02-Energy Poverty

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

Chapter 2

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

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Learning Outcomes

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

- ✓Describe the energy needs and uses in rural communities and how fuel sources are selected
- ✓Explain the state and trends of electricity access
- ✓Calculate statistics and measures relevant to electricity access such as the electrification rate and annual growth rate
- ✓Evaluate electricity service using the Multi-Tier Framework

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Energy Poverty is:
the lack of access to modern fuels

2.1 billion people rely on solid biomass for cooking/heating

685 million people do not have access to electricity

(*all courtesy: H. Louie*)

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Energy Poverty

Energy impoverished tend to:

- consume low amounts of energy overall
- rely on human and animal power for mechanical tasks
- devote considerable time to procuring and processing fuel
- spend a relatively large portion of their income on fuel

charcoal market outside Kitwe, Zambia

(*courtesy: H. Louie*)

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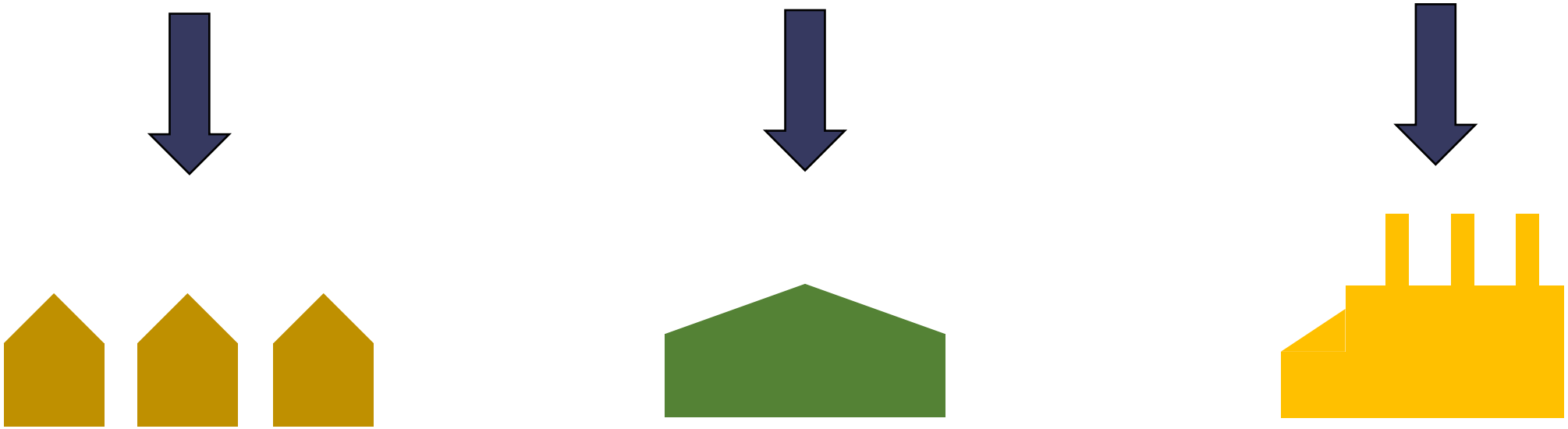
Rural Community Energy Needs



Households

Community Services

Productive Uses

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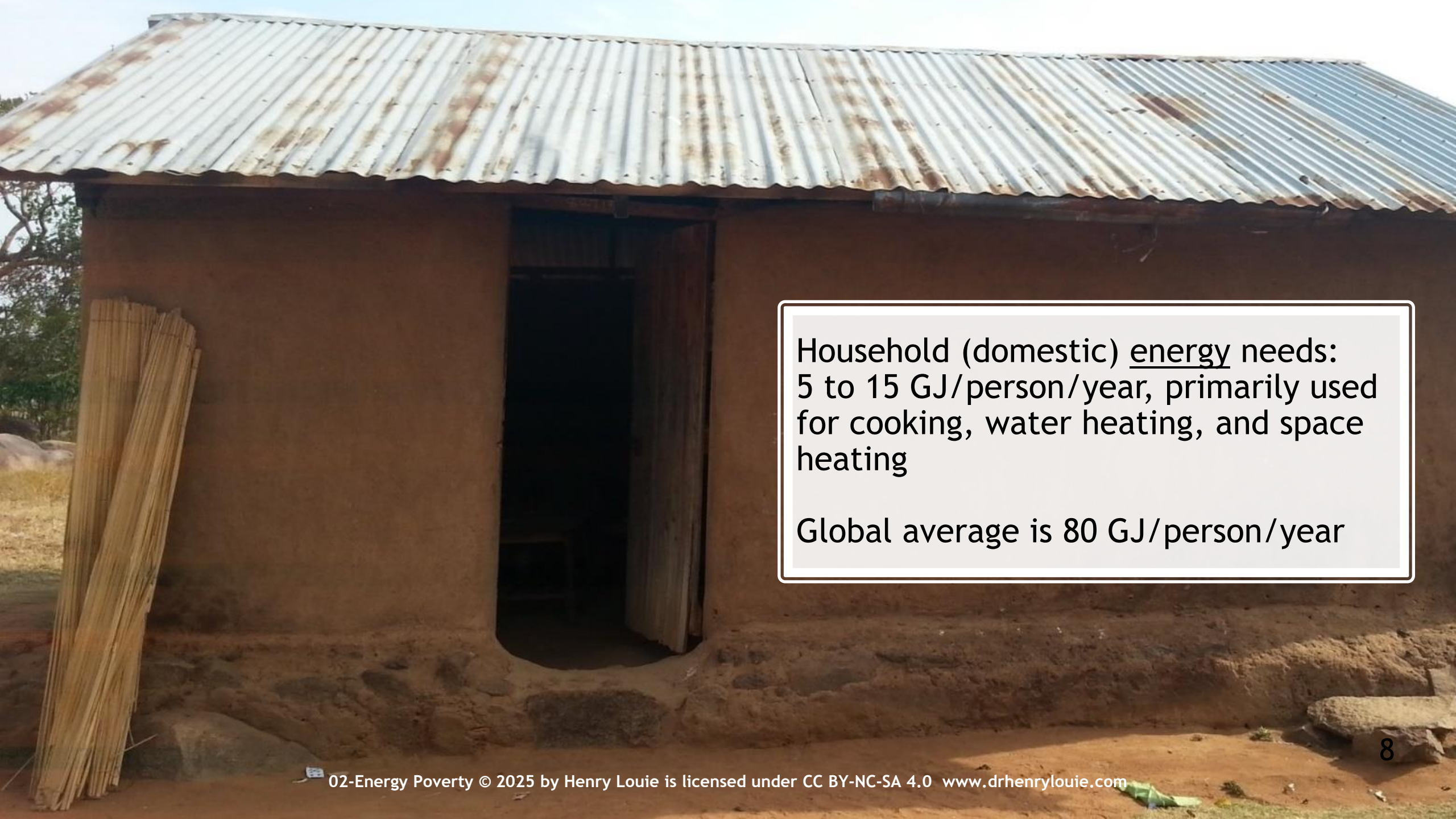

Household (domestic) energy needs:
5 to 15 GJ/person/year, primarily used for cooking, water heating, and space heating

Global average is 80 GJ/person/year

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Community Services

Health-care and educational facilities, government offices, places of worship, community centers, outdoor lighting (security, pathway)

Health Post (Zambia)

(*courtesy H. Louie*)

Primary School (Zambia)

(*courtesy H. Louie*)

Church (Kenya)

(*courtesy H. Louie*)

Streetlighting (Haiti)

(*courtesy Sigora Haiti*)

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Health-care facility electricity needs:
lighting, ITC, refrigeration (vaccines, medicine)
suction machines, diagnostic equipment, hot and clean water.
Electricity must be reliable.

(courtesy H. Louie)

solar-powered vaccine refrigerator

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Health-care Facility Electricity Requirements

Type	Power Rating (W)
Anaesthesia Machine	100-1440
Centrifuge	100-200
Dry Heat Sterilizer	500-750
Neonatal Incubator	300-1000
Portable ECG	30
Portable Ultrasound	22-28
Portable X-ray Machine	150-300
Suction Apparatus	70-180
Ultrasound	200
Vaccine Refrigerator	150-1000

Type	Energy (kWh/day)	Peak Power (kW)
Hospital (>120 beds)	15–35	9
Health Center (60–120 beds)	10–20	5
Health Clinic (<60 beds)	4–10	2.4
Health Post (intermittent use and equipment storage)	0	0

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Example 2.1

- Compute the daily energy requirements for the following equipment for a health-care facility:
  - one dry heat sterilizer operating two hours per day;
  - one ultrasound operating for 30 minutes per day;
  - one portable x-ray machine operating for one hour per day;
  - two portable ECG machines each operating 30 minutes per day.
- Assume the equipment uses the rated power provided in the Table on the previous slide. If a range of power is listed, select the mid-point value.

