"Solar Energy" WS 2014/2015

Lecture 18: Part 1: PV in Developing Countries

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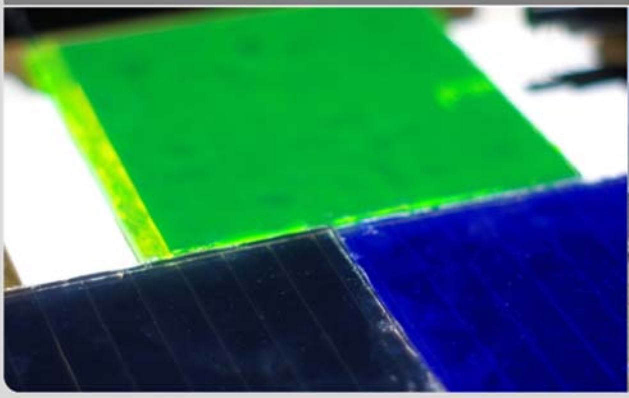


Energy and Early Man

- Survival: always main aim of mankind!
- For 1000's of years primary requirements were: food, shelter, and protection against harsh weather and wild animals
- The energy cycle as hunters-and-gatherers was simple:
  - o human energy: pursuit of game and manufacture of tools/weapons
  - o wood collected to keep fire burning for cooking, as well as providing warmth and light
  - o food from the hunt was basic fuel for human energy
  - o leftover animal grease also contributed to heat and light

Energy and Early Man

- Over the years, early man incorporated new options to fulfill the basic requirements of survival → altered energy cycles:
  - o gardening and fishing added new sources of food
  - o additional human energy needed for planting, weeding, harvesting
  - o gardening products provided a more predictable source of food for humans as well as feedstock for raising domestic animals
  - o animals in turn became source of high quality protein and also additional source of power
  - o gardening evolved into agriculture and along with animal husbandry, eventually displaced hunting as main activity
  - o domesticated animals took burden of load-pulling and back-carrying away from humans

Energy and Early Man

- Then technology was developed to simplify everyday activities ⇒ along with this progress came ever larger requirements for energy
- Early man had a estimated daily energy consumption rate of around 2500 kilocalories (1 kWh = 860 kilocalories)
- Value was ~5x larger in primitive agricultural societies
- During the low-technology industrial revolution in mid-1800s, per capita daily consumption 70 000 kilocalories in England, Germany and USA
- During this time, fuel wood and coal were main sources of energy, plus smaller contributions from petroleum and hydropower
- In last quarter of 20th century, dominant energy sources switched to petroleum, natural gas, nuclear energy and coal ⇒ average per capita consumption of energy in industrialized nations rose to over 230 000 kilocalories (267 kWh) per day!

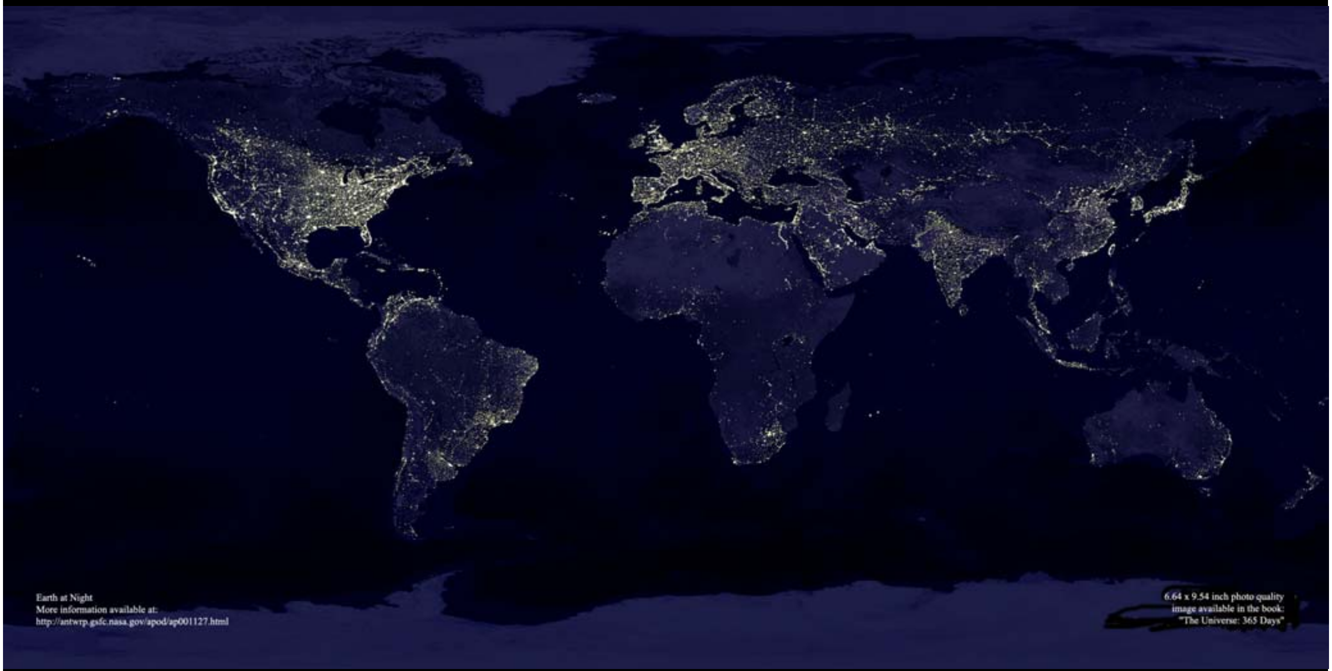
Electricity and Society

- With the development of the electric power industry ~1882, the face of the Earth was changed forever.
- Electric lighting began flooding the cities at night and electric motors became the main source of power in factories, and already four decades earlier long distance communication had been achieved via the electric telegraph.
- Over the years, electric inventions based increased productivity in factories and made our lives at home easier and more comfortable
- Modern life: endless chain of activities/events, fuelled by electricity:
- alarm clock wakes us up, followed by news on television or radio, the electric shaver and hair dryer, the coffee brewer, the blender and the microwave oven or electric stove, the refrigerator, the air conditioner, the computer,…

