"Solar Energy" WS 2021/2022

PV Technology:

Lecture 12: PV System Design

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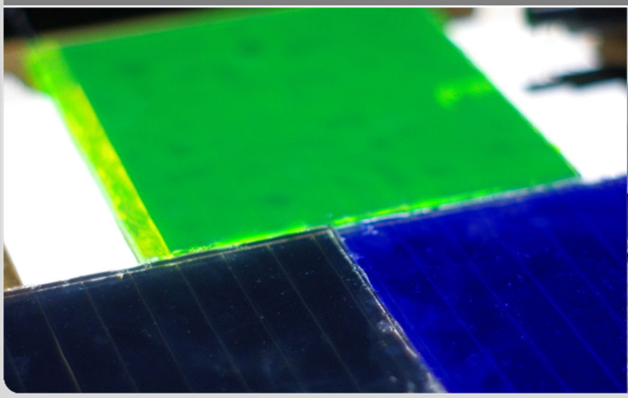
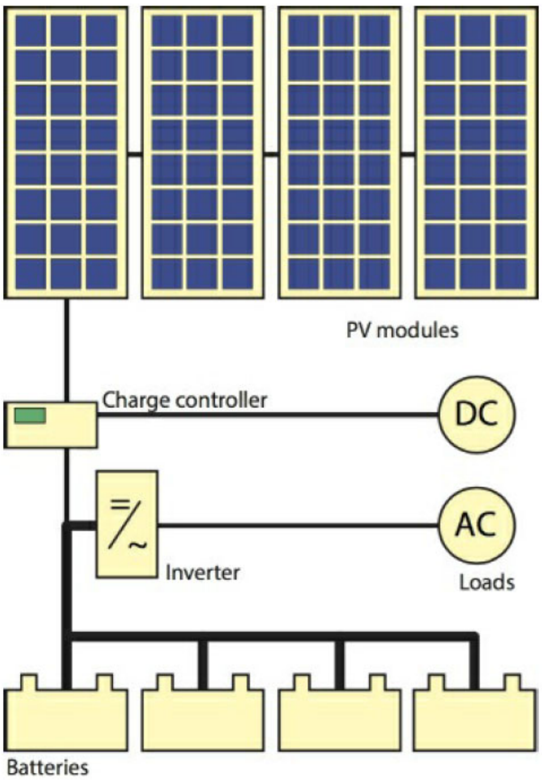


Simple Approach to Sizing PV Systems

- First step to design a simple stand-alone system
- Equipped with:
  - PV panels
  - Batteries
    + charge controller
  - DC loads
  - Inverter & AC loads



Source: textbook

Simple Approach to Sizing PV Systems

- Very simple assumptions – does not take any changes in performance due to weather into account – seven step plan:
  1) Determine total load current and operational time
  2) Add system losses
  3) Determine the solar irradiation in daily equivalent sun hours (ESH)
  4) Determine total solar array current requirements
  5) Determine optimum module arrangement for solar array
  6) Determine battery size for recommended reserve time
  7) Choose a suitable charge controller and inverter

Simple Approach to Sizing PV Systems

1) Determine total load current and operational time

- First decide on the decide on nominal operational voltage of PV system – typical voltages are 12 V, 24 V or 48 V, dominated by availability of batteries
- Next step: express daily energy requirements of loads in terms of current and average operational time in ampere-hours (Ah)
- For the DC loads, daily energy requirement (Wh) is calculated by multiplying the power rating (W) of each appliance by average daily operational time (h)
- Dividing the Wh by nominal PV system operational voltage $\Rightarrow$ obtain required Ah of appliance

Simple Approach to Sizing PV Systems

Example

A 12 V PV system has two DC appliances A and B requiring 15 and 20W respectively. The average operational time per day is 6 hours for device A and 3 hours for device B.

Daily energy requirements of devices expressed (in Ah) are:

Device A: 15W × 6 h = 90Wh

Device B: 20W × 3 h = 60Wh

Total: 90Wh + 60Wh = 150Wh

150Wh/12V = 12.5Ah

Simple Approach to Sizing PV Systems

For AC loads, need to express as a DC energy requirement since PV modules generate DC electricity

DC equivalent of energy use of an AC load ⇒ divide AC load energy use by inverter efficiency ⇒ assumed to be 95% for a good inverter

Example

A computer (device C, 40W, 2h/day) and TV (device D, 70W, 3h/day) are now connected to PV system. Daily energy requirements expressed in DC Ah are then:

Device C: 40W × 2 h = 80Wh D: 70W × 3 h = 210Wh

Total: 80Wh + 210Wh = 290Wh

DC requirement: 290Wh / 0.95 = 305Wh

305Wh/12V = 25.5Ah

Simple Approach to Sizing PV Systems

2) Add system losses

- Some PV system components adds a loss to our system
  - charge regulators require energy to function
  - lead-acid battery has a "round-trip efficiency" of ~85% (energy taken out / energy put in)
- Thus, total energy requirement of loads (from step 1) are now increased by 20 – 30% to compensate

Example

- Total DC requirements of loads plus system losses (20%) are as follows:
- (12.5Ah + 25.5Ah) × 1.2 = 45.6Ah

