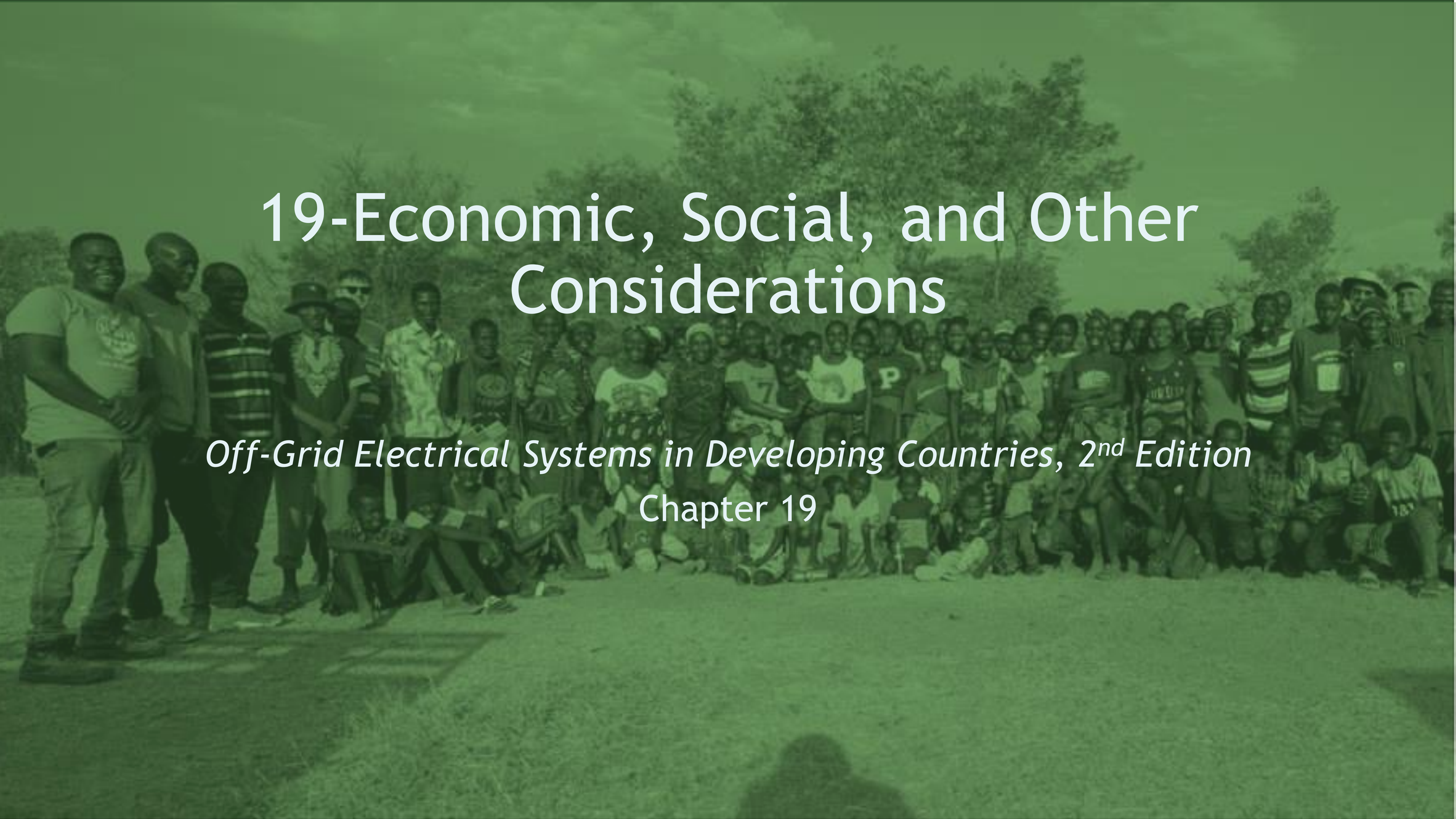


19-Economic, Social, and Other Considerations

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

Chapter 19

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:

- ✓Calculate the simplified levelized cost of energy for an off-grid system
- ✓Compare and contrast types of tariffs for off-grid users
- ✓Explain the role of regulations in off-grid electrification
- ✓Describe what a Monitoring and Evaluation program is in the context of off-grid electrification
- ✓Describe the importance and best practices of community engagement for off-grid systems