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Example 2.1

Multiply the power rating by hours of use to determine the energy requirement

$$E_{\text{total}} = (625 \times 2) + (200 \times 0.5) + (225 \times 1) + (2 \times 30 \times 0.5) = 1.605 \text{ kWh}$$

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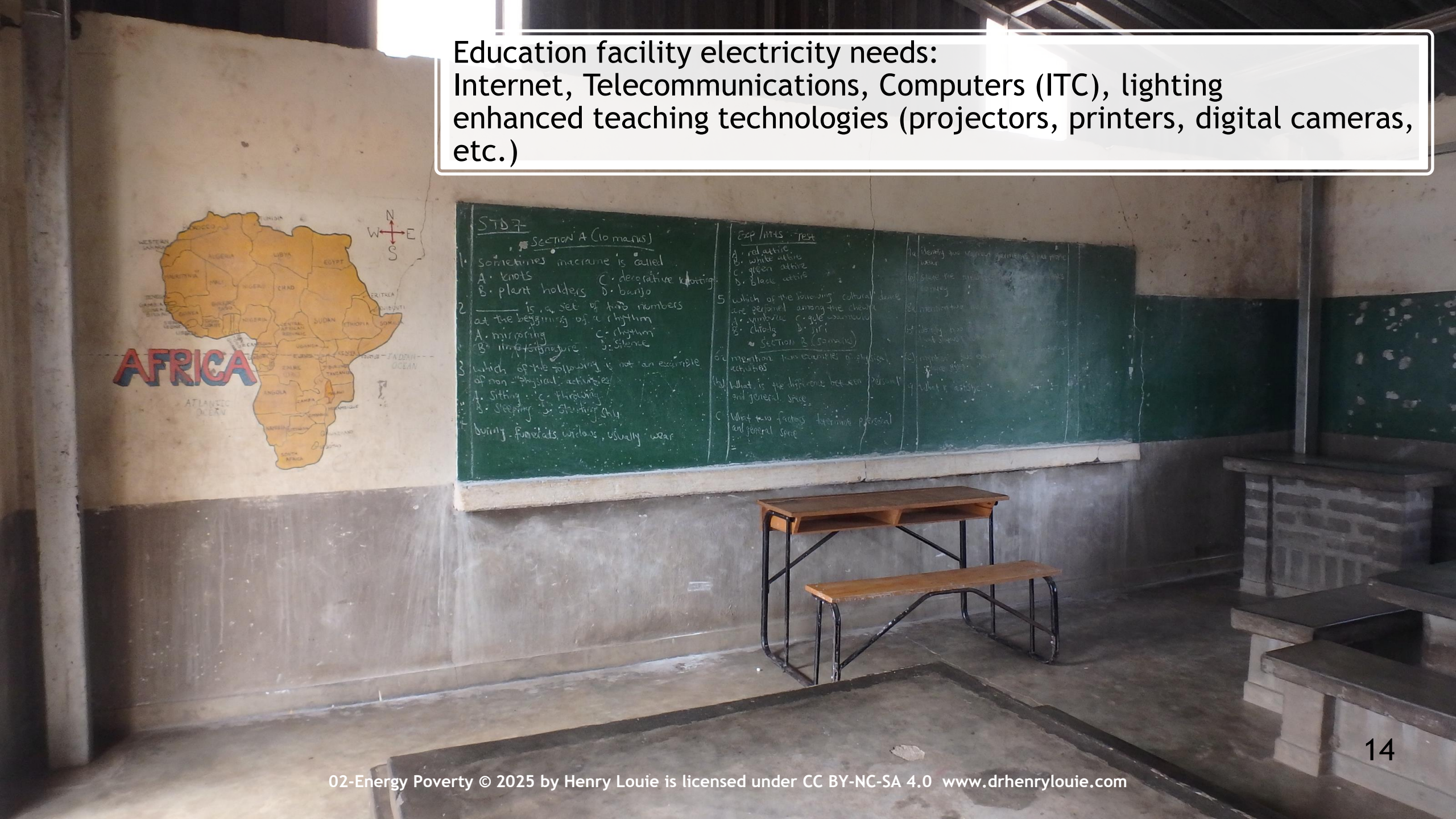
Education facility electricity needs:
Internet, Telecommunications, Computers (ITC), lighting
enhanced teaching technologies (projectors, printers, digital cameras, etc.)



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Education Facilities

- Two out of three primary schools in SSA have no access to electricity
- 200 million children attend a primary school without electricity
- Electricity needs:
  - 1 kWh/day for basic lighting
  - +10 kWh/day for computer labs

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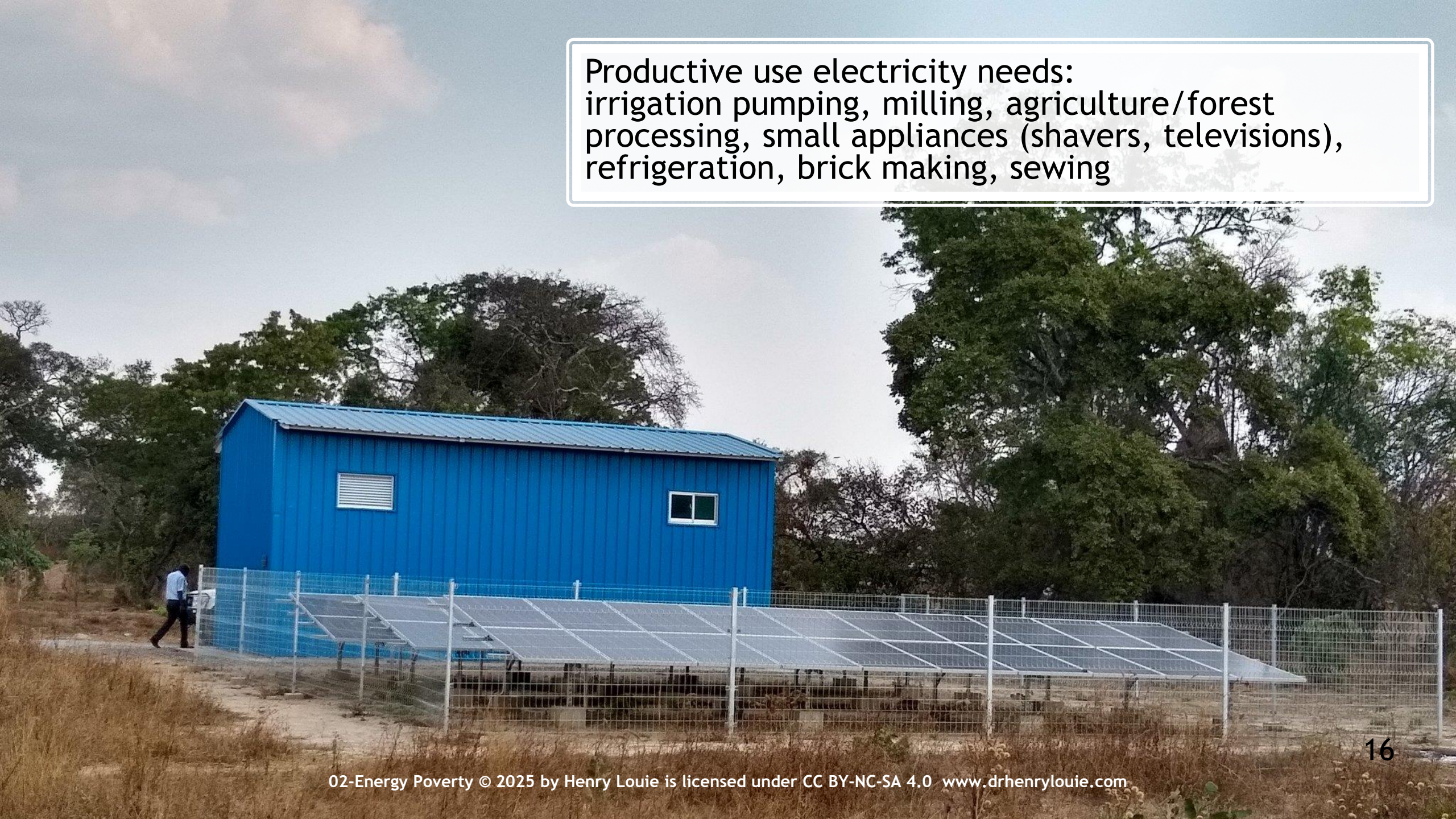
Productive use electricity needs:
irrigation pumping, milling, agriculture/forest processing, small appliances (shavers, televisions), refrigeration, brick making, sewing



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Productive Use of Electricity (PUE)

- PUE: electricity used to provide goods and services or to generally boost productivity (for example by pumping water for crops, reducing the distance traveled to access services)
- PUE generates income and wealth and often benefits the community more than household electrification
- Productive users often use more and can afford to pay more for electricity

(*courtesy of AgSol*)