Electricity and Society

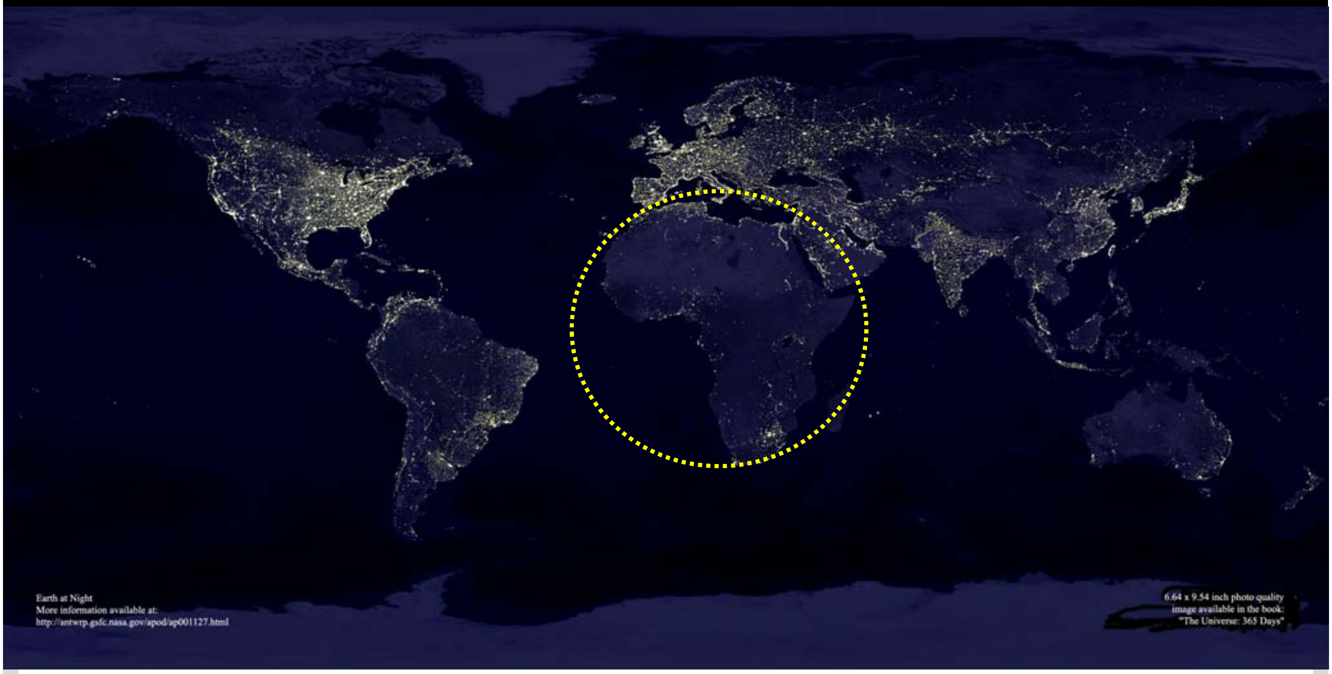
- Electricity has also been the main element in improving the quality of basic services for the well being of people, such as:
  - clean water
  - education,
  - medical care,
  - modern means of information and communication (e.g. internet)
  - as well as entertainment

- We take this for granted, but one third of humanity still remains in darkness…



- Bright lights of Europe…

… darkness in Africa…



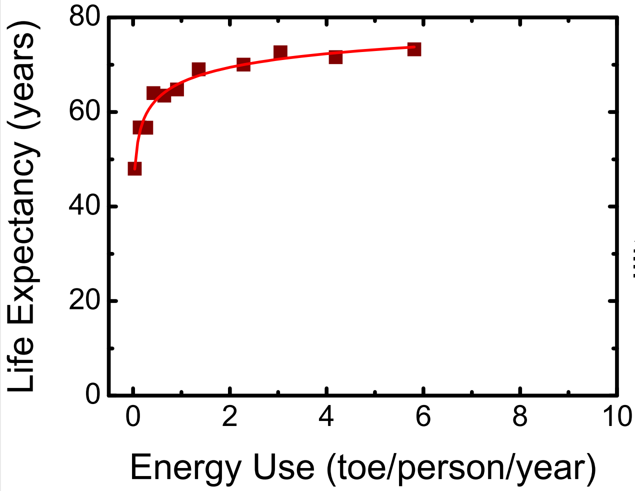
Electricity and Society

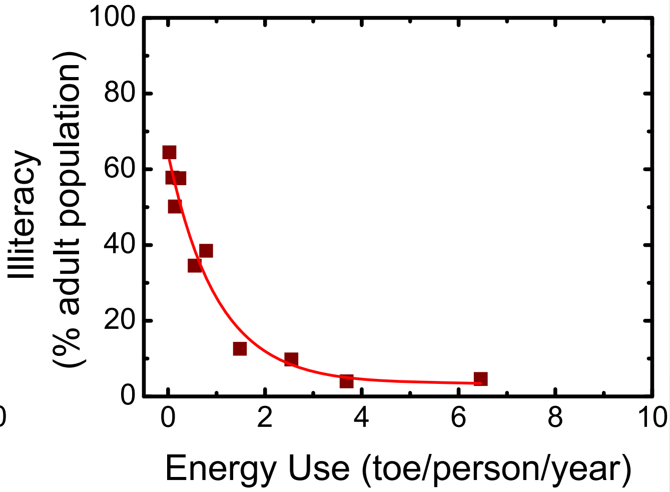
Karlsruher Institut für Technologie

- Not everybody has the fortune of enjoying all these benefits
- ~2 billion people, mostly in so-called developing countries, lack access to electricity and therefore remain in earlier stages of human development $\Rightarrow$ still relying on wood fires, kerosene lamps, etc
- Millions of people die every year from drinking polluted water
- Many suffer from the lack of basic medical services
- Modern means of communication often not available
- Illiteracy denies millions of people any possibility of gaining access to better opportunities

Electricity and Society

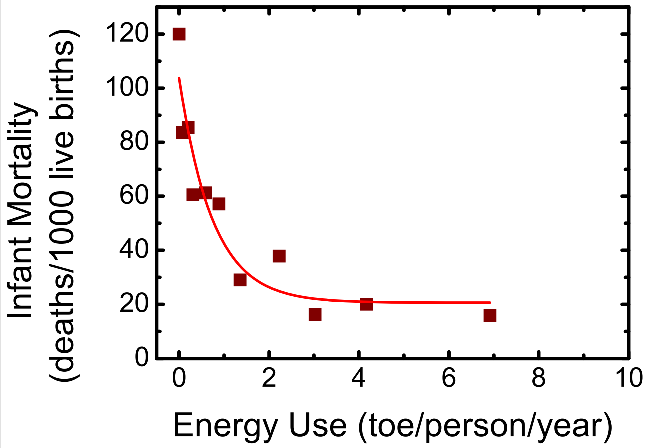
- The direct relationship between the per capita energy consumption and human development is well established
- Poverty and scarcity of energy services go hand-in-hand, and exist in a synergistic relationship





Source: World Energy Council, *Energy for Tomorrow's World*, Kogan Page Ltd, London 1993

Electricity and Society



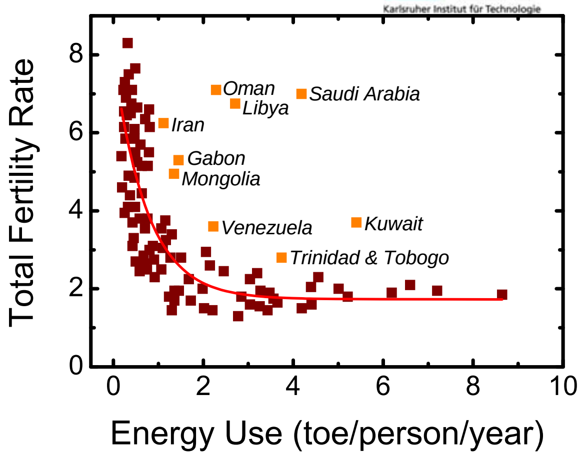


Table 3.8. Time Spent on Fetching Water and Collecting Firewood by Women and Men Engaged in the Activity (In hours and minutes)

		Benin (1998)			South Africa (2000)			Madagascar (2001)		
		Women	Men	Women/ Men	Women	Men	Women/ Men	Women	Men	Women/ Men
Fetching water	Urban	47	40	118%				56	54	104%
	Rural	1h 38	1h 15	131%				62	56	111%
	Urban and rural	1h 2	1h 2	100%	1h 2	46	135%	1h 2	55	113%
Collecting firewood	Urban	1h 5	1h 11	92%				1h 6	1h 13	90%
	Rural	1h 50	1h 30	122%				1h 14	1h 31	81%
	Urban and rural	1h 14	1h 23	89%	2h 17	2h 14	102%	1h 12	1h 26	84%

Source: World Energy Council, *Energy for Tomorrow's World*, Kogan Page Ltd, London 1993 and http://siteresources.worldbank.org/INTAFRREGTOPGENDER/Resources/gender_time_use_pov.pdf

Electricity and Society

Time Spent Gathering Fuel, Early 1980s

Country	Average Hours per Day	Explanation of Work
Southern India (6 villages)	1.7	Women contribute 0.7 hours; children contribute 0.5
Guajarat, India	3.0	In family of 5, 1 member often spends all his/her time on it
Nepal	1–5	Often 1 adult and 1–2 children do fuelwood collection
Tanzania	8.0	Traditional women's work
Senegal	4–5	Often is carried about 45km
Niger	4–6	Women sometimes walk 25 km
Kenya	3.5	Women do 75 per cent of fuel gathering
Ghana	3.5–4	1 full day's search provides wood for 3 days
Peru	2.5	Women gather and cut wood

Source: *World Resources* Institute, *World Resources Report* 1994-95, p.47 (New York: Oxford University Press).