Levelized Cost of Energy

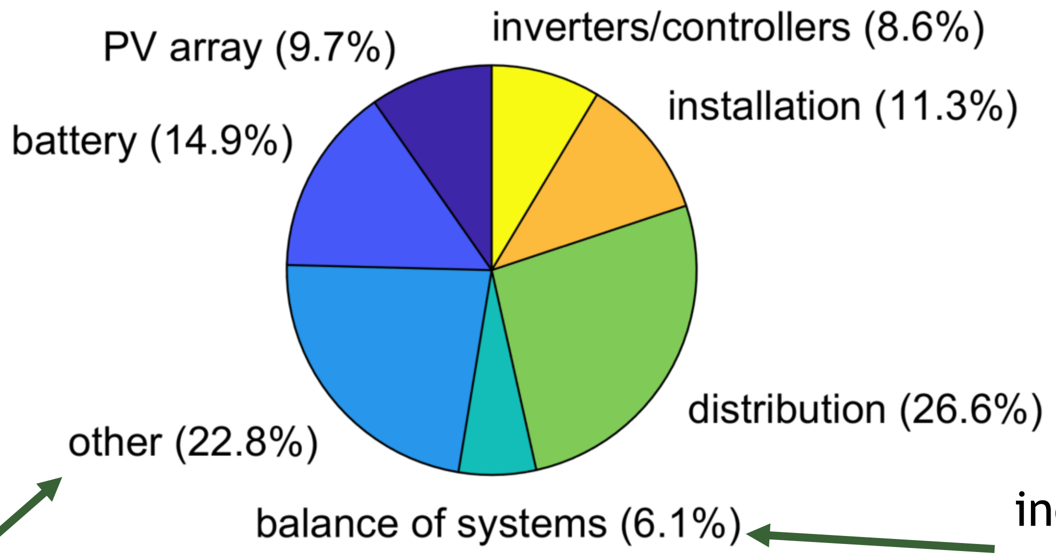
- Levelized Cost of Energy (LCOE): the cost of installing and operating a power plant over the course of its lifetime
    - often expressed as US$/kWh
- Convenient for comparing different energy sources
- Discount rate applied to future costs
- Typically accounts for:
    - installation
    - financing
    - 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 Cost of PV/Gen Set Hybrid Mini-Grids



including management, logistics, taxes, land, and more

including PV racking, gen set, powerhouse, civil works, and more

Component Costs

- A larger share of capital cost is the cost of the components
- Costs can vary significantly
  - larger capacity systems tend to have lower per unit costs
  - taxes and duties can significantly increase costs

Component	Cost
PV Array with Solar Inverter (US$/kW)	335–600
Lead-Acid Battery (US$/kWh)	155–225
Lithium-ion Battery (US$/kWh)	275–415
Inverter and Controllers (US$/kW)	325–715
Distribution and Meters (US$/connection)	165–331

Overnight Capital Costs

Overnight capital cost: cost of bringing the system to an operable state, assuming the cost is incurred (and the system was operable) overnight

$$c_{\mathrm{on,kW}}\ (\mathrm{US\$/kW}) = \frac{\mathit{overnight\,capital\,cost}\ (\mathrm{US\$})}{\mathit{system\,capacity}\ (\mathrm{kW})}$$

expressed as cost per kilowatthour of capacity

Overnight Capital Costs

- Convert to an annuity across *Y* years (the operating lifespan of the project) with interest rate of *i*

$$c_{\text{on,kW/yr}}\ (\text{US\$/kW/yr}) = \frac{c_{\text{on,kW}}}{\dfrac{(1+i)^{Y}-1}{i(1+i)^{Y}}}$$

- This is the capital cost, per kilowatt of capacity, spread out over the project lifespan, accounting for interest

Fuel Cost

- Fuel cost is the cost per kilowatthour of electricity produced by the system

needed fuel volume to generate 1 kWh of electricity

$$c_{\text{fuel,kWh}}\ (\text{US\$/kWh}) = p_{\text{fuel,lit}}\ (\text{US\$/liter}) \times v_{\text{fuel,kWh}}\ (\text{liter/kWh})$$

- Fuel for off-grid systems, if any, is often for gen sets so cost per liter is appropriate
  - Use average value of fuel cost and fuel volume
  - Equation can be modified for any other fuel cost—express as US$/fuel unit, and determine the required number of units to produce 1 kWh of electricity

Example 19.1

The capital cost for a hybrid diesel/PV mini-grid is US$100,000. The capacities of the gen set and PV array are 10 kW and 40 kW, respectively. The mini-grid generates on average 212 kWh/day. The average daily fuel consumption is 8.6 liters/day. Assume the cost of diesel is US$1.10/liter, the mini-grid's lifespan is 15 years, and the interest rate is 5%. Compute the annual capital costs per kilowatt of capacity and the fuel cost per kilowatthour.