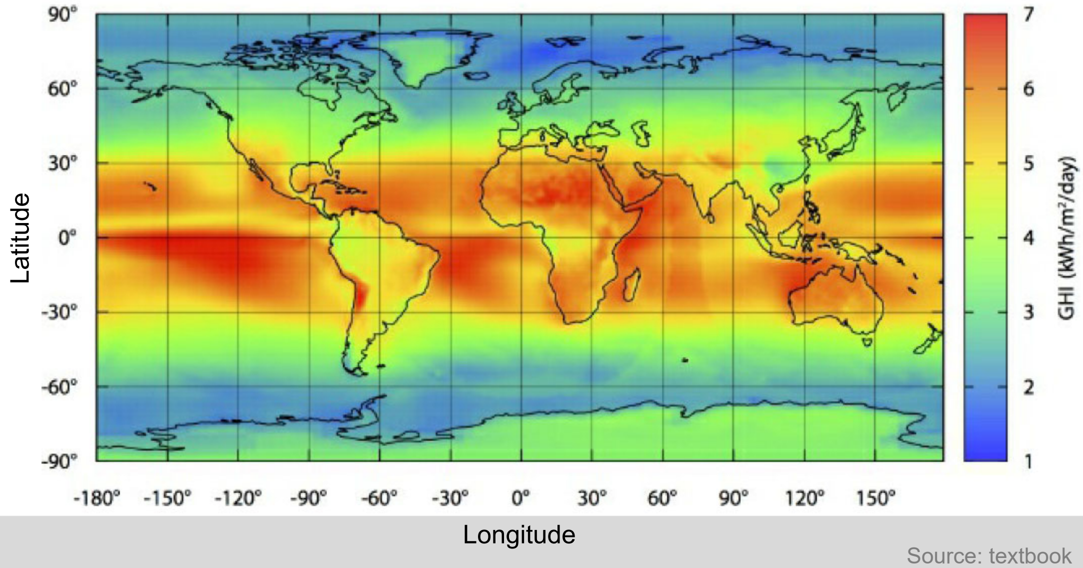
Simple Approach to Sizing PV Systems

3) Determine solar irradiation in daily equivalent sun hours (ESH)

- How much energy a PV module delivers depends on several factors ⇒ local weather conditions, seasonal changes, and installation of modules
- PV modules should be installed under the optimal tilt angle in order to achieve best year-round performance ⇒ if no other knowledge then choose latitude angle of location
- However, if PV system is only used during a specific period ⇒ tilt angle needs to be optimized, e.g. power output during winter is much less than annual average (and summer more)

Simple Approach to Sizing PV Systems

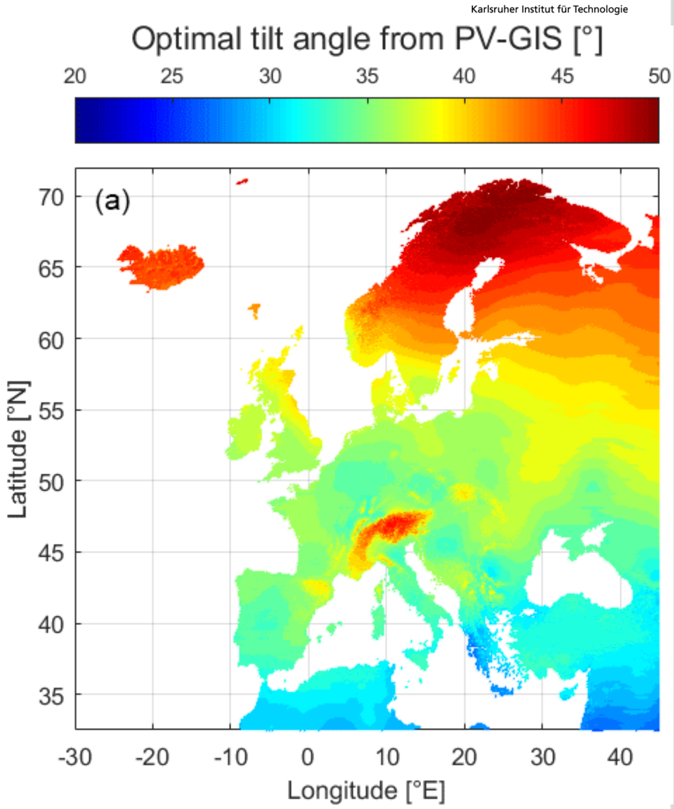
- World map shows average annual global horizontal irradiance (GHI) of the world in $kWh/m^2/day$
  $\Rightarrow$ equivalent to daily equivalent sun hours (ESH)
- Generally, insolation decreases with latitude but other variations are due to regional climates



Source: textbook

Simple Approach to Sizing PV Systems

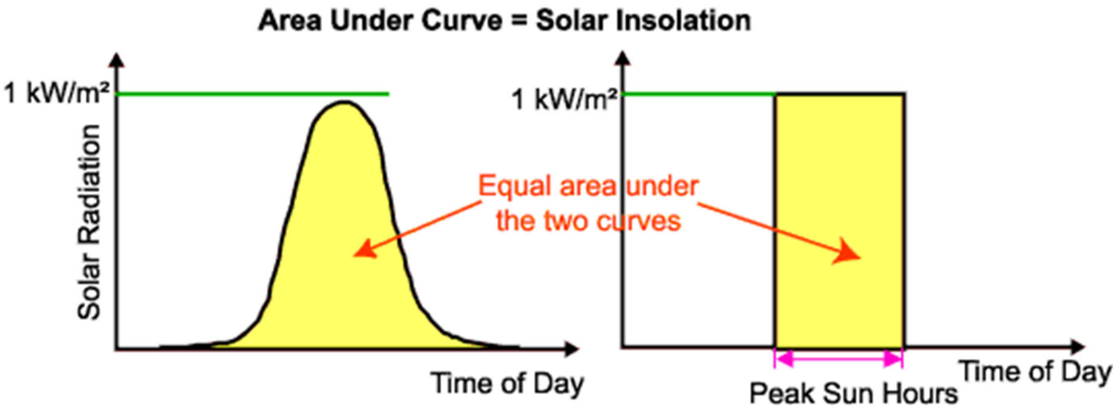
- General trend of increasing optimal tilt angle at higher latitudes observed within EU
- Optimal tilt angle ranges from 30° to 35° in Germany
- But also local effects due to, e.g. the Alps
- Greater cloud cover $\Rightarrow$ lower angle as clouds scatter solar radiation isotropically $\Rightarrow$ move panel closer to horizontal under cloudier skies $\Rightarrow$ harvest more diffuse solar radiation