- Fuel is carried up to 45 km!!
- Deforestation leads to loss of top soil and nutrients, mostly through wind and water erosion

Electricity and Society

- Thus, in 2015, with all the technology mankind has been able to create, survival is still the name of the game for millions and millions of people in remote rural areas of the world
- Energy services are essential for meeting basic human needs, reducing poverty, and promoting sustainable development
- Robust, cost-effective solutions required!

"The poor pay a much higher price for their energy services than any other group in society. The price can be measured in terms of time and labour, economics, health and social inequity, particularly for women."

The Centralized Electrical System

- Electricity: most sophisticated and flexible form of energy
- Drawbacks: electricity has to be used immediately after generation
  $\Rightarrow$ storing expensive, time-limited and inefficient
  $\Rightarrow$ also often needs to be transported over long distances from the point of generation (PoG) to the point of use (PoU), which can be inefficient and unreliable, especially when these points are far apart
- Early days of electric power industry, the PoG of electricity was right at the PoU and mostly generated using local and renewable sources of energy
- Water wheels originally used in the factories to mechanically power process machinery, were later retrofitted with electric generators

The Centralized Electrical System

- As demand for electricity increased (due to industrial and urban growth) $\Rightarrow$ distance between PoG and PoU became increasingly large $\Rightarrow$ electric companies searched for new ways to deliver their services within good profit margins $\Rightarrow$ needed to scale up
- Engineering research focused on alternatives to increase the power and hence the scale of the generating stations and the carrying capacity of transmission lines
- Thus, the concept of economies of scale was introduced in the electric power industry, which for over one hundred years has influenced decision making for new investments in electric systems

The Centralized Electrical System

- Since the generating units grew in size, electric companies often found themselves with excess generating capacity at the end of the construction of a new plant.
- The need to recover their investment in this excess capacity frequently motivated them strongly to look for new customers
- Transmission and distribution lines were extended to reach the new customers, so an extensive grid was eventually created.
- Sometimes, when demand was non-existent, it was artificially created. E.g. sometimes electrical appliances were donated to the customer by the electricity company!

Rural Electrification

- Agricultural processes also identified as potential applications for electricity $\Rightarrow$ power lines began extended into rural areas
- Due to fewer clients and lower intensity of electricity use $\Rightarrow$ investments in grid extensions harder to recover $\Rightarrow$ new institutional and financing mechanisms were developed to support the operation
- Official rural electrification programs introduced in most advanced nations $\Rightarrow$ initiative eventually trickled down to developing countries
- Major effort undertaken in 1960s and early 1970s to extend electricity grid into rural areas of developing countries
- But, by end of 20th century only a few developing nations had reached an acceptable degree of grid coverage in rural areas $\Rightarrow$ rest didn’t advance much due to problems faced by utilities incl. lack of capital to finance additional capacity and extensions $\Rightarrow$ rural electrification programs stalled

Breaking the Viscous Cycle

- The provision of small amounts of energy – especially electricity – changes the lifestyles of the rural population significantly
- Many tasks done mostly by women would be much easier if a small amount of electricity was available: provision of water, grain grinding, clothes sewing, etc…
- Electrical lighting:
  - facilitates movement at night inside the house,
  - helps prevent accidents,
  - eliminates need for kerosene (both a health and fire risk),
  - easier to spot threats (e.g. poisonous insects, wild animals)
  - helps respond quickly to critical situations (accidents, illness)
- A house with electricity is a symbol of status. Outdoor illumination promotes social interaction and after-hours outdoor activities, including studying and additional income generation

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Sources of Electricity

- Dry cell batteries are OK for supplying low-power loads such as torches and radios
- A television or computer would require a larger battery – car batteries often used, but are heavy and – if no car is available – then often need to be taken to a town (where there is grid or generator) to be recharged
- For larger loads, then people need to purchase a diesel generator (individually) or put pressure on the government to extend the grid

The PV Alternative

- PV is nowadays regarded as one of the most appropriate options to electrify dispersed population in remote places
- Single most attractive feature of PV technology is its modularity $\Rightarrow$ allows designers to tailor electricity-generating systems as small in capacity as a few watts, or as large as many megawatts
- Combined with the suitability of PV for autonomous operation, producing electricity with locally available sunshine, plus other characteristics such as lightweight, low-maintenance requirements and long useful life, has led people to consider PV as an attractive option for rural electrification
- Terrestrial applications were developed with the basic idea of powering loads in remote places, where the cost of extending the grid was just too high

The PV Alternative

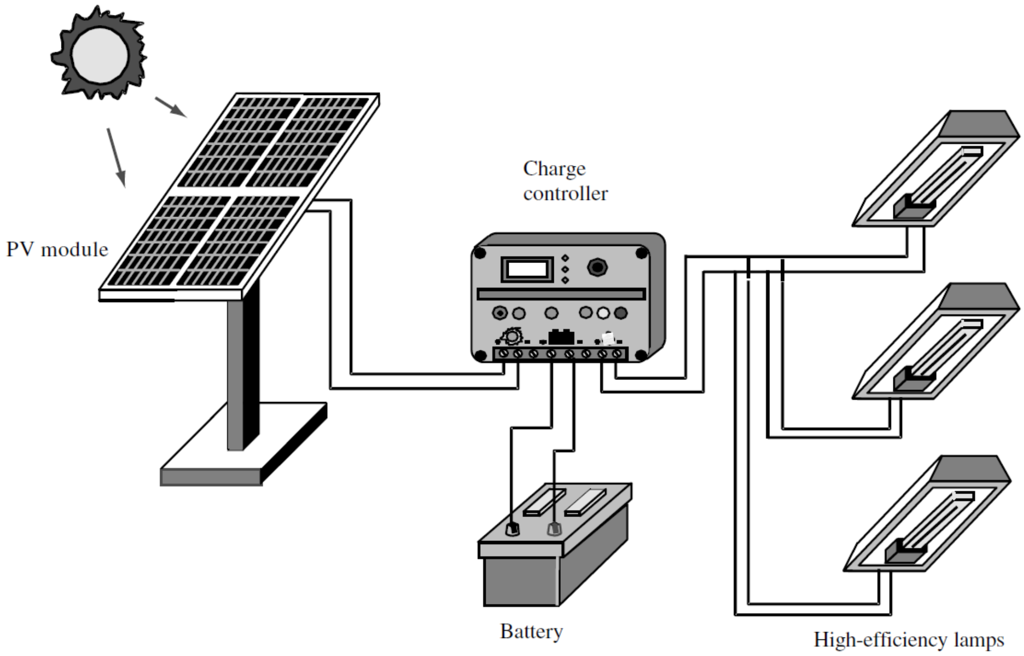
- Today, hundreds of thousands of PV systems installed around the world to substitute for candles and kerosene lamps, petrol- or diesel-powered generators, and for unreliable grid extensions
- Advantages of PV technology for rural electrification demonstrated via a number of early projects in between 1968 and 1977 in Niger, Mexico and India – applications included PV powered educational television, phones, medical dispensaries, and boarding schools
- Early work demonstrated not only technical viability of PV systems but also the benefits to the user. Some of these installations are still operational and in good condition, albeit with limitations of a 30 – 40 year old technology
- Unfortunately, a critical mass of early projects was never achieved as to make a noticeable impact on society, and the lessons derived from these very early projects mostly disappeared