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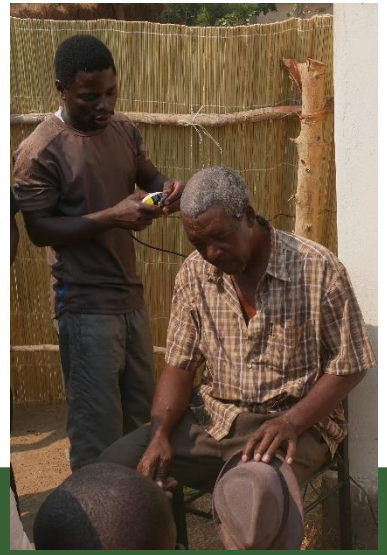
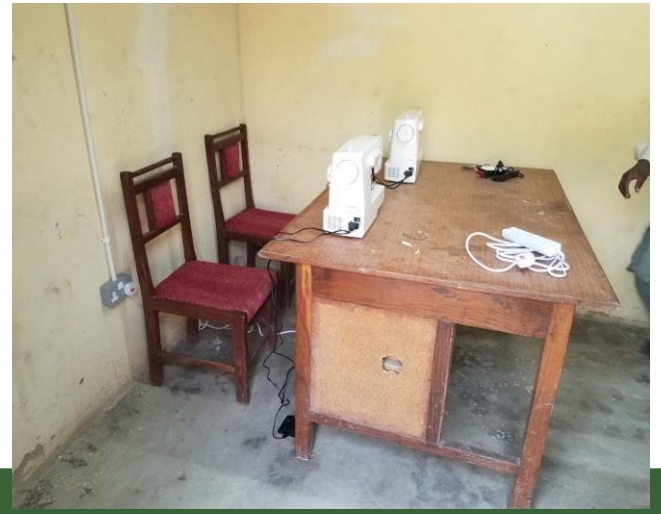
Examples of Productive Use of Electricity

(all *courtesy H. Louie/KiloWatts for humanity*)

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Fuels Used

- Animal dung
- Batteries
- Charcoal
- Crop residue
- Electricity
- Fuel wood
- Kerosene
- Liquid Petroleum Gas (LPG)

(*all courtesy H. Louie*)

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Energy Content

Energy content may vary greatly depending on the moisture content of the fuel

Fuel	Unit	MJ/Unit
Charcoal	kg	30.8
Dung	kg	14.5
Electricity	kWh	3.6
Kerosene	liter	35.0
LPG (Gas)	kg	45.0
Wood (Dry)	kg	16.0
Straw	kg	13.5

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Example 2.2

A household uses 100 GJ of fuel wood, 10 GJ of kerosene, and 10 GJ of LPG each year. Compute the quantity, in kilograms, of fuel wood and LPG, and the quantity, in liters, of kerosene required each year.

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Example 2.2

A household uses 100 GJ of fuel wood, 10 GJ of kerosene, and 10 GJ of LPG each year. Compute the quantity, in kilograms, of fuel wood and LPG, and the quantity, in liters, of kerosene required each year.

Using the values in the previous table, the quantities of each fuel source are

$$\textit{quantity of fuelwood} = \frac{100\ \text{GJ}}{0.016\ \text{GJ/kg}} = 6250.00\ \text{kg}$$

$$\textit{quantity of kerosene} = \frac{10\ \text{GJ}}{0.035\ \text{GJ/liter}} = 285.71\ \text{liter}$$

$$\textit{quantity of LPG} = \frac{10\ \text{GJ}}{0.045\text{GJ/kg}} = 222.22\ \text{kg}$$

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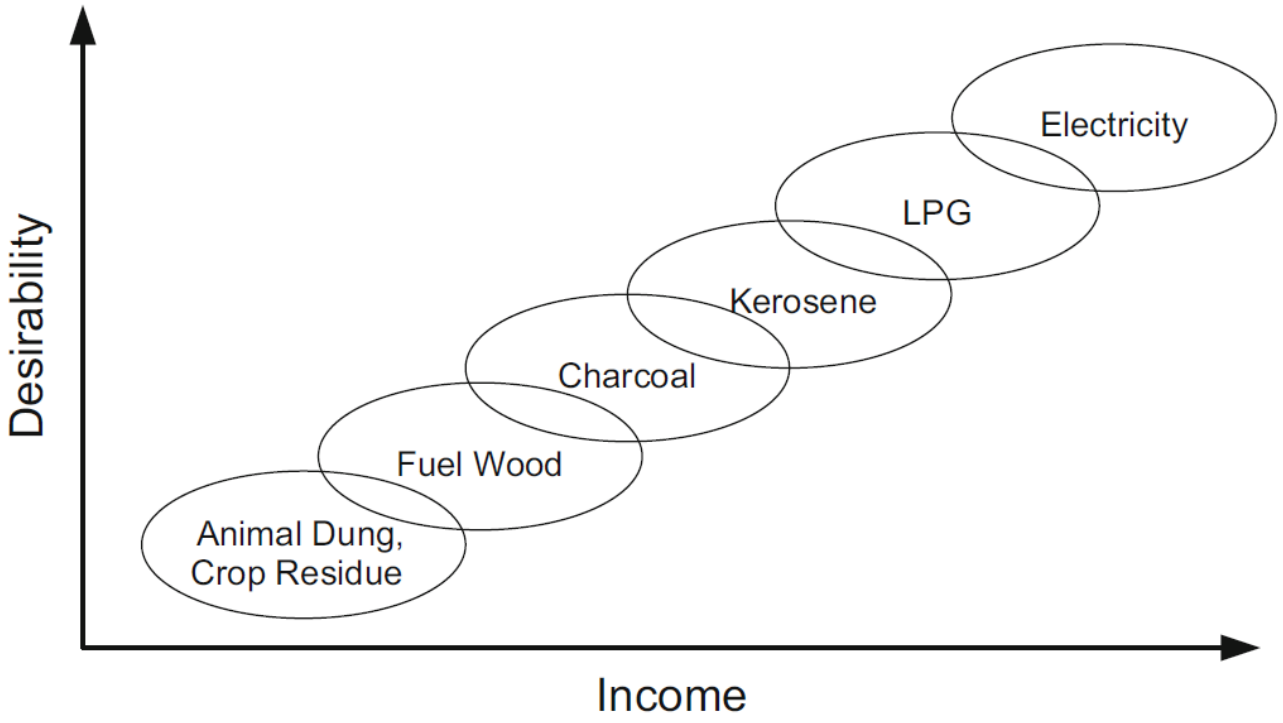
Energy Ladder: households tend to transition from less desirable fuels to more desirable as income increases



Recent research questions the validity of the Energy Ladder. Households simultaneously use multiple fuels ("fuel stacking"), and can be reluctant to change due to cultural reasons or to improve resiliency

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Fuel Choice Drivers

Quality

- ✓ High efficiency
- ✓ Controllable output
- ✓ Consistent performance
- ✓ Low/zero emissions

Convenience

- ✓ Point-of-use delivery/locally-available
- ✓ Reliable supply
- ✓ Little/no processing required
- ✓ Familiar/easy to use
- ✓ Versatile
- ✓ Safe
- ✓ Does not require storage

Cost

- ✓ Low fuel cost
- ✓ Low equipment cost
- ✓ Stable price
- ✓ Can be purchased in small or large quantities

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Fuel Stacking

- Most homes simultaneously use several fuels (“fuel stacking”)
- Example: a home may use
  - wood for heating
  - LPG for cooking
  - batteries for lighting
- Fuel stacking diversifies fuel sources and adds robustness to the fuel supply (in case of fuel shortages or price increases)

