymbol{I}_s| = \frac{S_{load}}{|\boldsymbol{V}_\phi|}$$

$$|\boldsymbol{I}_s| = \frac{2000 / 0.85}{230} = 10.23 \text{ A}$$

$$V_{\text{drop}} = |\boldsymbol{V}_{\text{s}} - \boldsymbol{V}_{\text{L}}| = 2\,|\boldsymbol{I}_{\text{s}} Z_{\text{w}}|$$

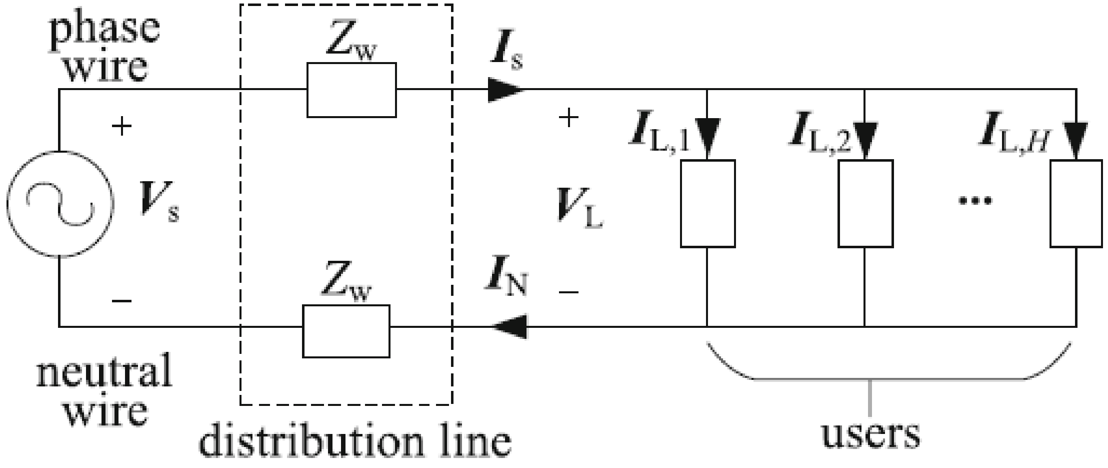
$$V_{\text{drop}} = 2\,|\boldsymbol{I}_{\text{s}} Z_{\text{w}}| = 15.67 \text{ V}$$

This a 6.8% drop. If this exceeds the requirement, then use a cable with lower impedance (larger cross section)

Power Loss: Single Phase Distribution

- The power loss is:

$$P_{\text{Loss}} = |\boldsymbol{I}_{\text{s}}|^2 R_{\text{w}} + |\boldsymbol{I}_{\text{N}}|^2 R_{\text{w}} = 2|\boldsymbol{I}_{\text{s}}|^2 R_{\text{w}} = 2|\boldsymbol{I}_{\text{L}}|^2 H^2 R_{\text{w}}$$



- From our example

$$P_{\text{Loss}} = |\boldsymbol{I}_{\text{s}}|^2 R_{\text{w}} + |\boldsymbol{I}_{\text{N}}|^2 R_{\text{w}} = 2|\boldsymbol{I}_{\text{s}}|^2 R_{\text{w}} = 146.5 \text{ W}$$

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