The PV Alternative

- What prevailed in the minds of decision makers over the years was the notion that PV was too expensive and not too reliable – in spite of the tremendous progress PV technology has made in recent years in terms of cost, efficiency and reliability!
- Progress in materials technology, electronics and PV systems engineering, along with a large drop in price of the main components of the PV system and a better understanding of the needs and expectations of the rural people, have resulted in a large variety of ideas, proposals and technological schemes to use PV as a source of electricity to promote human and economic development in rural areas of the developing world
- But barriers remain to enter the rural market on a massive scale

The PV Alternative

- Most common is a “solar home system” (SHS): one PV panel (10-40W), one charge controller, one LA battery, and some lights



The PV Alternative

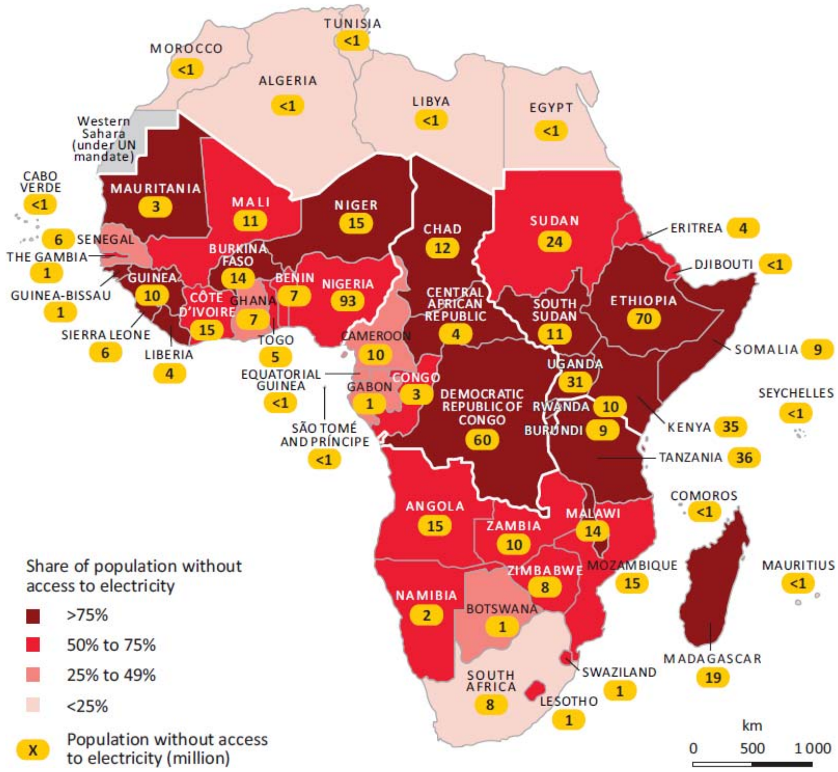
- Many success stories:
- Schools can be supplied with modern audiovisual means, educational television, and internet, as shown by the project aldea solar in Honduras
- In Mexico, over 13 000 PV powered telephones now link tens of thousands of people in remote communities with the rest of the world, through terrestrial PV powered transmitting stations and satellite links
- In Cuba, the Ministry of Health has implemented a system of rural clinics powered by photovoltaics
- A large number of PV water-pumping projects have been implemented around the world

The PV Alternative

- Dispersed PV systems
  - Solar home systems
    - Basic lighting
    - Lighting & entertainment
    - Full domestic service
  - Application-specific
    - Communal services
      - Schools (educational TV, internet)
      - Communal center, Church (lighting, loudspeaker, VCR, satellite link, etc.)
      - Health center (micro surgery sets, vaccine refrigerators, sterilizers, etc.)
      - Water (supply, disinfection)
      - Communications (telephone, CB radio, local radio broadcasting station)
      - Outdoor lighting (street & sportyard lamps)
    - Productive uses
      - Agriculture (microirrigation, greenhouse operation)
      - Productive activities (milling, sawing, sewing, grinding, etc.)
      - Animal husbandry (watering, milking, etc.)

The PV Alternative

- So why are there 1.3 billion people in the world without access to electricity …?
- 620 million of them alone in Africa



Barriers to PV Implementation

- The answer is found in the number of barriers a new technology such as this has to overcome to fully enter the market
- In the case of PV, some such barriers are well known, while others remain unknown; some are technical in nature and others having to do with institutional, social and financing issues
- Like conventional electricity is generated; in large centralised plants, transmitted and then distributed to reach the individual consumer…
- PV is produced in a small number of facilities in China, Europe, USA, Japan and transported across the world to reach the final user in very remote rural areas
- At each step a number of operations need to take place, which involve different degrees of complexity and cost ⇒ bringing PV solution to those sites where the grid has not been able to reach can be a very difficult task, unless all barriers are successfully removed

Barriers to PV Implementation

- Technical Barriers:
- PV systems are claimed to be reliable and long lasting
- True and proven as far as the PV module is concerned, but not for other system components
- Batteries are perhaps the weakest link
  - exposed to overcharging and over-discharging, which reduces their useful lifetime
  - also demand a fair amount of – albeit simple – attention and regular maintenance
- However, even simple technical tasks may prove challenging in rural areas where a high degree of illiteracy and a lack of familiarity with modern technology, and with electricity in particular, is more the rule than the exception

Barriers to PV Implementation

- SHS face other problems, mostly with charge controllers and lamps – basically as a result of an industry that has until now had an uneven degree of development (and hence regulation)
- Two schools of thought underline the issue:
  1) simple, sturdy, low-tech, low-purchase-cost devices, vs.
  2) high-tech, sometimes a bit complex but perhaps lower life cycle-cost devices
- A huge field study was conducted in Mexico: 1740 SHS (out of ~60000 installed under government financing) were evaluated to:
  1) assess the physical and operative condition of the systems,
  2) probe the degree of satisfaction of the users, and
  3) evaluate the efficacy of measures previously implemented to make the projects sustainable
- Largely showed that from the technical point of view things look good with most SHS samples performing well