Source: Adv. Sci. Res. 15 (2018) 51–62

Simple Approach to Sizing PV Systems

- Solar cells are characterized with AM1.5G spectrum $\Rightarrow$ normalized to have a total irradiance of 1,000 W/m^2
- “1 equivalent sun” = solar irradiance of 1,000 W/m^2
- ESH – sometimes referred to as "peak sun hours“ $\equiv$ solar insolation that a particular location would receive if the sun were shining at its maximum value for a certain number of hours

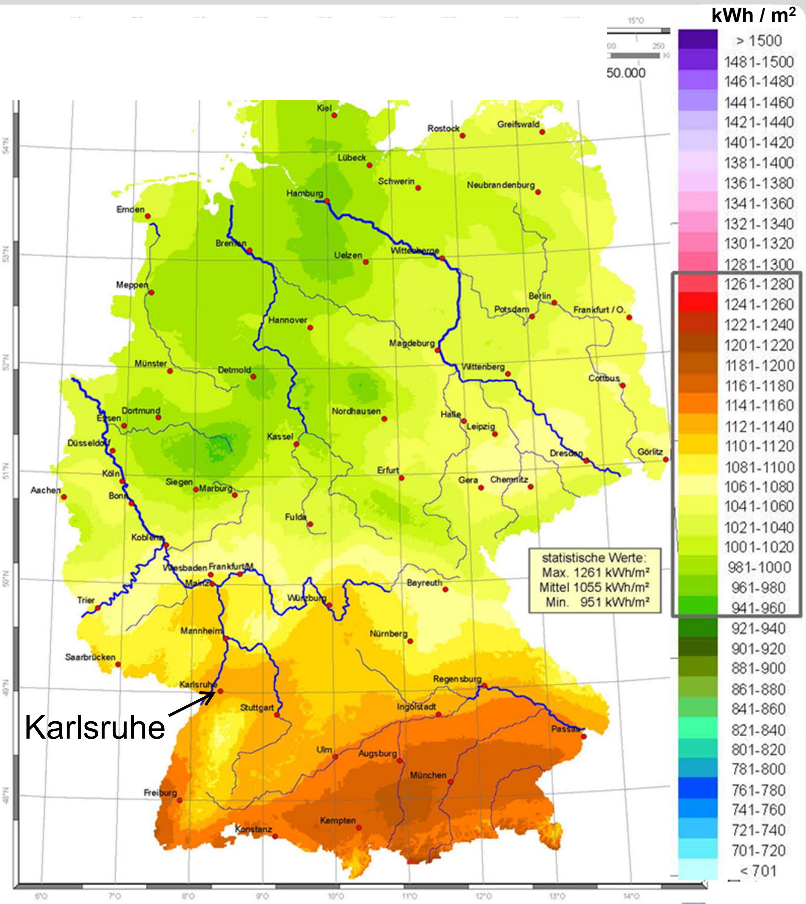


Source: https://www.pveducation.org/pvcdrom/properties-of-sunlight/average-solar-radiation

Simple Approach to Sizing PV Systems

Average annual solar irradiance map for Germany (1981 - 2010)

Average of ~1100 kWh / m^2 per year on a <u>horizontal</u> surface



Source: German Weather Service https://www.dwd.de/DE/leistungen/solarenergie/lstrahlungskarten_mi.html?nn=16102

Simple Approach to Sizing PV Systems

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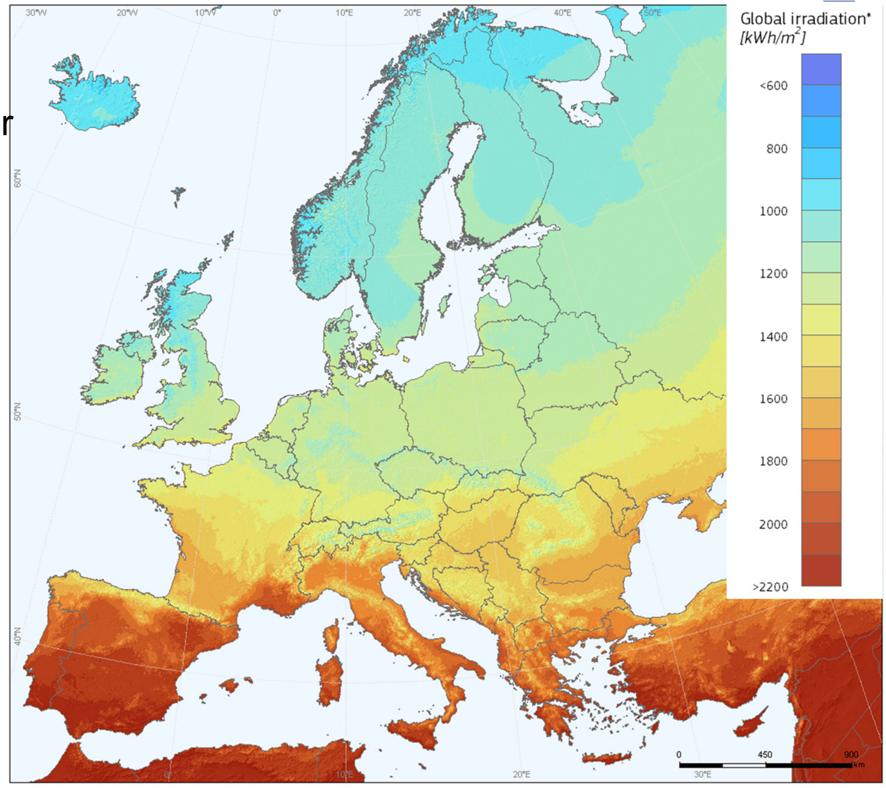
Average solar irradiance of ~1300 kWh/m^2 per year at <u>optimal tilt angle</u>

Dividing by 365.25 days per year = 3.56 kWh / m^2 per day = 3.5 ESH per day



Source: http://re.jrc.ec.europa.eu/pvgis/cmaps/eur.htm

Simple Approach to Sizing PV Systems

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4) <u>Determine the total solar array current requirements</u>