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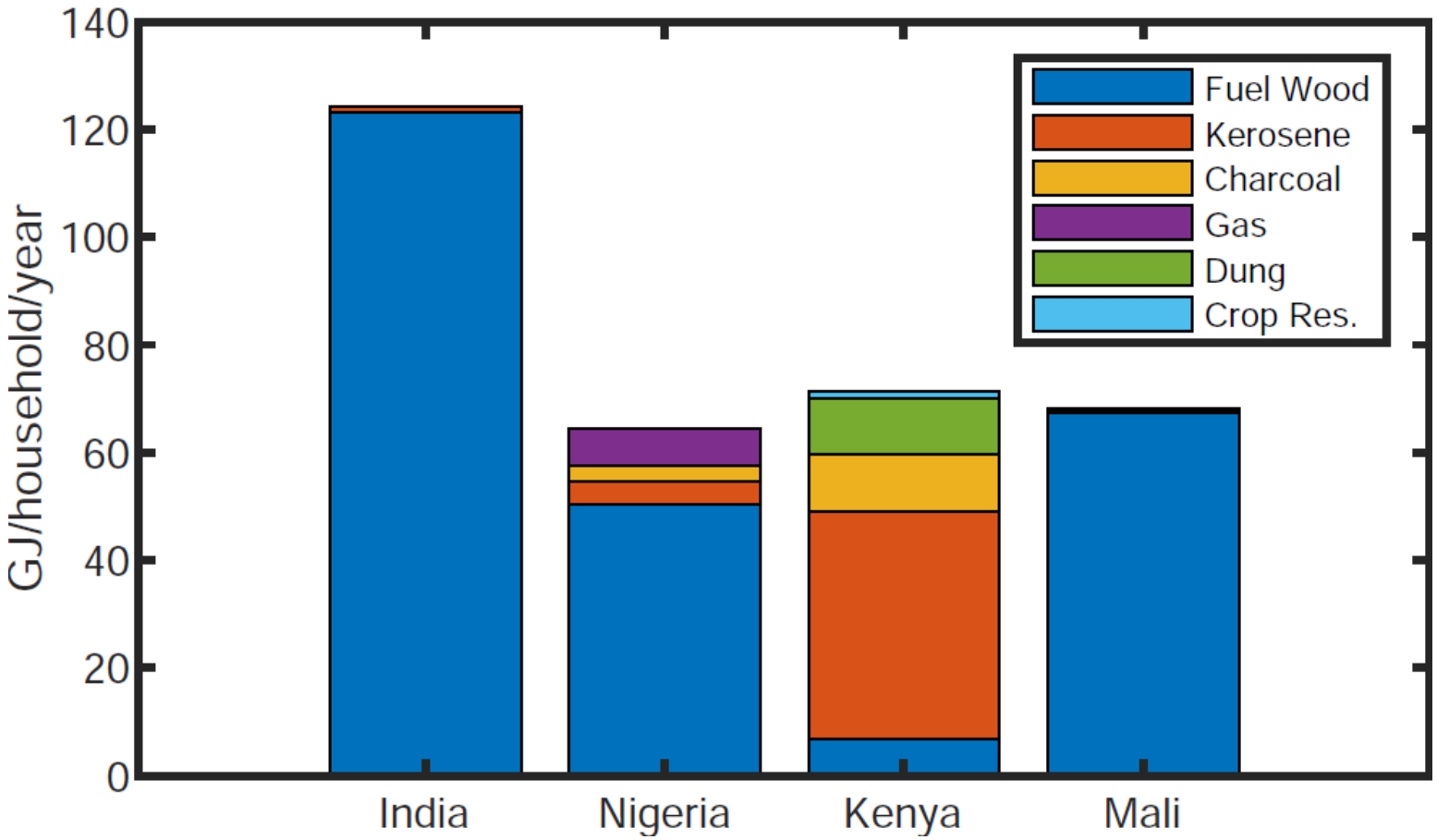
Majority of household energy in rural areas is from fuel wood



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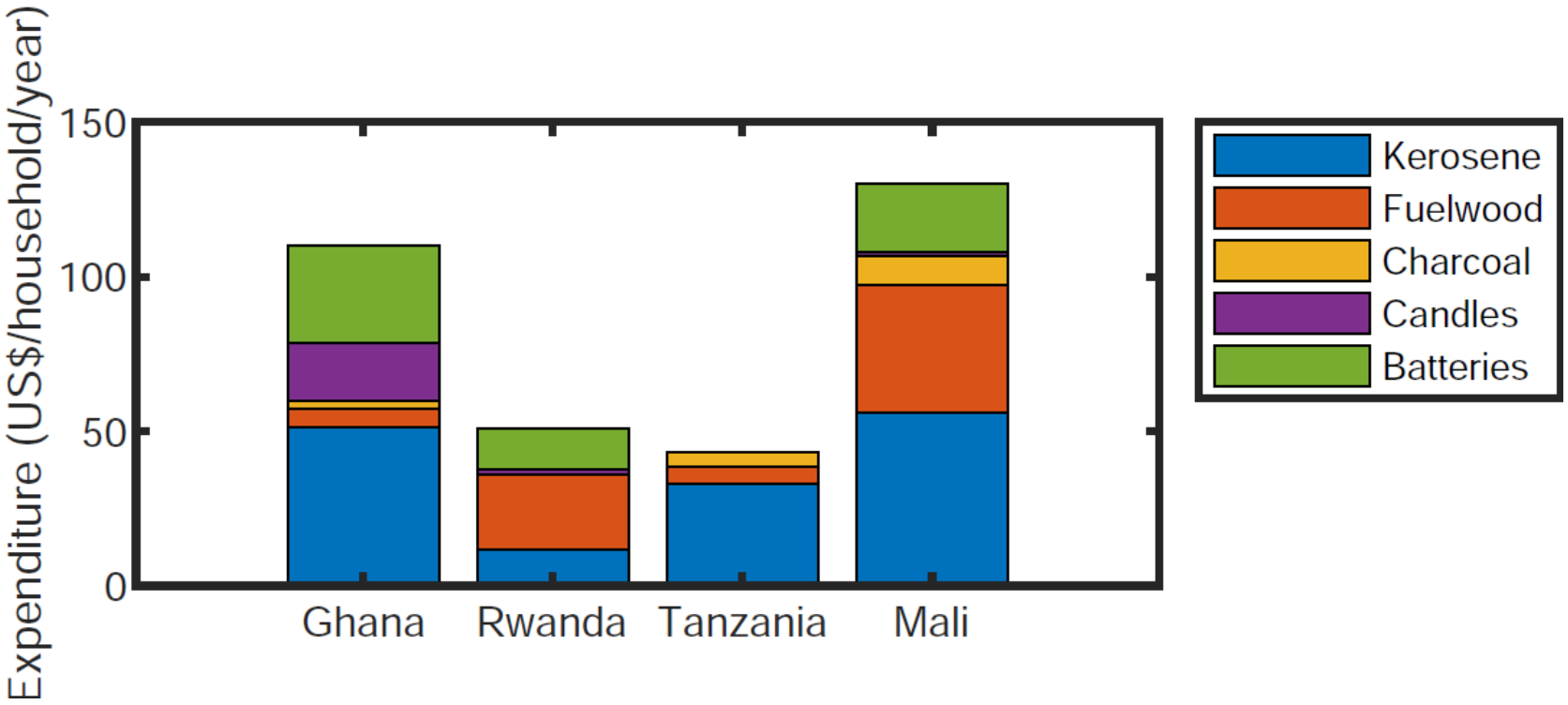
Fuel Expenditure

- Wide variety in expenditure, typically ranges from US$40 to US$140/household/year
- Fuel expenditure should be less than 5% to 10% of household's income



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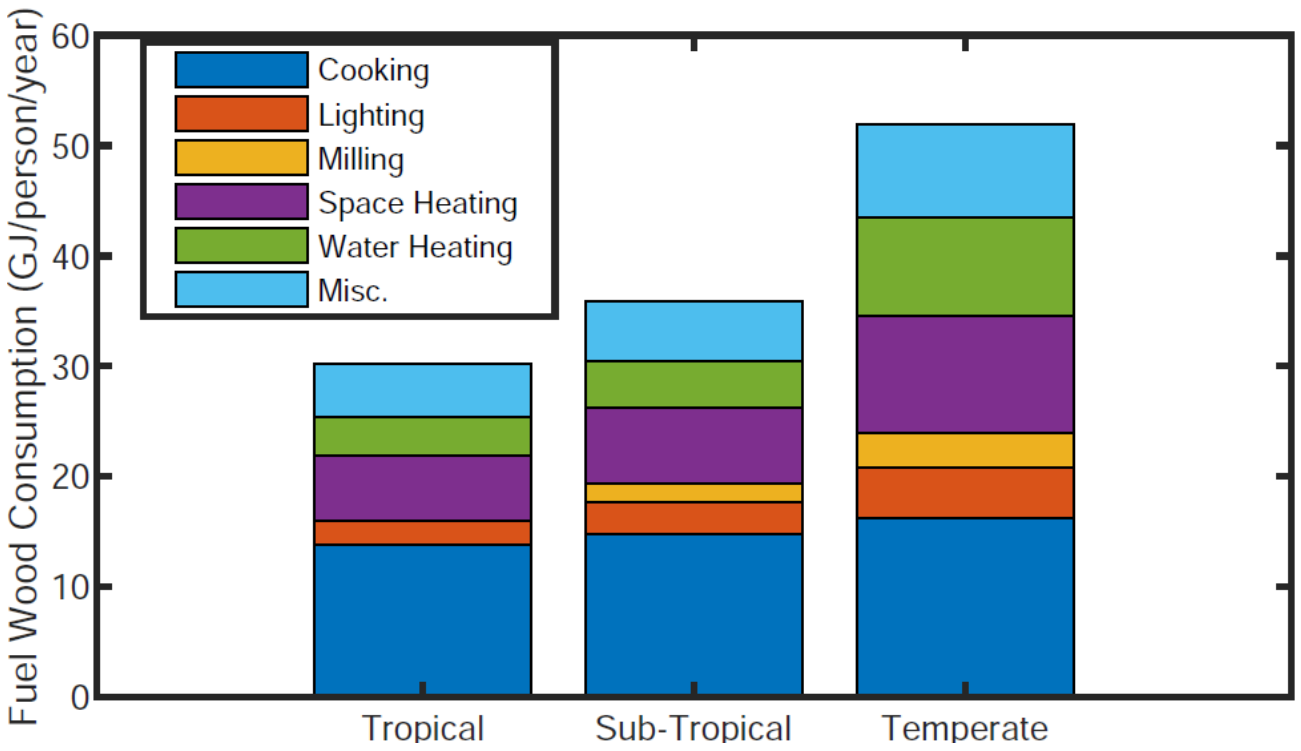
Fuel Wood Use