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Pay careful attention to the units of each variable. Overnight capital cost per kW of capacity

$$c_{\text{on,yr}} = \frac{\textit{overnight capital cost}\ (\text{US\$})}{\textit{system capacity}\ (\text{kW})} = \frac{100{,}000}{10+40} = \text{US\$}2000/\text{kW}$$

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Overnight capital cost per kW per year:

$$c_{\text{on,kW/yr}} = \frac{c_{\text{on}}}{\dfrac{(1+i)^{Y}-1}{i(1+i)^{Y}}} = \frac{2000}{\dfrac{(1+0.05)^{15}-1}{0.05(1+0.05)^{15}}} = \text{US\$192.68/kW/year}$$

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The fuel costs are:

$$c_{\text{fuel,kWh}} = p_{\text{fuel,lit}} \times v_{\text{fuel,kWh}} = 1.10 \times \frac{8.6}{212} = \text{US\$0.045/kWh}$$

Note that we consider the total production from the system, regardless of whether or not it is generated from the PV array or gen set in this calculation

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 $/kW/yr (related to the capacity of the project)
  - Employee salary, monthly data charges, etc.
- Variable (O_v): related to the actual energy production from the project, in US$/kWh
  - Replacing oil filters, wind turbine blades, etc.

Simplified Levelized Cost of Energy

The simplified levelized cost of energy (sLCOE) is:

$$sLCOE\ \text{(US\$/kWh)} = \frac{c_{\text{on,kW/yr}} + c_{\text{fix,kW/yr}}}{E_{\text{kW/yr}}} + c_{\text{fuel,kWh}} + c_{\text{var,kWh}}$$

yearly energy production

fixed O&M costs per kilowatt of capacity per year

variable O&M costs per kWh

Simplified Levelized Cost of Energy

- sLCOE approximates the cost of producing each kilowatt hour of electricity
- Lower values of sLCOE indicate the system can generate electricity at a lower cost
- LCOE is the minimum that an operate can charge for electricity (per kilowatt) without losing money
- Typical LCOE for hybrid mini-grids approx. US$0.35/kWh to US$0.60/kWh, but are decreasing

sLCOE for Mwase

Consider the Mwase PV mini-grid from Chapter 16

Capacity: 4.71 kW

Energy production: 10.05 kWh/day

Parameter	Value
Lifespan, Y	15 (yr)
Interest Rate, i	5%
Overnight Capital Cost, $c_{\text{on,kW}}$	15,015 (US$); 3188(US$/kW)
Annual Production, $E_{\text{kW/yr}}$	3668.3 (kWh); 778.8 (kWh/kW)
Fuel Price, $p_{\text{fuel,lit}}$	1.0 ($/liter)
Fuel Consumption, $v_{\text{fuel,kWh}}$	0 (liter/kWh)
Fixed O&M, $c_{\text{fix,kW/yr}}$	2400 (US$/yr); 510 (US$/kW/yr)
Variable OM, $c_{\text{var,kWh}}$	0 (US$/kWh)

sLCOE for Mwase

The overnight capital cost is:

$$c_{\text{on,kW/yr}} = \frac{3188}{\dfrac{(1+0.05)^{15}-1}{0.05(1+0.05)^{15}}} = \text{US\$307.1/kW/yr}$$

$$sLCOE = \frac{307.1+510}{778.8} + 0 + 0 = \text{US\$1.05/kWh}$$

Parameter	Value
Lifespan, Y	15 (yr)
Interest Rate, i	5%
Overnight Capital Cost, $c_{\text{on,kW}}$	15,015 (US\$); 3188(US\$/kW)
Annual Production, $E_{\text{kW/yr}}$	3668.3 (kWh); 778.8 (kWh/kW)
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Cost Per Connection