Barriers to PV Implementation

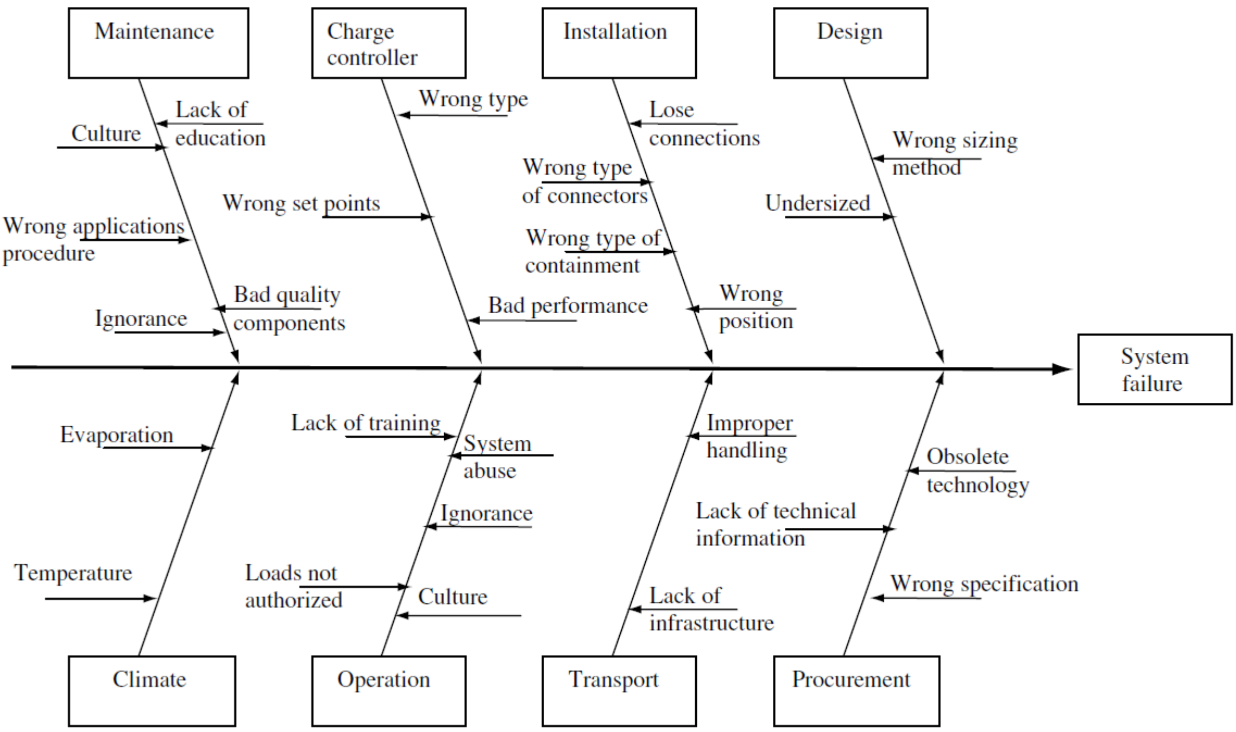


Figure 23.3 Cause–effect diagram showing a variety of factors leading to a failed system

Barriers to PV Implementation

- Cost:
- For a commercial operation to be financially sustainable a flow of goods has to be properly matched by a counter-flow of money
- PV manufacturing companies invest in factories and raw materials, pay wages to their workers and taxes to their governments and are obliged to deliver revenues to their shareholders ⇒ all expenses plus profits essentially set the base price of products
- Then, PV components from different companies are transported to specific points for systems integration ⇒ packaged systems are fed into the distribution channels for retailing ⇒ finally installed where end user wants them
- But, by time a PV system is installed on the user's premises, its base price has increased a number of times

Barriers to PV Implementation

- So, people need money to get their systems installed
- Considering that many people in rural areas of developing countries earn US$1-2/day ⇒ important questions emerge when one considers PV as the solution to rural electrification problem
  - Are people willing to pay for the system?
  - How much can they afford to pay?
  - What mechanisms can be instrumented to make systems more affordable?
  - If people cannot pay, should they remain in darkness or should somebody come to their rescue?
  - What roles can governments and NGOs play?
  - Even if people can pay, should they bear full system cost?

Barriers to PV Implementation

- Not trivial questions considering that the miracle of full-scale rural electrification requires ~US$300,000 must flow from poorest regions of world to developed countries for the provision of PV systems
- So, fuel is free and systems are low maintenance and long lasting, but capital cost remains as stumbling block for introduction of PV
- Number of schemes have been tried to remove this barrier:
  1) Social route: poverty alleviation programs and other socially driven mechanisms used by governments and aid organisations $\Rightarrow$ make funds available for purchase of PV systems in favour of the least privileged people;
  2) Fiscal route: taxes, import duties and other fiscal levies are removed to lower the local price of PV system $\Rightarrow$ makes PV more affordable for final user $\Rightarrow$ at same time creates a local market;

Barriers to PV Implementation

3) Business route: banks, private companies and entrepreneurs provide different schemes to make finance available for purchase of PV system $\Rightarrow$ help to create a market for PV at same time

- One way or another, each of these routes somehow benefits from the intervention of governments, multilateral organizations and lending institutions
- Naturally, the businesses where PV system component manufacturing takes place benefit too! There is no PV panel manufacturing in Africa…

Barriers to PV Implementation

- Not everyone living rural areas is necessarily poor ⇒ some people choose to live there (e.g. their source of income attached to the natural resources locally available)
- They still don't have electricity from the grid, but then usually rely on diesel generators for electricity ⇒ could purchase PV system without financial assistance ⇒ already a good market that is being tapped in a number of countries, such as Colombia and Mexico
- Some estimates indicate that 25-50% of people living in remote places could purchase a SHS provided some sort of financial assistance was available ⇒ substantial market size ⇒ schemes are being tried by private entrepreneurs and multilateral development organizations, e.g. in Kenya, Zimbabwe and Dominican Republic
- But, the poorest of the poor (largest portion of the world's rural population) will never afford to buy their own PV systems

Barriers to PV Implementation

- Business route: two alternative models are used, both of which have pros and cons:

1) Sales model:

- PV system is purchased on credit by user ⇒ person owns and takes over responsibility of system maintenance and spare parts
- Money usually borrowed by user from: a) system supplier, b) finance institution, or c) other credit organization such as a revolving fund or local microfinance operation
- Either way, the money is obtained at a cost ⇒ total cost of PV system increases ⇒ paid back in periodic instalments under prearranged terms and conditions
- Sales model preferred by those who like the social status of system ownership and are willing to maintain the equipment ⇒ if the system does not work the owner still has to pay!

Barriers to PV Implementation

2) <u>Service model</u>:

- People not willing to take any risks ⇒ opt for service model where supplier retains ownership of PV system ⇒ charges a monthly fee for electricity delivered to user
- Supplier maintains system and is responsible for providing user with electricity, according to system capacity
- This type of service provided via simply an open market provider or a community-based provider
- Risk assumed by service supplier also has a cost ⇒ reflected in monthly fee charged
- Estimated that added monthly fee over 10 years could be double the life cycle-cost of same PV system when purchased on credit

Barriers to PV Implementation

2) <u>Service model</u>:

- Experience shows fee-for-service models exhibit great disparity in amount of monthly fee charged to individual users – reasons?
- Some projects may involve a subsidy
- Definition of responsibility of service suppliers, e.g. some retain responsibility over the PV module and charge controller only (least troublesome parts of a SHS!), while dumping the responsibility of replacing the battery (weakest link!) and the lamps on user
- The monthly fee/payment collection may be expensive task, due to the time and effort it may take supplier to reach customer – only to find out person not home!
- Also, many poorer farmers only have money during harvest period
- Fee-for-service model most applicable to the most accessible and higher density rural communities

Barriers to PV Implementation

M-KOPA solar home system:

- Contains: PV panel, controller, USB phone-charger + 3 LED lights
- Control box contains a rechargeable battery, a GPS cell modem, LCD status screen, and connection to 4-watt solar cell, LED lights, and USB port
- Each M-KOPA SHS has a unique customer ID number ⇒ used to add credit to user's account

Barriers to PV Implementation

M-KOPA solar home system:

- Made in USA by d.light but currently available only in Kenya. Why?
- Innovative payment plan fits with pre-paid mobile culture (e.g. on-grid customer also purchase electricity from utility via mobile)
- Retail price is 2500 KES (~US$29) but more like a deposit
- After that user pays 40 KES per day (US$0.45) to keep device operational ⇒ context: an estimated 3 million Kenyan *homes* (not people) spend ~70 KES daily on kerosene and phone charging
- Payments via M-PESA mobile payment system ⇒ customers make them directly from mobile phones ⇒ M-KOPA's built-in modem checks payment status and number of days of credit is displayed
- Daily payments are part a rent-to-own agreement with M-KOPA ⇒ after buying 360 days worth of electricity customer owns the system outright ⇒ no more future payments

Barriers to PV Implementation

- Social route:
- Governments act in various capacities along the social route
- Financing purchase of SHS for poor people the most critical one
- Government financing of SHS: seen by some as unnecessary intervention that distorts the market and creates dependence in the user's minds (e.g. argument is that users will not buy privately once the government has provided systems for free)
- Most critics forget that rural electrification has been historically subsidized by governments not only in developing countries but also in some of the most advanced nations $\Rightarrow$ in that sense PV is no different
- To date, largest volume of SHS installed around world were via government or donor-led programs