- Most important fuel for rural households
- Can be obtained with no or little cost (travel of 5km common)
- Burden on collection and processing (usually women/girls) 5 to 25 hours per week
- Typical consumption 1 to 5 kg/person/day but up to 10 kg/person/day in cold climates (several tonnes per year)



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Kerosene (“paraffin”)

- Commonly used in many parts of Sub-Saharan Africa
- Often subsidized by government
- Used for lighting, starting fires
- Less than 10% of energy supply, but can be 50% of expenditure
- Dangerous & unsafe
  - cancer, respiratory infection, asthma, tuberculosis, cataracts
  - accidental ingestion
  - fires and burns

kerosene dispensed into a water bottle can lead to accidental ingestion by children

(*courtesy H. Louie*)

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Charcoal

- Desirable solid fuel
- High specific energy makes it easier to store, transport, and use
- Create through “pyrolysis”
  - thermal-chemical reaction
  - high temperature with little/no oxygen over several hours or days
  - 75-85% carbon
  - 6 kg of dry wood per 1 kg of charcoal
- More expensive than fuel wood
- Contributes to deforestation or degradation

charcoal production mound in Zambia

(*courtesy KiloWatts for Humanity*)

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Replace or Complement?

- Off-grid systems can be designed to partially or completely replace traditional fuels, or to complement them by powering devices that traditional fuels cannot supply (e.g. a mobile phone)
- Size, cost, and design of the system depends on the strategy selected

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Example 2.4

Consider a household whose energy consumption is 60 GJ (16,667 kWh) per year from fuel wood and kerosene. Of this, 36 GJ from fuel wood is used for cooking and water heating on a cook stove with an efficiency of 12%, and 20 GJ is from fuel wood is used for space heating. Kerosene is used for lighting, with an annual consumption of 4 GJ.

Compute the annual energy required, in kilowatthours, to replace the fuel with electricity from the national grid. Assume the electric cook stove is 75% efficient and the electric lamps consume 45 kWh per year.

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Example: Electric Cookstove Consumption

Of this, 36 GJ from fuel wood is used for cooking and water heating on a cook stove with an efficiency of 12%... Assume the electric cook stove is 75% efficient.

The electric cookstove reduces the consumption from water heating and cooking to:

$$36 \text{ GJ} \times 0.12/0.75 = 5.76 \text{ GJ} = 1600 \text{ kWh}$$

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Example: Heating

…20 GJ from fuel wood is used for space heating

Assuming the same energy for heating is required from electricity

20 GJ x (1 kWh/0.0036 GJ) = 5555 kWh

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Example: Total

The total electrical energy for complete replacement is:

1600 kWh + 5555 kWh + 45 kWh = 7201 kWh

cooking heating lighting

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Example 2.5

Compute the annual expenditure of the same household if electricity is used to completely replace the traditional fuels, assuming the electricity is $0.15/kWh.

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Exercise

The consumption is 7201 kWh, so the annual cost is

7201 kWh x $0.15/kWh = $1080.15

This is likely far too expensive for a rural household.

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Replace or Complement?

- Complete replacement of traditional fuels is not practical in most situations
- Common strategy:
  - Replace expensive, low-quality, and/or harmful fuels such as kerosene (lighting) and disposable batteries
  - Complement traditional fuels for applications like mobile phone charging, radios, television
  - Retain traditional fuels for heating and cooking

Use traditional fuels for thermal applications (heating, cooking)

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How much electricity does a household need?

Household electricity requirements depends on local context and level of service provided

20 to 100 kWh/person/year

365 kWh/household/year
(1 kWh/day)

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Electricity Services

Service	Very-Low Power	Low-Power	Medium-Power	High-Power	Very High-Power
1. Lighting	Task	General	--	--	--
2. Communication & entertainment	Phone charging, radio	TV, computer, printer	--	--	--
3. Space cooling & heating	--	Fan	Air cooler	--	Air conditioner
4. Refrigeration	--	--	Refrigerator, freezer	--	--
5. Mechanical loads	--	--	Water pump, food processor	Washing machine	Vacuum cleaner
6. Product heating	--	--	--	Iron, hair dryer	Water heater
7. Cooking	--	--	Rice Cooker	Toaster, microwave	Electric range (cooker)

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Electricity Services

Services	Consumption (kWh/person/year)
Task lighting	1
Light or TV or radio	2
Light, phone, radio, small TV	22
Light, phone, radio, TV, fan, productive uses	220

Type of technology used also affects consumption (e.g. LED versus compact florescent light)

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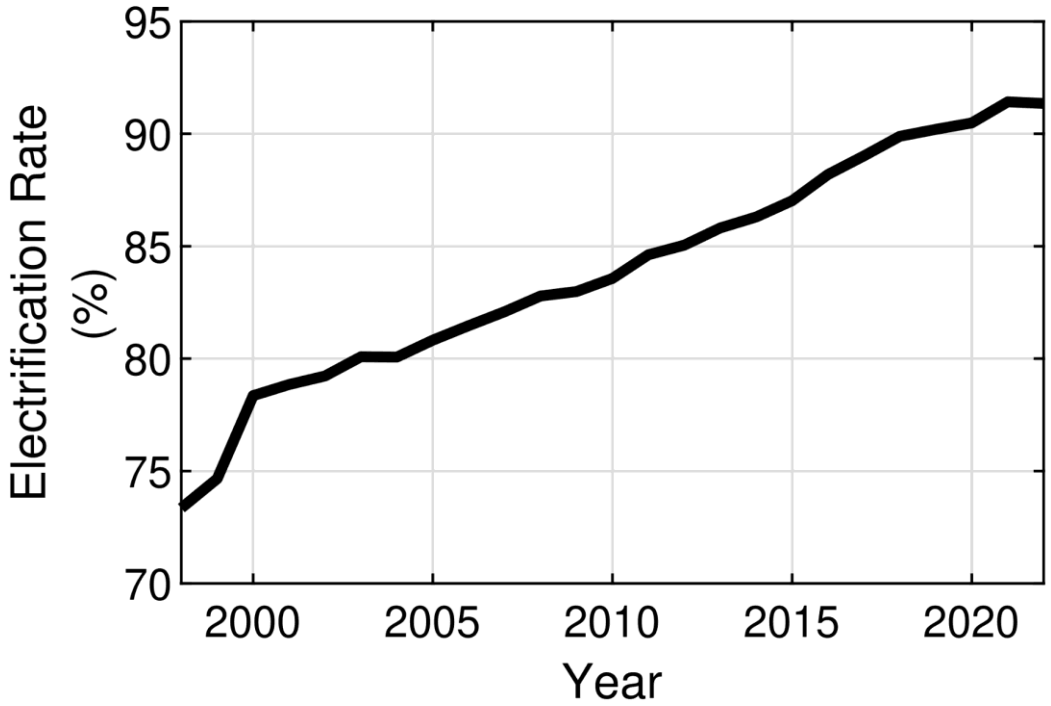
$$\text{Electrification Rate (\%)}: 100 \times \frac{\text{population whose house is connected to national grid OR has Tier 1 access}}{\text{total population}}$$