- Capital cost divided by the number of end-user connections
  - typically 50-300 user connections per mini-grid
- Common metric for assessing commercial viability of mini-grid
- Typical range for hybrid mini-grids US$450 to US$1300/connection
- Per connection costs tend to decrease as number of connections increase, but after several hundred connections, medium-voltage distribution is often needed which can increase costs and require additional engineering and workforce capacity

Tariffs

- Tariff: rate or payment structure for electricity service
- All commercial off-grid systems such as mini-grids and metro-grids have a tariff
- Common types
  - fixed
  - energy-based
  - demand-based
- Tariff should be such that at least LCOE is collected

Common for a combination of these to be used

Fixed Tariff

- User is charged a flat (constant) fee for service
- Does not depend on actual consumption
- Often a monthly fee
- Advantages
  - Easy to implement (no meters needed, simple bookkeeping)
  - Conceptually simple (users understand it)
- Disadvantages
  - Encourages over-consumption
  - Discourages use of energy efficiency appliances

Energy-Based Tariff

- Fee is based on <u>energy</u> consumption, for example US$0.25/kWh
- Rate can be fixed or variable
  - Progressive variable: rate increases with consumption (e.g. US$0.20/kWh for 0-2 kWh each month, then US$0.30 for 3-10 kWh, etc.). Discourages high consumption.
  - Regressive variable: rate decreases with consumption (e.g. US$0.30 for 0-2 kWh each month, then US$0.020 thereafter). Encourages high consumption

Energy-Based Tariff

- Advantages
  - better approximates LCOE
- Disadvantages
  - requires energy meter
  - not intuitive---users may not be familiar with typical consumption of appliances

Demand-Based Tariff

- Fee is based on power consumption
- High power users are charged more than low power users
  - High power users are more likely to also be high energy users
- Can be based on connection capability or by fuse

Example 19.2

A household is served by a mini-grid with following tariff structure: a fixed fee of US$1 per month, US$0.15 for the first kilowatthour of energy, and US$0.25 for each kilowatt hour thereafter. The household consumes 17.5 kilowatthours each month. Determine the amount of money they must pay each month.

Example 19.2

A household is served by a mini-grid with following tariff structure: a fixed fee of US$1 per month, US$0.15 for the first kilowatthour of energy, and US$0.25 for each kilowatt hour thereafter. The household consumes 17.5 kilowatthours each month. Determine the amount of money they must pay each month.

$$\text{total fees} = \text{fixed fee} + \text{energy fee} = 1 + (1 \times 0.15) + (16.5 \times 0.25) = \text{US\$}5.275$$

Other Tariffs

- Several other types of tariffs are possible
- Lifeline: extremely low tariff (or even free) for small amounts of electricity each month. Lifeline tariffs can improve goodwill and community acceptance
- Time-of-use: energy tariff depends on when energy is consumed. It may be higher to discourage consumption in the evening or during the rainy season

Average Revenue Per User (ARPU)

- ARPU: total revenue divided by number of users (customers) in a month or year
- Anticipated ARPU is a commonly used metric to gauge economic viability of a mini-grid

Regulations

- Regulations: laws and requirements associated with providing electricity access
- Off-grid electricity access regulations may apply to:
  - Technical standards: component and design requirements, etc.
  - Economics: tariff structure, subsidies, taxes, etc.
  - Quality of service: reliability, accessibility, power quality, etc.
  - Environment: protection, remediation, and restoration of water and land, emissions, wildlife protections, etc.
  - Contractual agreements: user, vendor and operator terms and conditions, etc.
  - Licenses: for construction and operation in certain areas, etc.
  - Grid inter-connection: ownership, operation, and financial considerations should the off-grid system connect to the grid

Regulations

- Regulations may vary greatly from country to country
- Some countries have no regulations, some have exemptions for small-capacity systems
- Regulatory approval often takes more than a year

Electricity Theft

- Grid-connected theft
  - Electricity theft (also known as non-technical losses) is generally low (1-2% of generation)
  - In certain developing countries, electricity theft is rampant, >15% of generation
  - Worldwide losses due to electricity theft are estimated to be $25 billion per year ($4.5 billion in India alone)
- Off-grid system electricity theft happens mostly in mini-grids and metro-grids