Barriers to PV Implementation

- Government intervention may help aggregate markets, reduce transaction costs and (if properly done) create a better setting for quality assurance and local industry development
- This has been experienced with government-financed PV projects in Mexico $\Rightarrow$ proper institutional mechanisms implemented $\Rightarrow$ local industry has also emerged around government-financed projects $\Rightarrow$ now even local production and exports BoS components
- >2500 rural Mexican communities have been electrified with PV
- Money from government: for rural electricification and promoting local development
- People have instrumented a variety of cost-recovery and money-making mechanisms, which allows for system maintenance and additional communal projects

Barriers to PV Implementation

Trained Human Resources:

- Properly trained people to develop and operate programs and carry out projects are very important!
- PV systems and their implementation in rural areas often regarded as very simple
- However, disregard for complexities behind the process has resulted in a large number of failures, e.g. 1) large number of PV projects in rural areas around the world haven't lasted more than a few years; or 2) how others are still not complete because of logistical aspects not considered; or 3) how many are under-performing due to poor engineering and construction practices
- But, with proper training, PV systems packaging is increasingly being carried out by local companies in developing countries
  $\Rightarrow$ promotes use of local labour as well as materials

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Lecture 18: Part 2 – Case Study: PV-Powered Water Treatment in Tanzania

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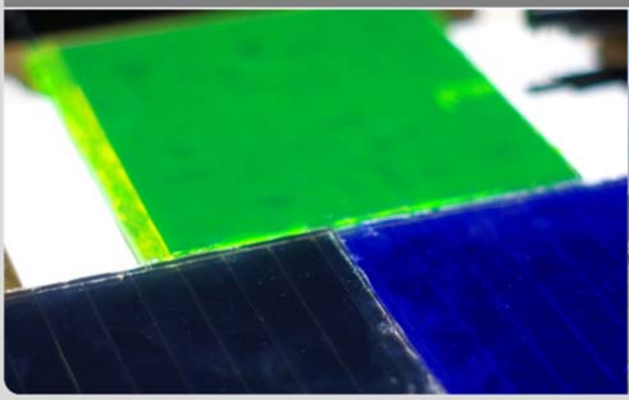


Broader Considerations

Energy-Water Nexus

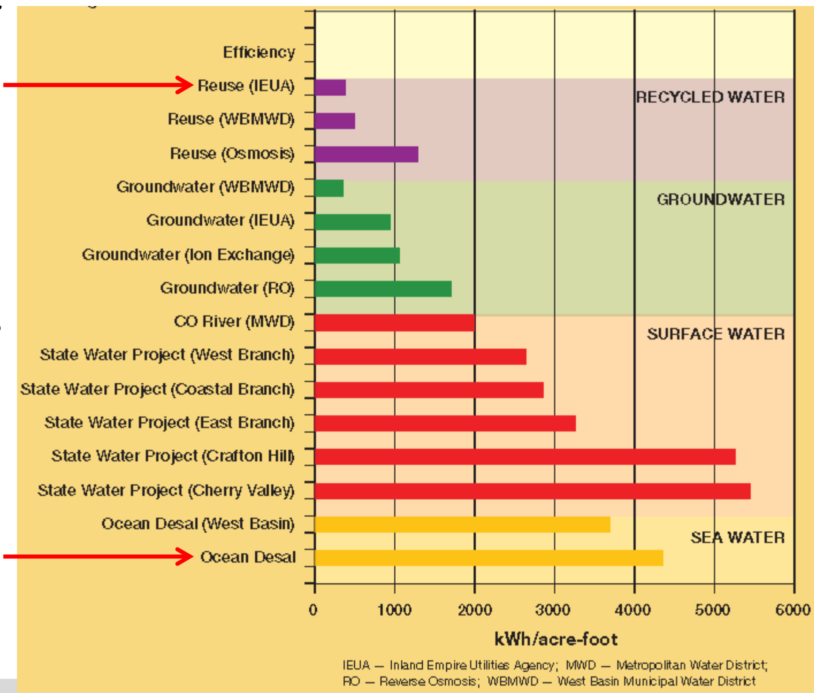
- Interdependence describes how energy is required to supply clean water, while water is needed to supply energy
- Paradox of increased risk of water supplies drying up as climate warms
- But mitigating climate change could mean shifting to more water-intensive alternative energy sources.
- Combined with the ever-increasing need for drinking water from the world’s burgeoning global population
- Water required to produce 1MWh of electricity (average UK household consumption for two months):
    - 38 L for natural gas,
    - 2,100 L for coal,
    - 75,000 L for nuclear,
    - nearly 1,000,000 L for biodiesel!

⇒ PV and wind consume no water during operation

Broader Considerations

Energy-Water Nexus

- Conversely, we can look at the energy intensity of drinking water supply
- Not surprisingly, seawater desalination has the highest value at ~3kWh of energy required to produce 1000 L of drinking water, while recycled water consumes about 10X less

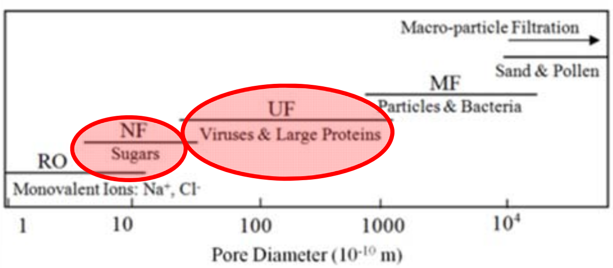


No Clean Water and No Electricity

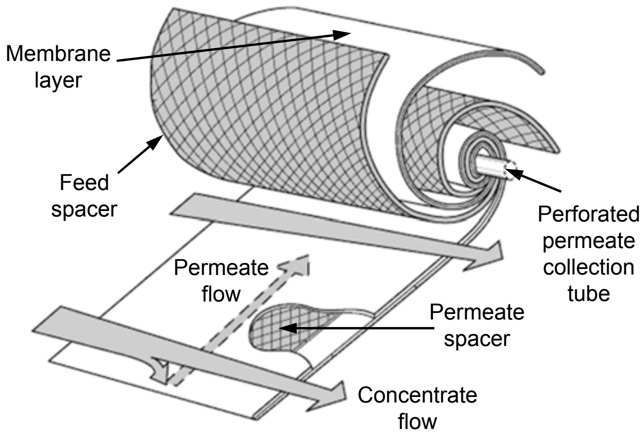
- 1.1b people lack access to clean drinking water
- 3.4m die each year due to water-borne disease
- 1.3b people have no access to electricity
- >95% affected are in Africa or Asia
- 84% in rural areas (not reached by UN MDGs)
- Further problems: dissolved contaminants (e.g. As, F) causing disease, disability and deaths

→ *Solution: development of small-scale decentralised water treatment systems powered by solar and/or wind energy*

Background
Membrane Technology



Commercially available membrane filtration technologies



Spiral wound membrane module construction used in RO and NF

- Treats water via a physical filtering or sieving approach
- Removal of a wide range of contaminants
- Can handle varying feed water quality and quantity
- Minimal requirement for chemicals
- Feed pressure required depends on membrane and feed water