- Current to be generated by PV array determined by dividing total DC energy requirement (calculated in step 2 and expressed in Ah) by the daily ESH (step 3)

Example

- Total DC requirements of loads (incl. system losses) = 45.6Ah. The daily ESH for Germany is ~3.5 hours
- Thus, required total current generated by the solar array is 45.6Ah / 3.5 h = 13.0A

Simple Approach to Sizing PV Systems

5) Determine optimum module arrangement for solar array

- Ideally, required total solar array current (step 4) is obtained with minimum number of modules
- Output voltage of PV modules should match battery voltage
- c-Si PV modules typically contain 36 or 72 cells connected in series for systems based on 12 V or 24 V, respectively ⇒ V_{oc} = 21.6 V or 43.2 V, respectively ⇒ V_{mp} ~18 V or ~36 V, respectively
- Number of modules in parallel is calculated by dividing the total current required from the solar array (step 4) by the current generated by the module at maximum power

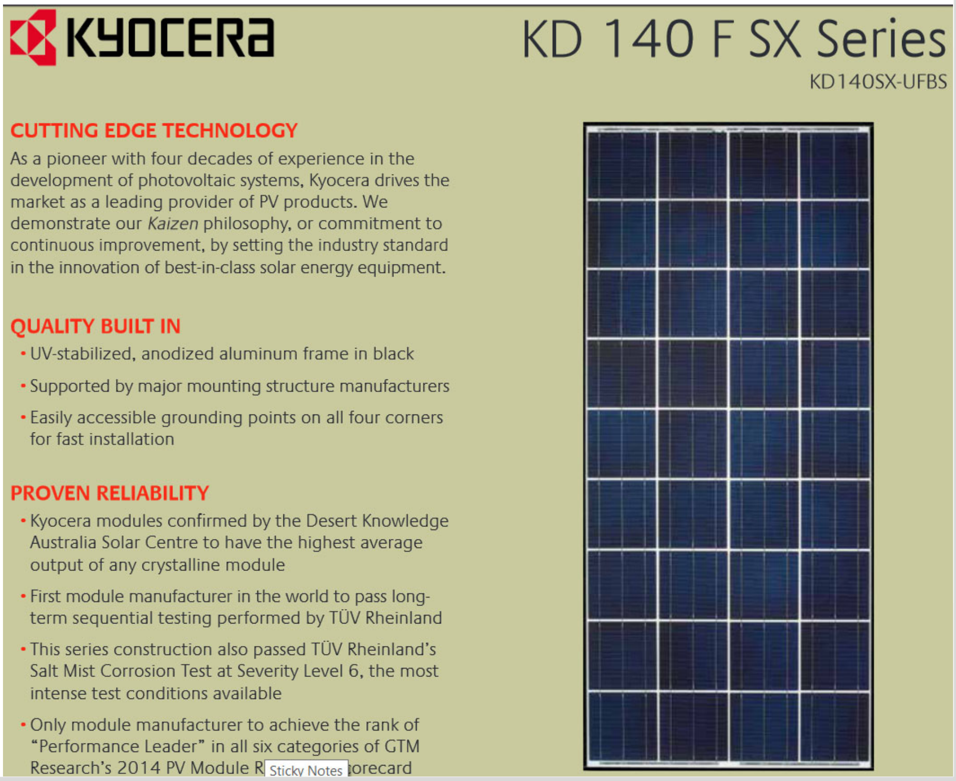
Simple Approach to Sizing PV Systems

- Number of modules in series is determined by dividing the nominal PV system voltage with voltage at maximum power
- Both voltage and current are given in datasheet
- Total number of modules = (# series) x (# parallel)

Example

- Required total current generated by PV array is 13.0 A
- Using Kyocera KD140 modules (nominal power of 140 W, 36 cells connected in series): V_{mp} = 17.7 V and I_{mp} = 7.9 A
- # modules in parallel is 13.0 A / 7.9 A = 1.6 ⇒ 2 modules
- # modules in series is 12 V / 17.7 V = 0.67 ⇒ 1 module
- Total # modules in PV array = 2 × 1 = 2 modules

Simple Approach to Sizing PV Systems



KYOCERA

KD 140 F SX Series

KD140SX-UFBS

CUTTING EDGE TECHNOLOGY

As a pioneer with four decades of experience in the development of photovoltaic systems, Kyocera drives the market as a leading provider of PV products. We demonstrate our *Kaizen* philosophy, or commitment to continuous improvement, by setting the industry standard in the innovation of best-in-class solar energy equipment.

QUALITY BUILT IN

- UV-stabilized, anodized aluminum frame in black
- Supported by major mounting structure manufacturers
- Easily accessible grounding points on all four corners for fast installation

PROVEN RELIABILITY

- Kyocera modules confirmed by the Desert Knowledge Australia Solar Centre to have the highest average output of any crystalline module
- First module manufacturer in the world to pass long-term sequential testing performed by TÜV Rheinland
- This series construction also passed TÜV Rheinland's Salt Mist Corrosion Test at Severity Level 6, the most intense test conditions available
- Only module manufacturer to achieve the rank of "Performance Leader" in all six categories of GTM Research's 2014 PV Module R Sticky Notes orecard

Source: www.enfsolar.com/pv/panel-datasheet/crystalline/25974

Simple Approach to Sizing PV Systems

6) Determine battery size for recommended reserve time

- For safe operation of PV system, need to anticipate periods of cloudy weather and plan a reserve energy capacity stored in the batteries ⇒ referred to as number of days of autonomy
- Value depends on how critical load is, e.g.
  Lighthouse 15 days
  Telecommunications system 10 days
  Residential system 5 days
- The capacity (Ah) of batteries is calculated by multiplying the daily total DC energy requirement of PV system (step 2) by the number of days of autonomy