2022 Electrification rate: 91%.
685 million without access to electricity

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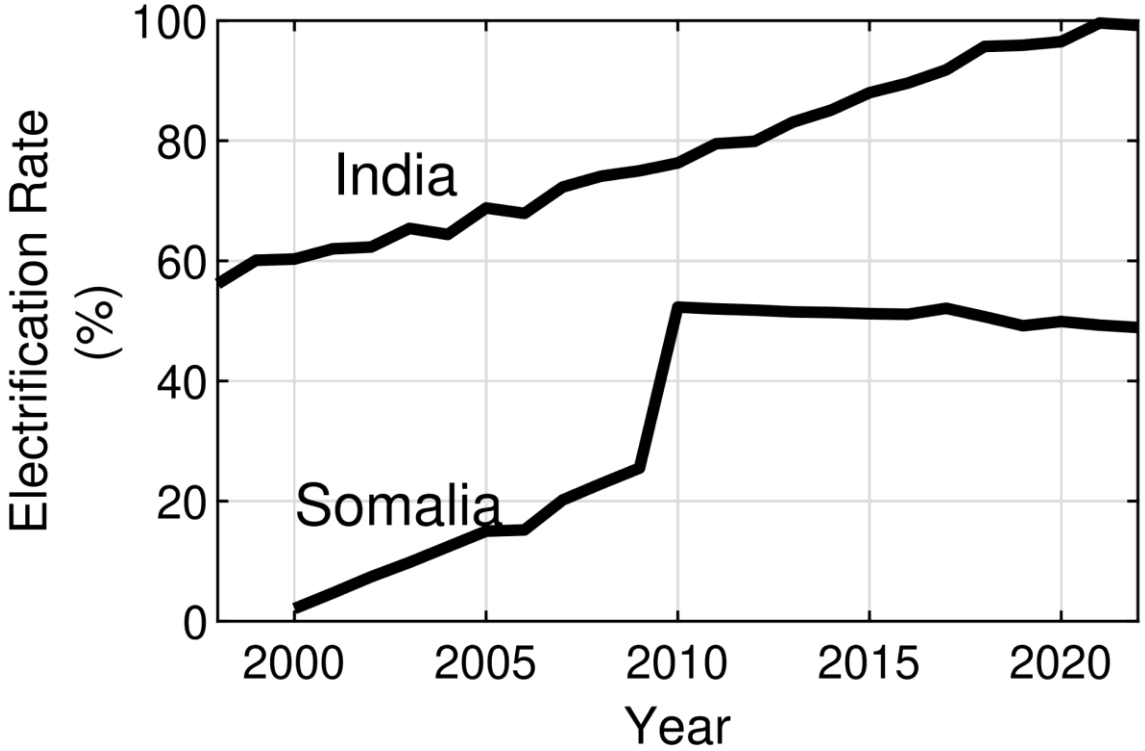
Uneven Progress

- Some countries have experienced rapid increases in the electrification rate (India, notably)
- Stagnant or decreases in other countries



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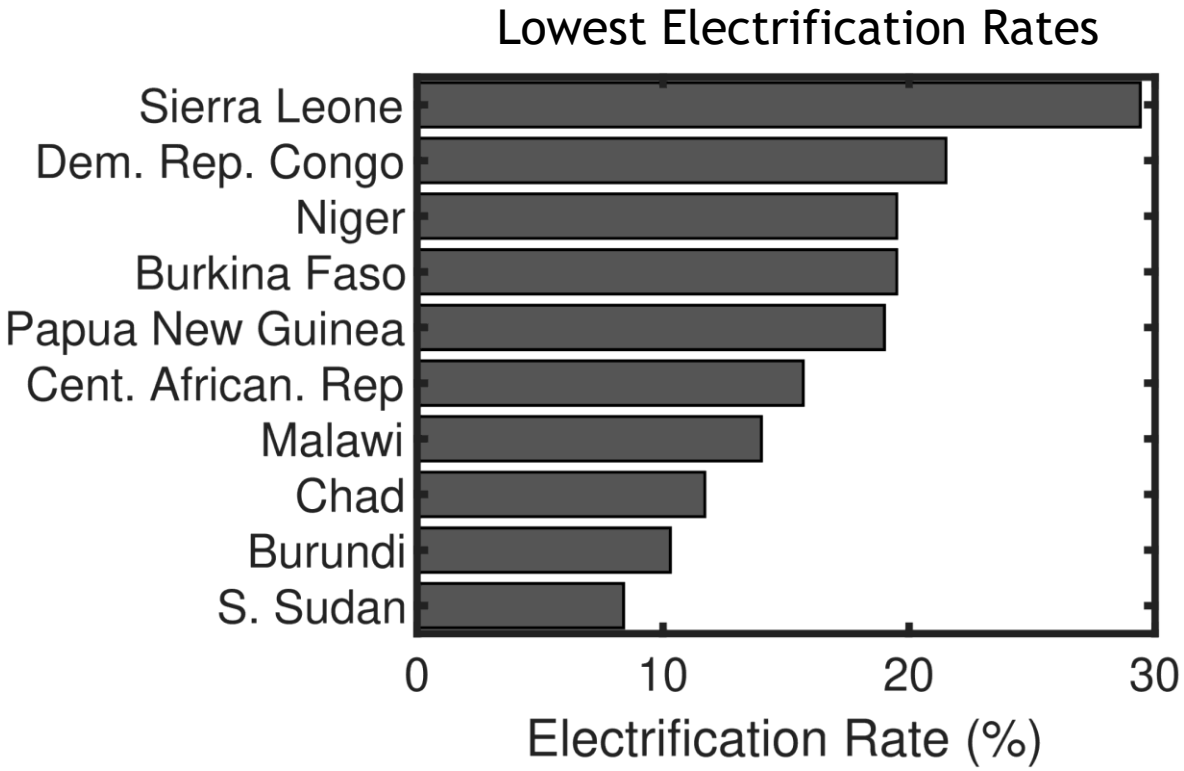
Electricity Access Around the World

>80% of people without electricity live in SSA

Rural penalty

- urban electrification rate: 98%
- rural electrification rate: 84%
- rural electrification rate in SSA is 30%



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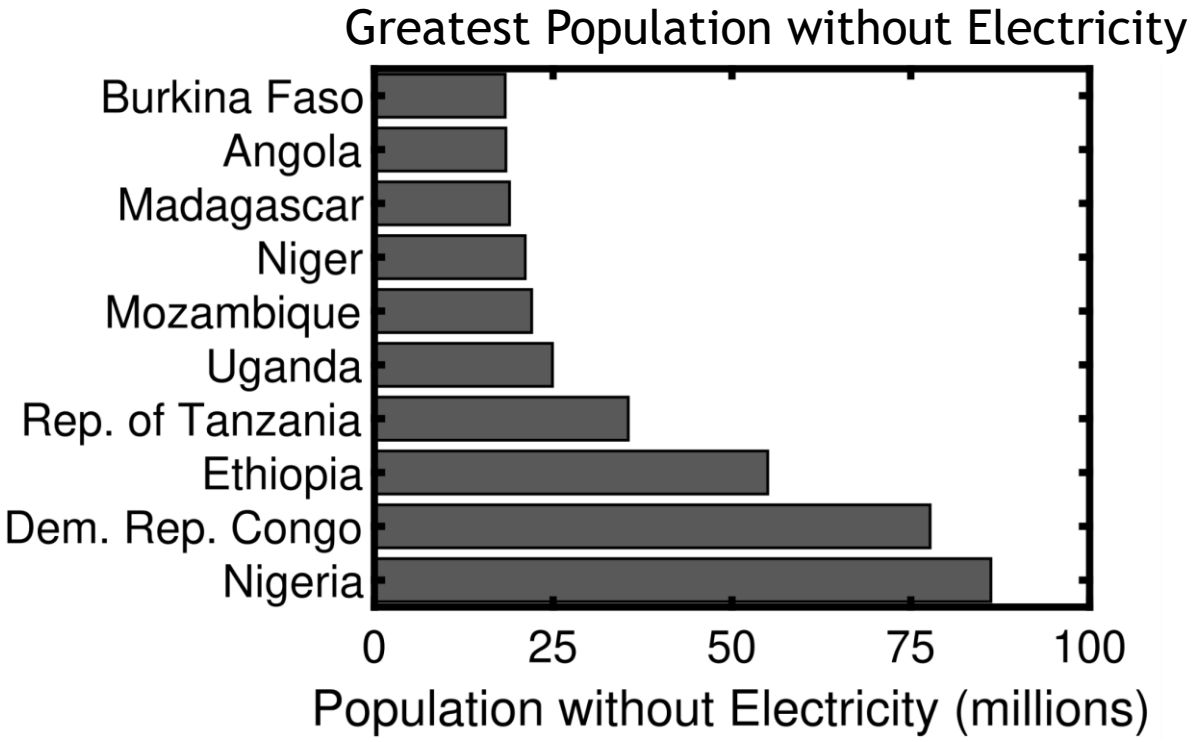
Electricity Access Around the World

Approximately 75% of un-electrified live in just 20 countries (18 of which are in SSA)