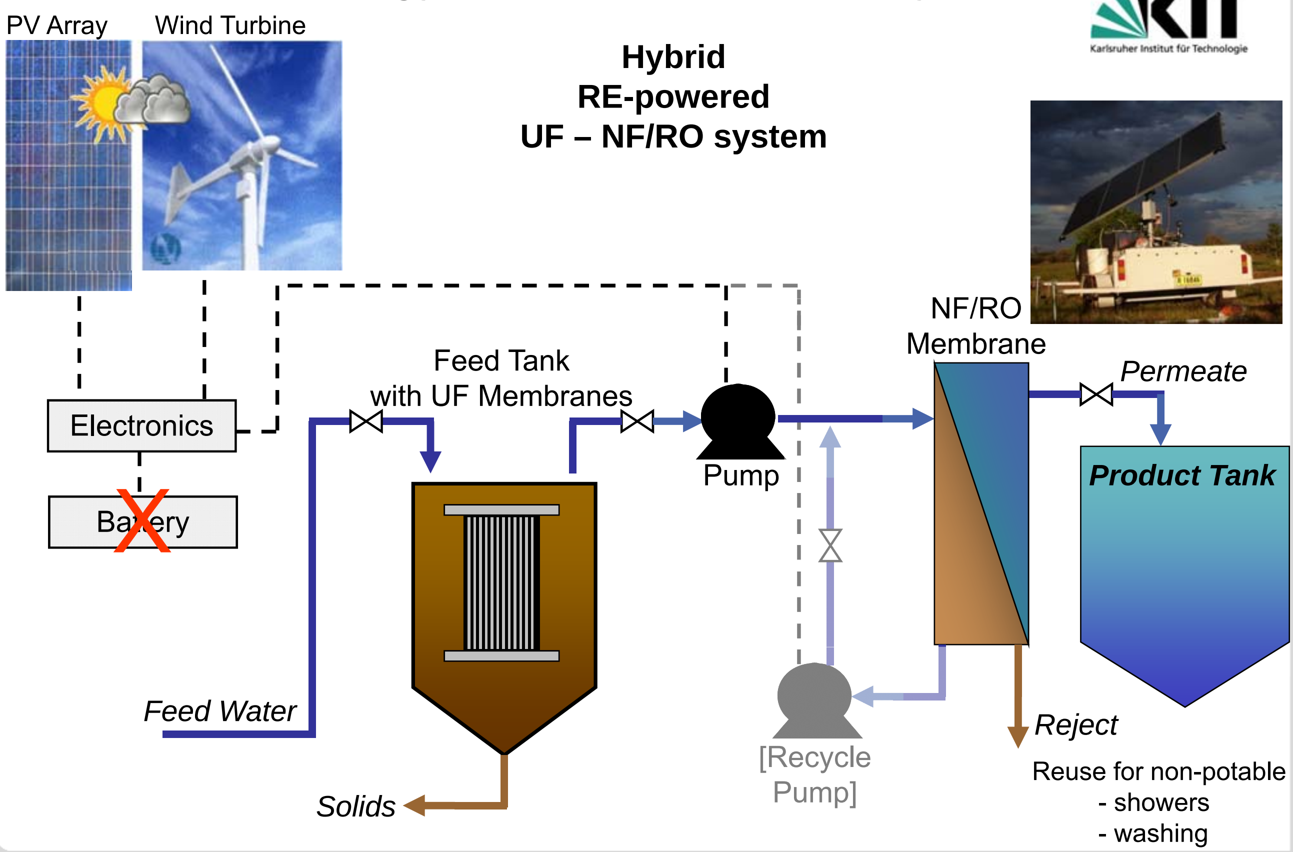
Renewable Energy Powered Membrane Systems

Research Objectives

- Design robust and autonomous membrane systems powered *directly* by renewable energy
- Removal of *dissolved* contaminants in remote locations (current focus brackish water desalination / fluoride / organic matter removal)
- Determine impact of *fluctuating energy* on system performance (specific energy consumption & water quality)

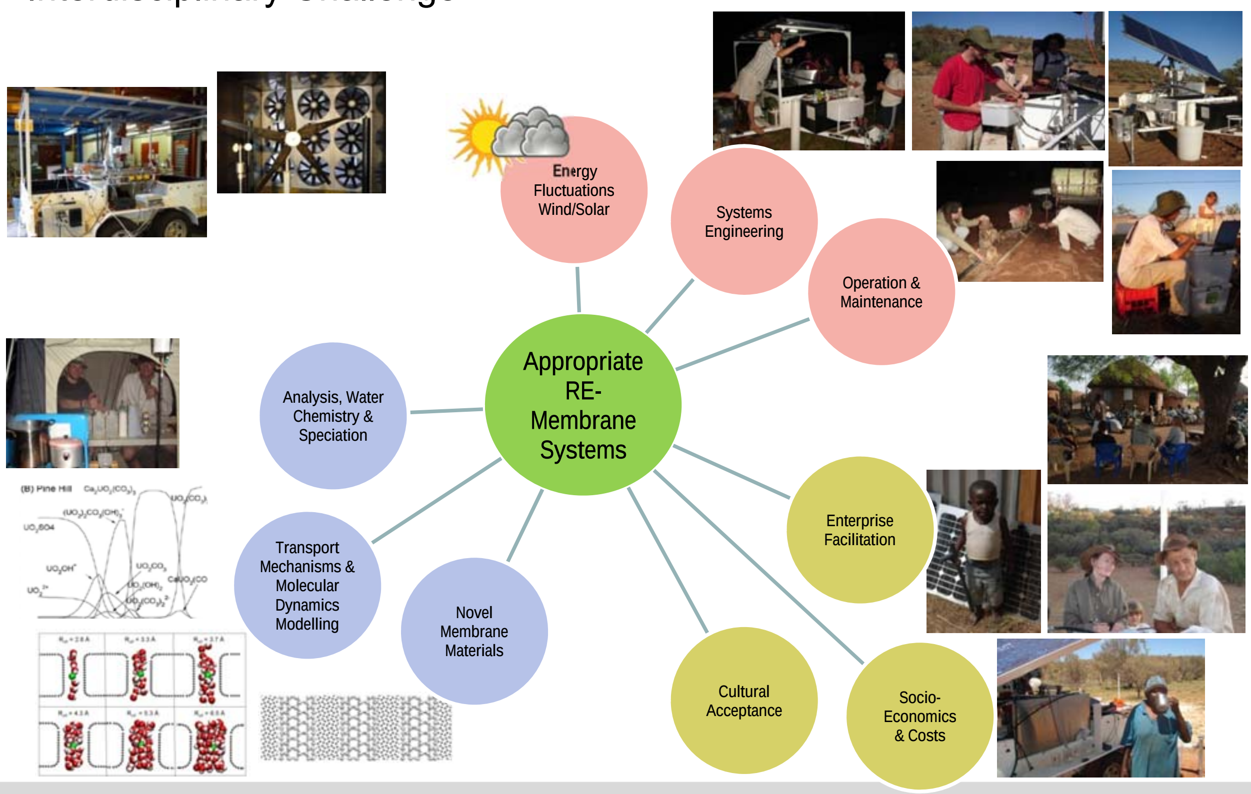
→ *Extensive laboratory and field work (e.g. outback Australia 2005 & Tanzania 2014)*

Renewable Energy Powered Membrane Systems



Renewable Energy Powered Membrane Systems

Interdisciplinary Challenge



Renewable Energy Powered Membrane Systems

Why Leave out Batteries?