Simple Approach to Sizing PV Systems

- To prolong life of the batteries (e.g. lead-acid)
  ⇒ recommended that battery is discharged 70% <u>maximum</u>, i.e. 70% depth-of-discharge (DoD) ⇒ 50% even better
- Reduced DoD ⇒ prolongs battery lifetime ⇒ obviously makes system more expensive

Simple Approach to Sizing PV Systems

Example

- Recommended number of days of autonomy for a residential house in Germany is 5 days
  ⇒ battery capacity required by the system is
  45.6 Ah × 5 = 228 Ah
- Correcting for max 70% DoD:
  ⇒ 228 Ah / 0.7 = 325 Ah

Options:

- Sonnenschein A600 Solar Gel (2V, 370Ah)
  ⇒ need 6 in series
- Sonnenschein Solar Block Gel (12V, 100Ah) ⇒ need 3 in parallel

Source: https://www.solar-wind.co.uk/2v-6v-12v-deep-cycle-solar-batteries-gel-agm-lead-carbon-opzv/

Simple Approach to Sizing PV Systems

7) Choosing a charge controller and inverter

- Charge controller will see a maximum current of 7.9A x 2 = 15.8 A
- Round up to 20A

Source: https://www.fraron.de/en/solar-cells-solar-accessories/mppt-solar-charge-controller-20a-for-12v-24v-battery-systems-max-pv-voltage-100v-with-internal-bluetooth/a-85888781/

Simple Approach to Sizing PV Systems

- For off-grid installations, inverter sizing is critical ⇒ must be sized to meet the full load (demand) under all conditions
- Worst case is when all devices are running at once:

Device A:	15W
Device B:	20W
Device C:	40W / 0.95 = 42W
Device D:	70W / 0.95 = 74W
Total:	151W

Assumed inverter η = 95%

- Rounding up ⇒ 200W continuous power
- Good to allow for more power ⇒ enables future expansion of system,
  e.g. small DC fridge consumes ~100W (non-continuous)

Source:

Simple Approach to Sizing PV Systems

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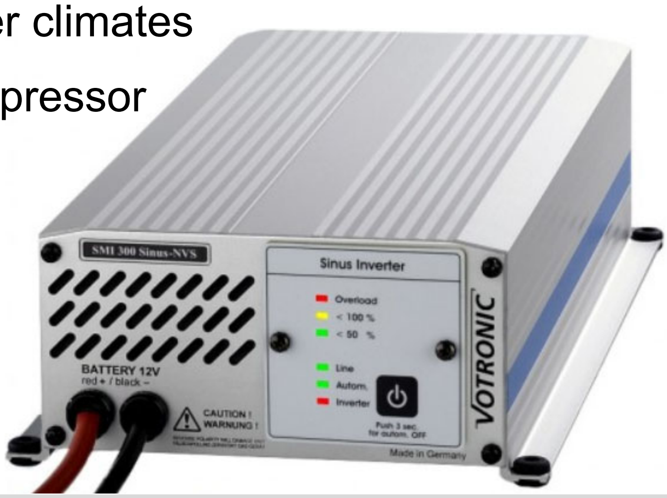
- Choose an inverter that can supply 300 W continuous
  ⇒ able to supply 600 W (for a few minutes)
- N.B. inverter output is derated (reduced) at higher ambient temperatures, e.g. a 1000 W inverter rated at 20°C may only output a continuous power of 800 W at 40°C ⇒ take into account especially in warmer climates
- If the load is a motor or compressor
  ⇒ large start-up currents
  ⇒ inverter size should be minimum 3x the capacity of those appliances (first 3-6 seconds)



Source: https://www.offgridtec.com/en/electronics/voltage-inverters/12v-to-230v-inverters/votronic-3156-mobilpower-smi-300-sinus-nvs-12v-230v-spannungswandler.html

Simple Approach to Sizing PV Systems

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- In the simplified approach here, the following factors were ignored/assumed:
  - Real load profiles
  - Temperature effects in PV modules
  - Ideal orientation of PV modules

Source:

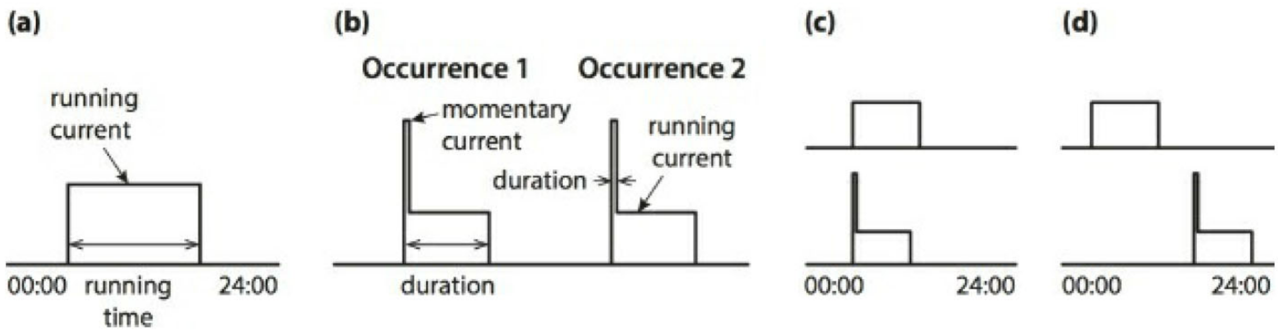
Load Profiles

a) One simple load draws constant power for certain time

b) Now the consumed power does not remain constant ⇒ peaks correspond to switching electrical appliances on/off

c) A household has several different loads that can be switched on at the same time (coincident) or….