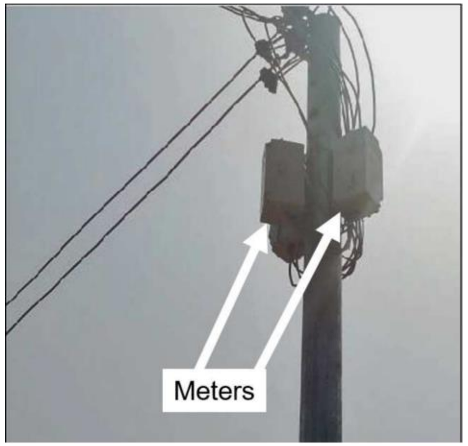
Classifying Electricity Theft

- Fraud: consumer tries to deceive the utility (e.g. meter tampering)
- Stealing: illegal connections to distribution lines
- Billing irregularities: bribing utility employees to manipulate bills (e.g. decimal point moving)
- Unpaid bills: refusal to pay for electricity or late payment; government agencies (police, for example) and officials often refuse to pay expecting their service to not be cut-off

Discouraging Theft

Approaches to reduce theft include:

- use pre-pay metering
- use tamper-proof meters, or place meters outside homes or atop poles
- have internal business controls to discourage bribery
- meter each line individually at the powerhouse



(*courtesy GVE Projects*)

Monitoring and Evaluation (M&E)

- M&E plan are used to understand the impact an electrification program has
- Monitoring: routine measurement or observation of users and others affected by the system
- Evaluation: periodic assessment of how or to what extent the off-grid system is meeting its objectives

Monitoring and Evaluation (M&E)

Identify problem
to be solved

Develop solution

Determine how success
will be evaluated

Example: Solar Lantern Program

- Problem: low levels of you education in an off-grid community because they are unable to study and read in the evening
- Proposed Solution: make solar lanterns with LED lights available to families with children
- Metrics: performance of students on national exams and attendance

Example: Solar Lantern Program

- Baseline data collected before program
- Surveys and focus groups provide feedback on program, including indicators such as number of evening hours a student uses the solar lantern
- Program adjusted depending on collected data
  - Example: different solar lanterns may be offered if they do not last long enough

Monitoring and Evaluation (M&E)

- M&E can apply to technical and economic aspects of the project
- Investors and donors may require M&E plans and programs and certain metrics tracked
- Community should be involved in developing M&E program
  - What metrics are important to them?
  - What voice do they have in expressing concerns about an on-going project?

(*courtesy NRECA International*)

Community Engagement

- Off-grid programs impact community directly and indirectly
- Impacts can be beneficial, burdensome, anticipated, and unexpected
- Important to engage community early and often throughout program

(*courtesy P. Dauenhauer*)

Community Engagement Best Practices

Build relationships

Speak and listen

Be linguistically and culturally appropriate

Be inclusive

Be realistic and transparent

Engage with traditional structures

Community Participation

- Seek ways for community to participate in off-grid program
  - hire individuals during construction or operation
  - community group responsible for operation and maintenance
  - community ownership
  - co-operative arrangement (certain members, own, operate, and profit from the system)
- Greater involvement in all stages (planning, implementation, operation) can increase community acceptance and goodwill

communities can contribute "sweat equity" during construction

(*courtesy KiloWatts for Humanity*)

Capacity Building

- Electricity access programs are an opportunity for “capacity building”
- Capacity building: increase the skills, experience, and infrastructure of a community
- Ways to build capacity
  - hire local, in-country vendors, installers, etc. whenever possible
  - offer training to local community (technical, business, safety, etc.)
  - do not rely on volunteer labor from abroad

(*courtesy P. Dauenhauer*)

Summary

- Economic performance of an off-grid system often measured by Levelized Cost of Energy, typically US$0.40 to US$0.60 for mini-grids
- Tariffs set the payment structure for users
- Regulations may dictate how to system is designed and operated, tariff structure and other factors
- Monitoring and evaluation tracks how an off-grid program is meeting (or not meeting) its objectives
- Community participation and capacity building can improve the likelihood of a successful program and can amplify its impact

What Next?

- No class or textbook can fully prepare you to implement off-grid systems
- Gain field experience through work or volunteerism
- Electricity access is a meaningful, rewarding career