- ~80% round trip efficiency for lead acid batteries

  ⇒ requires ~20% larger RE generator
- Perform worse and degrade faster at higher temperatures
- 1500 charge/discharge cycles ⇒ 2 – 5 year life…
- … but PV modules have 20+ year warranty ⇒ need to replace battery bank ≥ 4 times throughout life-cycle of system
- Environmental hazard if not disposed of / recycled in correct manner

No batteries used in powering main pump – only for sensors, datalogger and other R&D monitoring equipment

Renewable Energy Powered Membrane Systems

Energy Fluctuation: Research Questions

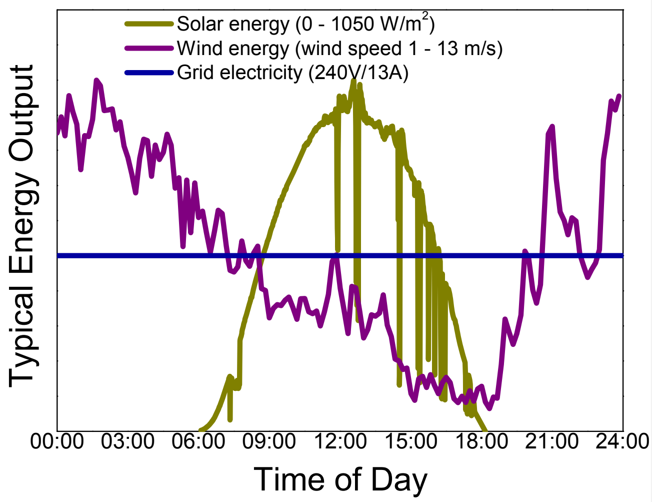
- How do energy fluctuations affect membrane system performance (operating parameters/performance)
- What is the scale of fluctuations of photovoltaics and wind (e.g. frequency, amplitude, down time)
- What energy scenarios are good/bad (e.g. poor water quality, fouling prevention, energy efficiency
- Are fluctuations unhealthy? If so, can these be controlled / buffered?

→ *Synergy between energy research, sensors, robust control systems and membrane technology*

Renewable Energy Powered Membrane Systems

Energy Fluctuation: Highlights

- Fluctuation affects pressure & flowrate (and hence water productivity)
- Fluctuation affects the water quality (no pressure: reduced convection and increased diffusion)
- Supercapacitors are great for short term fluctuations (avoid frequent switching off & increase productivity)
- Long term effects of fluctuation (positive or negative) not yet determined



Energy output from grid, wind & solar energy

Renewable Energy Powered Membrane Systems
Exciting Field Work

- **Australia 2005**
  - Treatment of most difficult brackish groundwaters in outback Australia
  - Socio-economic study of end-users
- **Tanzania 2014**
  - Treatment of ground-and surface waters high in fluoride, inorganic carbon and organic matter
  - Extensive community demonstration

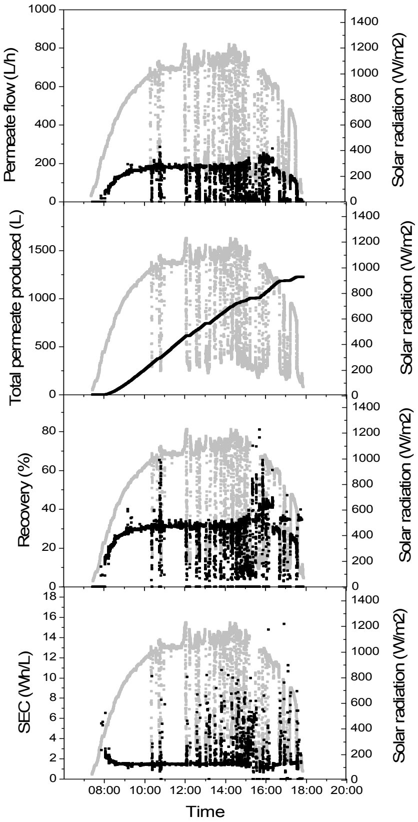
Renewable Energy Powered Membrane Systems
Ultrafiltration Pretreatment of Blackwater

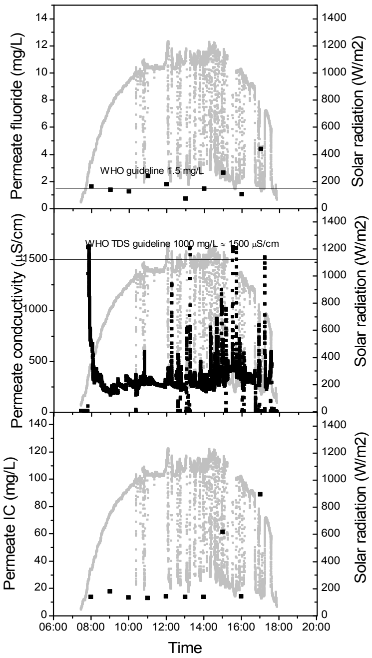
- Extreme amounts of organic matter in water – looks dark brown or nearly black
- Able to remove these organics using ultrafiltration (UF) membrane
- Many local school groups came to visit us and learn about our research
- Some villagers did not want to drink the water as they did not believe what we were doing was possible and therefore we must be doing black magic!

Renewable Energy Powered Membrane Systems

UF-NF/RO in TZ

- Mdori: extreme fluoride concentration of 60 mg/L (40x WHO limit) and highly brackish feed water
- Overall F concentration in tank <1.5 mg/L
- During energy fluctuation concentration increases



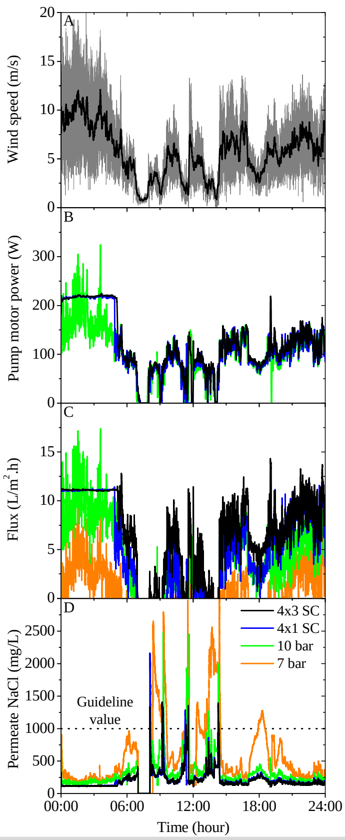


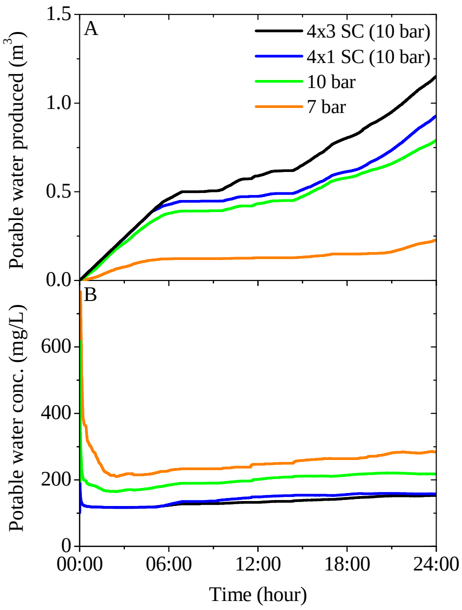
Mdori, Tanzania 28 Feb 2014

Renewable Energy Powered Membrane Systems

Energy Buffering

- Average wind speed of 6 m/s with range from 0 – 20 m/s
- Wind-membrane system shut down at wind speeds ≤ 3 m/s
- Maximum rate of pressure change of ΔP ≤ 0.7 bar/s (within manufacturer's limits for a 'soft' start)
- Large increase in permeate production with supercapacitors
- Produce up to 1.2 m^3 on quite windy day





Cumulative production of the wind-membrane system over 24hrs

Renewable Energy Powered Membrane Systems
Where to from here?

- RE-Membrane Technology is can solve the water problems of remote areas, in particular removal of dissolved contaminants
- A lot of challenges remain to be overcome, e.g.
  - operation & maintenance
  - intelligent control systems
  - ensure system robustness

  ⇒ now needs the implementation of a number of systems for longer term operation
- Next generation membrane materials will provide an entirely new outlook for international development

Now looking for partnership with a company to build such systems in partnership with KIT