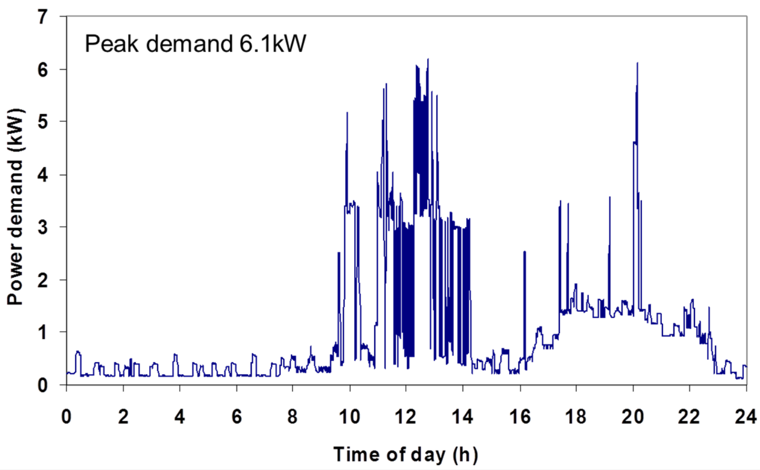
d) … at different times (non-coincident)



Source: textbook

Load Profiles

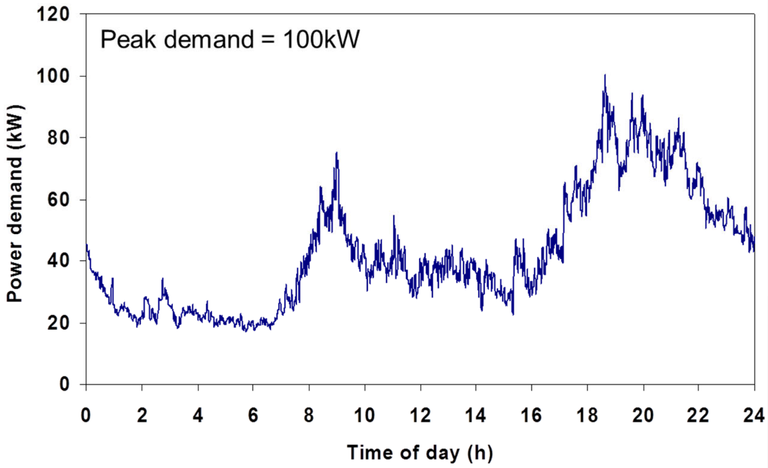
- Simplest analysis of load profiles ⇒ determine loads over a 24-hour basis using an arbitrary day
- But do not forget about:
  1) Loads that do not fit in a 24-hour scheme because they are not used every day, e.g. washing machines
  2) Seasonal loads, e.g. air conditioning or a heat pump
- A real residential load profile can be quite complex!



Source: Dr. David Jenkins, Heriot-Watt University, U.K.

Load Profiles

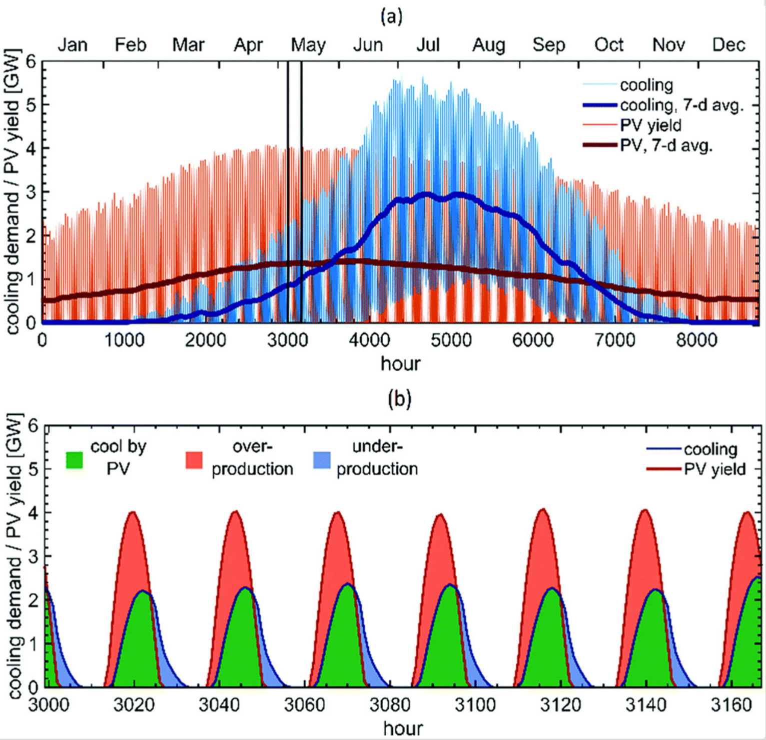
- Note, from a large-scale electricity supply point-of-view, situation gets better once the loads of 50 houses are combined ⇒ load is less “peaky”



Source: Dr. David Jenkins, Heriot-Watt University, U.K.

Load Profiles

- Best case, consumption of load matches generation of PV electricity
- E.g. using PV to power air-conditioning loads in Phoenix, AZ (USA)