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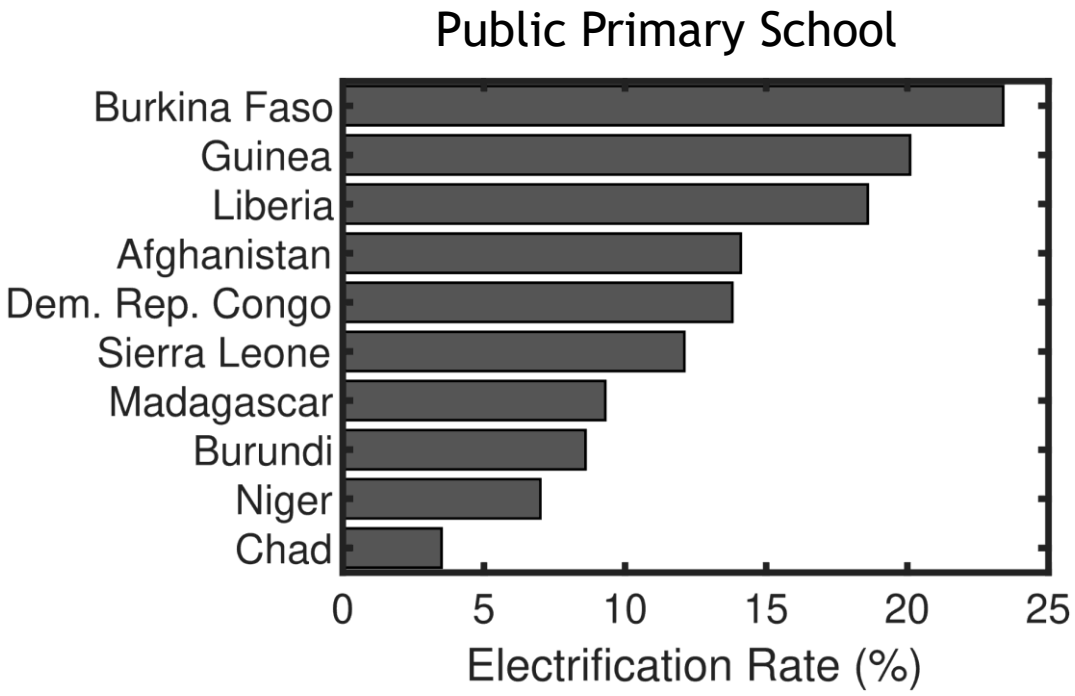
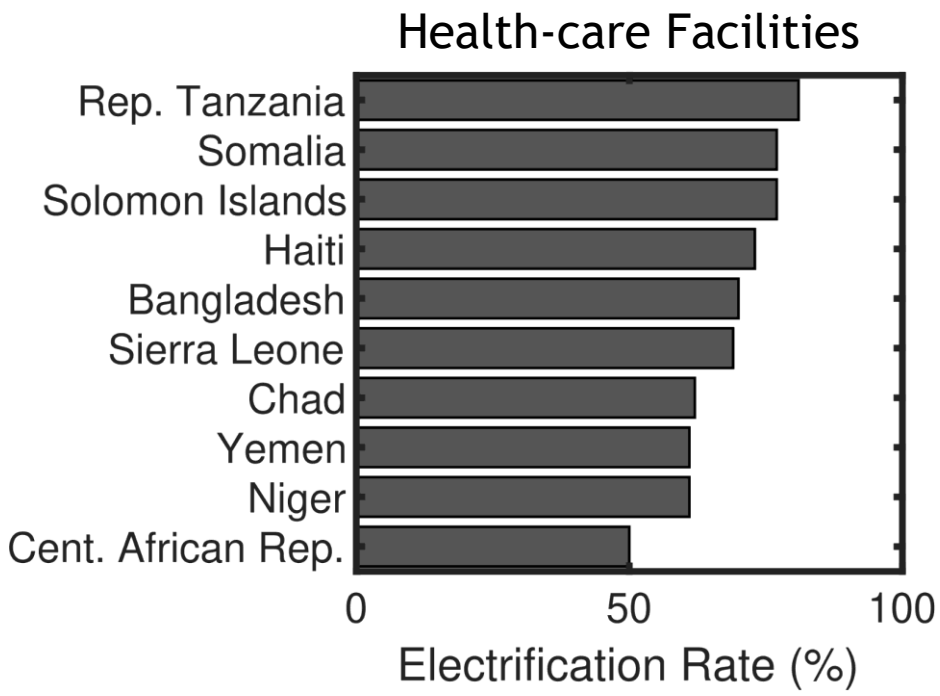
Community Service Electrification Rates





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Electricity Access in Refugee Settlements

- Approx. 120 million forcibly displaced people
  - 37 million are refugee
  - 20% of refugees live in refugee settlements (“camps”)
- Refugee settlements
  - size: 1000s to over 100,000 people
  - Age: temporary to decades old
  - electricity access: 90% of people in refugee settlements do not have electricity

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Electricity Access in Refugee Settlements

- Barriers to electricity access:
  - refugee camps often in countries/regions with low electrification rates
  - infrastructure investments by host countries may be a low priority
  - politically challenging to invest infrastructure in a “temporary” settlement
- Electricity access, if available, is often limited to administrative offices and facilities

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Electricity Access in Informal Settlements

- 1 billion people live in informal settlements (“slums”)
- Informal settlement: area where people do not have secure housing
  - Inhabitants squat or rent
  - housing often does not comply with building codes
  - often located geographically or environmentally hazardous areas
  - very low income
  - very few/limited services and infrastructure

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Electricity Access in Informal Settlements

- Barriers to electricity access:
  - utilities will not connect electricity to informal structures (those not satisfying building codes/regulations)
  - ad hoc, undocumented nature of buildings make it difficult to plan/design systems
  - fear of electricity theft or “sub metering” may cause equipment to overload
  - no proof of home ownership

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Calculating Population with and without Access

- Population with access = total population x electrification rate

- Population without access = total population x (100 – electrification rate)

- Electricity access is a binary indicator, so

population with access plus population without access = total population

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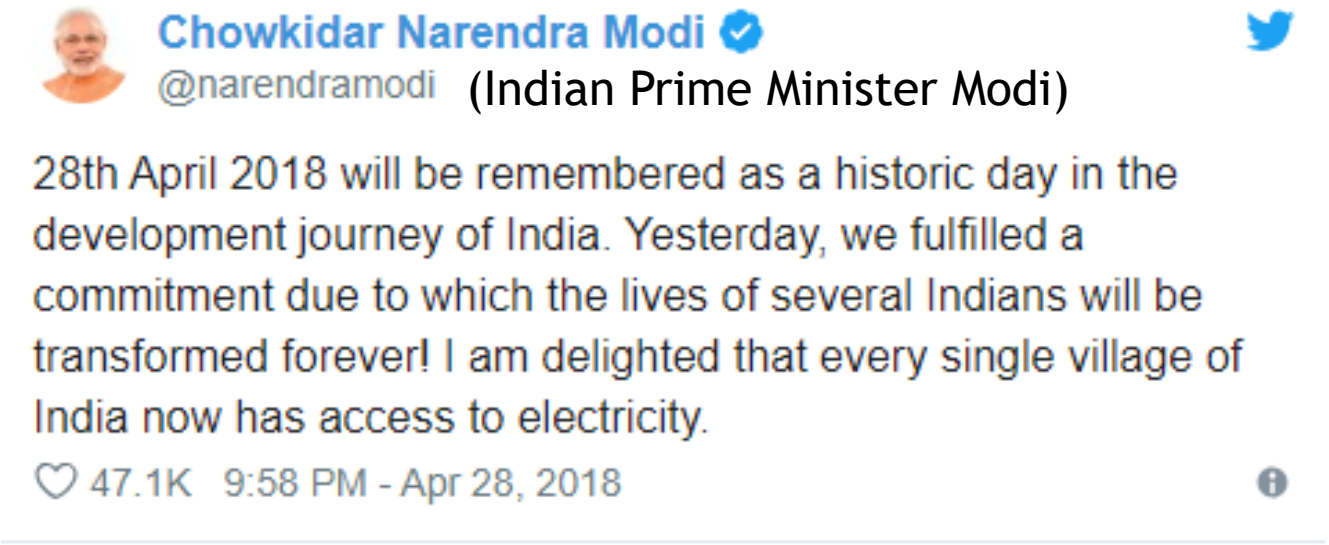
The headlines



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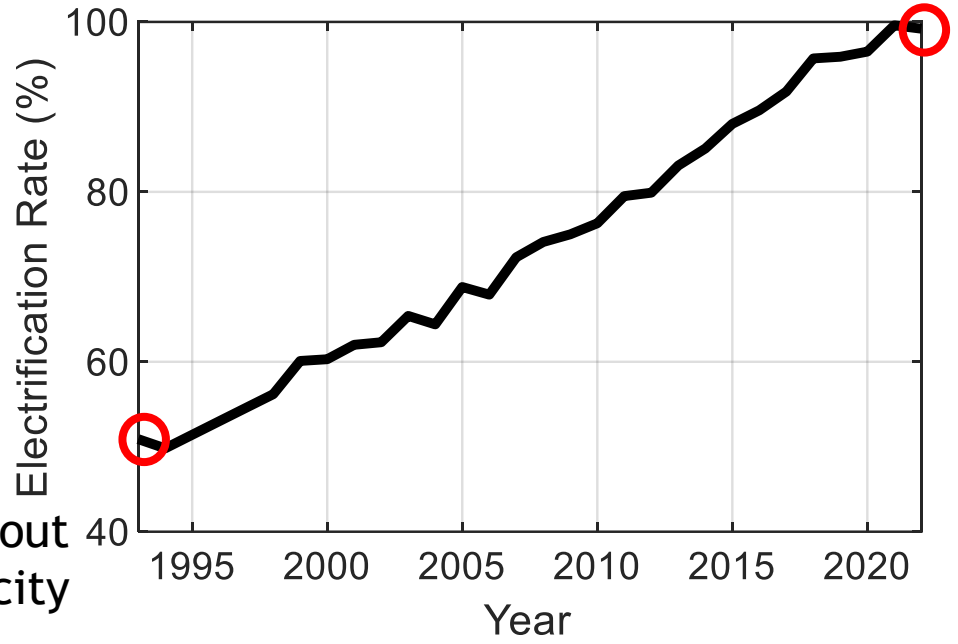
India’s Progress



11 million people without electricity

450 million people without electricity

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The headlines

Every village in India now has electricity. But millions still live in darkness. --Washington Post

https://www.washingtonpost.com/world/asia_pacific/every-village-in-india-now-has-electricity-but-millions-still-live-in-darkness/2018/04/30/367c1e08-4b1f-11e8-8082-105a446d19b8_story.html?utm_term=.717711e32ff9

Modi Announces '100% Village Electrification', But 31 Million Indian Homes Are Still In The Dark --Forbes

https://www.forbes.com/sites/suparnadutt/2018/05/07/modi-announces-100-village-electrification-but-31-million-homes-are-still-in-the-dark/#64670d0763ba

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Achieving Universal Electricity Access

Universal electricity access: global electrification rate of 100%

Time

Realistically, universal access is decades away.