Source: Energy Environ. Sci., 2019, 12, 2706-2716

Temperature issues in PV systems

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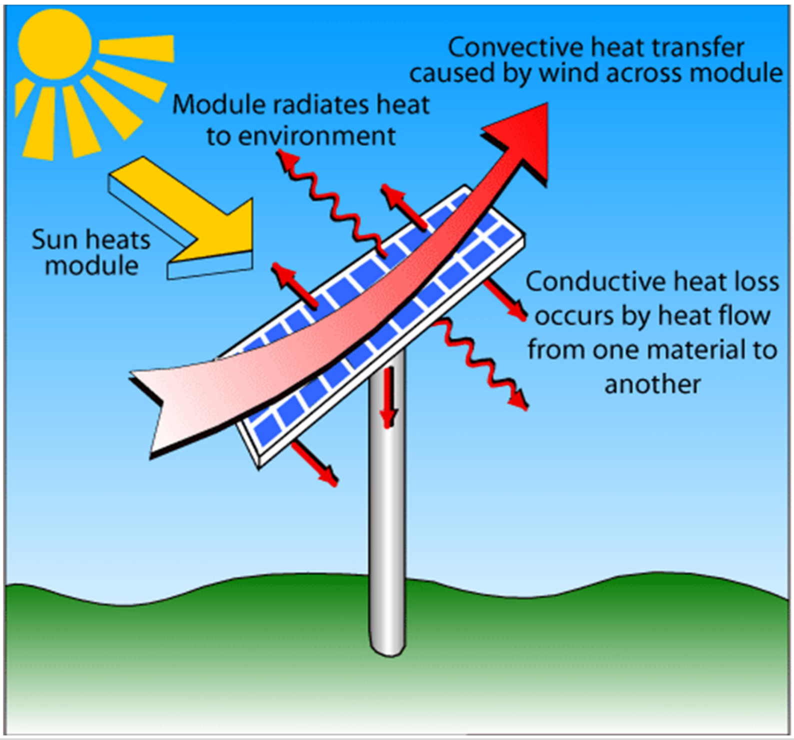
- Three main mechanisms of heat loss from PV module:
  i) conduction,
  ii) convection, and
  iii) radiation

- Remember: temperature strongly influences PV module performance



Source: http://pveducation.org/pvcdrom/modules/heat-loss-in-pv-modules

Temperature issues in PV systems

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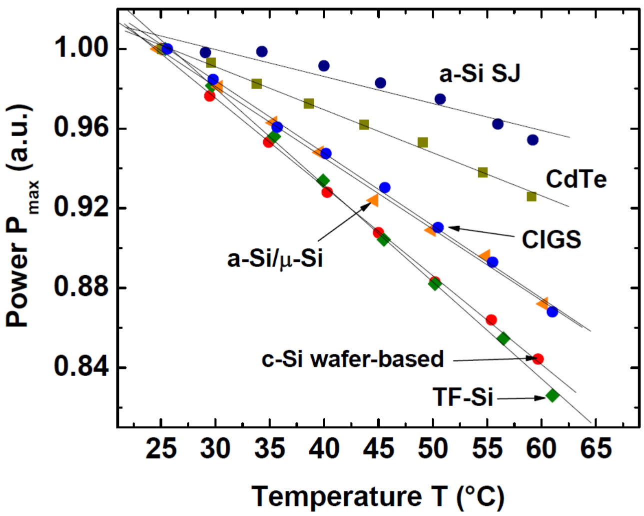
- Effect on P_{max} (and efficiency):
- Overall, c-Si wafer based PV modules suffer the most at higher temperatures (-0.45% rel. loss in power per °C increase in T) and CdTe the least

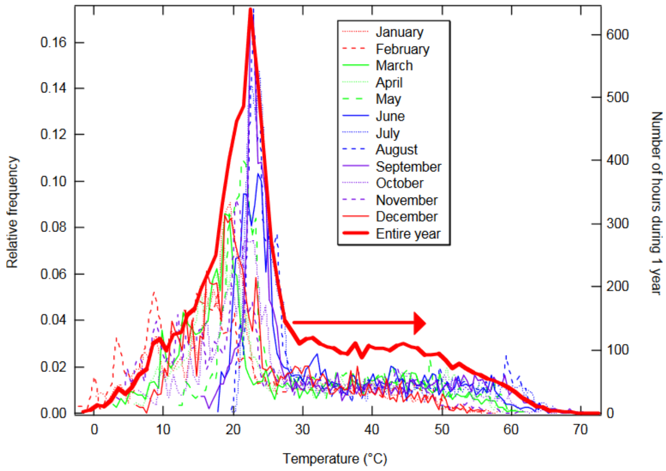
	Pmax γ_{rel} (%/°C)	Voc β_{rel} (%/°C)	Isc α_{rel} (%/°C)	FF κ_{rel} (%/°C)
Error	± 0.027	±0.021	±0.019	-
a-Si (SJ)	-0.13	-0.33	+ 0.12	+ 0.10
CdTe	-0.21	-0.24	+ 0.04	- 0.01
Microm. (a-Si/μcSi)	-0.36	-0.37	+ 0.05	- 0.04
CIGS	-0.36	-0.31	+ 0.02	- 0.08
c-Si wafer-based	-0.45	-0.33	+ 0.06	- 0.19
TF - Si	-0.48	-0.41	+ 0.15	- 0.22

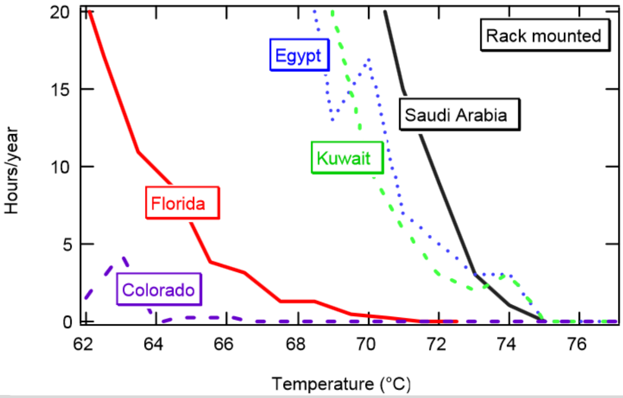


Source: Virtuani et al. "Overview of temperature coefficients of different thin film photovoltaic technologies." In *25th European photovoltaic solar energy conference and exhibition/5th World conference on photovoltaic energy conversion*, pp. 6-10. 2010.