Investment

Estimated annual investment through 2030 is US$45 billion per year.
Present investment is approx. US$10 billion per year.

universal access is technically feasible, with relatively limited environmental impact depending on consumption

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Is progress really being made?

Malawi in 2010

- total population: 14.8 million
- electrification rate: 9%

Malawi in 2012

- total population: 15.7 million
- electrification rate: 10%

An increase of 1 percentage point in electrification rate shows progress

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Is progress really being made?

Malawi in 2010

- total population: 14.8 million
- electrification rate: 9%
- population without electricity: 13.47 million

Malawi in 2012

- total population: 15.7 million
- electrification rate: 10%
- population without electricity: 14.13 million

number of people without electricity increased by 600,000!

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Discussion

Do you consider Malawi to be making progress on electricity access?

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Is progress really being made?

Sub-Saharan Africa in 2013

- total population: 0.952 billion
- electrification rate: 36.5%
- population without electricity: 604.5 million

Sub-Saharan Africa in 2014

- total population: 0.979 billion
- electrification rate: 37.7%
- population without electricity: 609.9 million

More people without access in 2014 than in 2013

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Is progress really being made?

Sub-Saharan Africa in 2012

- total population: 929 million
- electrification rate: 37%
- population without electricity: 590 million

Sub-Saharan Africa in 2022

- total population: 1.21 billion
- electrification rate: 51%
- population without electricity: 590 million

electrification rate increasing AND population without access is about the same

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Annual Growth Rate (AGR)

- Annual Growth Rate: quantifies the change in electricity access over a period of time
- AGR considers population growth dynamics as well as change in electricity access

$$AGR = \frac{(A[y] - A[y-t]) - (P[y] - P[y-t])}{P[y]} \times \frac{1}{t}$$

$$= \frac{\text{(pop. without access year in year } y - t \text{)- (pop. without access in year } y\text{)}}{P[y]} \times \frac{1}{\Delta t}$$

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Annual Growth Rate (AGR)

$$AGR = \frac{(A[y] - A[y-t]) - (P[y] - P[y-t])}{P[y]} \times \frac{1}{t}$$

$$= \frac{\text{(pop. without access in year } y-t\text{) - (pop. without access in year } y\text{)}}{\text{population in year } y} \times \frac{1}{t}$$

$A[y]$: number of people with access to electricity in year y

$P[y]$: population in year y

t: period of time considered, years

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Exercise

Compute the AGR of Malawi between 2010 and 2012

Malawi in 2010

- total population: 14.8 million
- electrification rate: 9%
- population without electricity: 13.47 million

Malawi in 2012

- total population: 15.7 million
- electrification rate: 10%
- population without electricity: 14.13 million

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Exercise

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Malawi in 2012

- total population: 15.7 million
- electrification rate: 10%
- population without electricity: 14.13 million

$$AGR = \frac{\text{(pop. without access in year } y - t\text{) - (pop. without access in year } y\text{)}}{\text{population in year } y} \times \frac{1}{t}$$

$$= \frac{13.47 - 14.13}{15.7} \times \frac{1}{2} = -0.021$$

If population without electricity increases, then the AGR will be negative

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Multi-Tier Framework (MTF)

- Electrification rate is problematic
  - ignores quality of electricity supply
  - treats all electricity supplies the same
  - ignores cost, reliability, and availability of electricity supply
- Multi-tier framework (MTF) is a more comprehensive way of measuring electricity access

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Electricity Supply MTF

- Electricity access of a home is assigned a Tier (0 to 5)
- Seven attributes considered:
  - Capacity
  - Availability
  - Reliability
  - Affordability
  - Formality
  - Health & Safety
  - Quality

Each attribute is assigned a tier (0 to 5). Tier of the supply is set to the lowest attribute tier

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Electricity Supply MTF

Attribute		Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity			≥3W ≥12Wh	≥50W ≥200Wh	≥200W ≥1000Wh	≥800W ≥3400Wh	≥2000W ≥8200Wh
Availability	Daily Night		≥ 4 h ≥ 1 h	≥ 4 h ≥ 2 h	≥ 8 h ≥ 3 h	≥ 16 h ≥ 4 h	≥ 23 h ≥ 4 h
Reliability						≤ 14 disruptions per week	≤ 3 disruptions/week AND total duration < 2 h
Affordability					365 kWh/yr < 5% of annual household income		
Formality						bill paid to supplier or authorized agent	
Health & Safety						no past accidents and no perception of shock/electrocution risk	
Quality						voltage problems do not affect use of desired appliances	

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- Power Capacity: 700 W
- Energy Capacity: 15,400 Wh
- 22 hours of availability per day, 4 hours of which are after sunset
- 7 disruptions per week
- Consumption of 1 kWh per day costs 4% of daily income
- Bill for electricity supply is paid to the supplier
- No past accidents and no perceptions of future risk; supply meets local electrical code
- Voltage spikes and sags are common, occasionally damaging equipment

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- Power Capacity: 700 W
- Energy Capacity: 15,400 Wh

Tier 3 power capacity
Tier 5 energy capacity
Overall Capacity is lowest of the two sub-attributes (Tier 3)

Attribute	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity		≥3W ≥12Wh	≥50W ≥200Wh	≥200W ≥1000Wh	≥800W ≥3400Wh	>2000W ≥8200Wh

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- 22 hours of availability per day, 4 hours of which are after sunset

Attribute		Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Availability	Daily		≥ 4 h	≥ 4 h	≥ 8 h	≥ 16 h	> 23 h
	Night		≥ 1 h	≥ 2 h	≥ 3 h	≥ 4 h	≥ 4 h

4 at night hours satisfies Tier 4 and Tier 5, so use the highest tier (Tier 5)

Daily: Tier 4
Night: Tier 5
Overall Availability is lowest of the two sub-attributes (Tier 4)

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- 7 disruptions per week

Attribute	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Reliability					≤ 14 disruptions per week	≤ 3 disruptions/week AND total duration < 2 h

Reliability Attribute: Tier 4 (there is no Tier 0, 1, 2, or 3)

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- Consumption of 1 kWh per day costs 4% of daily income

Attribute	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Affordability				365 kWh/yr < 5% of annual household income		

Affordability Attribute: Tier 5 (there is only Tier 2 or Tier 5)

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- Bill for electricity supply is paid to the supplier

Attribute	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Formality					bill paid to supplier or authorized agent	

Formality Attribute: Tier 5 (there is only Tier 3 or Tier 5)

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- No past accidents and no perceptions of future risk; supply meets local electrical code

Attribute	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Health & Safety					no past accidents and no perception of shock/electrocution risk	

Health & Safety Attribute: Tier 5 (there is only Tier 3 or Tier 5)

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- Voltage spikes and sags are common, occasionally damaging equipment

Attribute	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Quality					voltage problems do not affect use of desired appliances	

Quality Attribute: Tier 5 (there is only Tier 3 or Tier 5)

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Example 2.8

Determine the energy access tier of a customer whose supply has the following characteristics:

- Capacity: Tier 3
- Availability: Tier 4
- Reliability: Tier 4
- Affordability: Tier 5
- Formality: Tier 5
- Health & Safety: Tier 5
- Quality: Tier 3

Electricity supply for this customer is the lowest of the attributes (Tier 3)

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Multitier Framework

- Evaluating MTF requires more and higher quality input data, which may be challenging to collect
- MTF identifies ways to improve supply (e.g. improving reliability), which is helpful in developing electricity access strategies
- MTF is subjective, but provides a more complete picture of electricity access in a country than the electrification rate

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Summary

- Energy poverty is the lack of access to modern fuels
- Energy impoverished use fuels like animal dung, crop waste, wood, charcoal and kerosene
- Electricity requirements depend on if existing fuel sources are being replaced or complemented
- Electricity access is measured by the electrification rate as well as the Multi-tier framework

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