Temperature issues in PV systems

- Top graph: measured temperatures of c-Si PV modules (rear side of PV module) in Florida





- Bottom graph: measured module temperatures (rear side of PV module) at different locations
- *N.B. not cell temperature!*

Source: Kurtz et al. (NREL) - http://www.nrel.gov/docs/fy09osti/45986.pdf
https://www.mbcontrol.com/pv-module-temperature-sensor/

Temperature issues in PV systems

- The 25°C cell operating temperature (as per STC) rarely occurs
- Hard to measure actual operating temperature of a solar cell inside PV module
- To estimate effects of temperature, PV manufacturers often specify the “nominal operating cell temperature” (NOCT)
- More realistic value of cell temperature in module (T_M) under an irradiance (G_M) of 800 W/m^2, ambient temperature (T_a) of 20 °C, and a wind speed of 1 m/s
- Determined empirically via:

$$T_M = T_a + \frac{T_{NOCT} - 20°}{800} G_M$$

Temperature issues in PV systems

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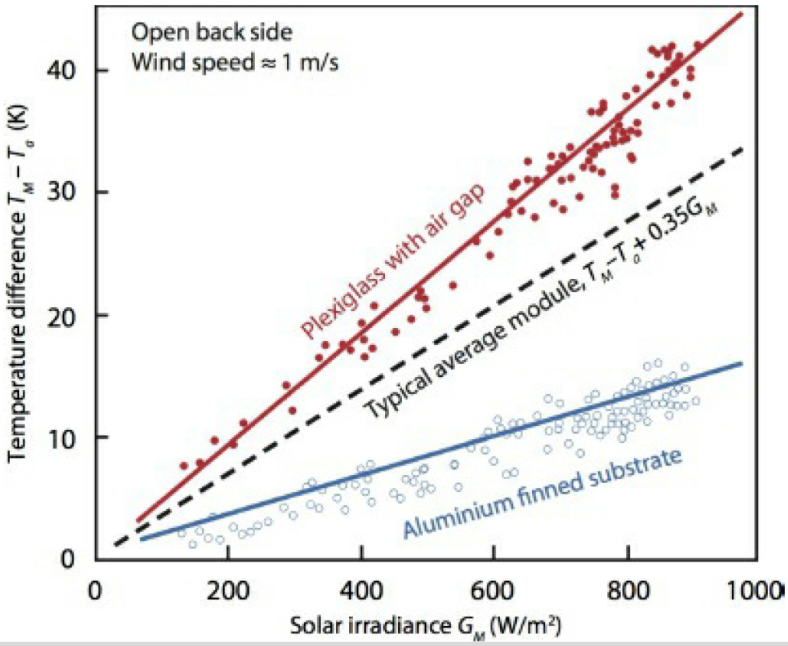
- Model is based on experimental observations showing a linear relationship between ($T_M - T_a$) and G_M
- Based on very old data from early 1980s from NASA
- Worst case: extra plexiglass cover $\Rightarrow$ added insulation
- Best case: aluminium heatsink with fins on rear side of module $\Rightarrow$ assists with heat loss



Source: textbook

Temperature issues in PV systems

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- E.g. quoted NOCT for Kyocera module is 45°C
- At NOCT, this 140W STC-rated module now has **P_{max} = 101 W** (more realistic estimate for real world usage)

ELECTRICAL SPECIFICATIONS

Standard Test Conditions (STC) *STC=1000 W/M² irradiance, 25°C module temperature, AM 1.5 spectrum**		
	KD140SX-UFBS	
P_{max}	140	W
V_{mp}	17.7	V
I_{mp}	7.91	A
V_{oc}	22.1	V
I_{sc}	8.68	A
$P_{tolerance}$	+7/-0	%

Nominal Operating Cell Temperature Conditions (NOCT) *NOCT=800 W/M² irradiance, 20°C ambient temperature, AM 1.5 spectrum**		
T_{NOCT}	45	°C
P_{max}	101	W
V_{mp}	16.0	V
I_{mp}	6.33	A
V_{oc}	20.2	V
I_{sc}	7.03	A

Temperature Coefficients		
P_{max}	-0.46	%/°C
V_{mp}	-0.52	%/°C
I_{mp}	0.0066	%/°C
V_{oc}	-0.36	%/°C
I_{sc}	0.06	%/°C
Operating Temp	-40 to +90	°C

Source: www.enfsolar.com/pv/panel-datasheet/crystalline/25974

Temperature issues in PV systems

Mounting:

- Rack-mounted panels run typically 3°C cooler than NOCT

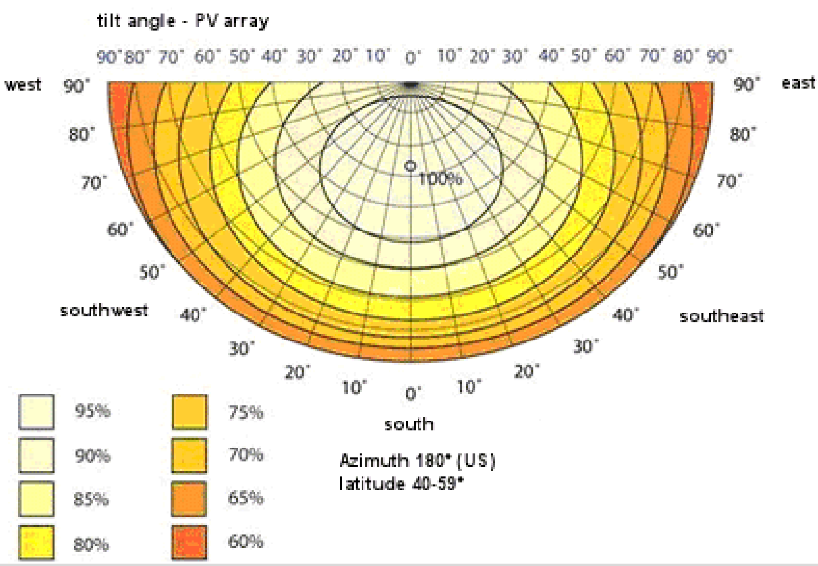
- Directly-mounted panels (e.g. directly on roof with no air gap) typically 11°C hotter than NOCT

Source: https://tatabluescopesteel.com/products-solutions/lysaght/ilios-solar-mounting-system-solutions/
https://nakedsolar.co.uk/solar-pv/solar-panel-mounting/

Orientation of PV modules

- PV modules are not always installed:
  - at optimal tilt angle
  - facing directly south

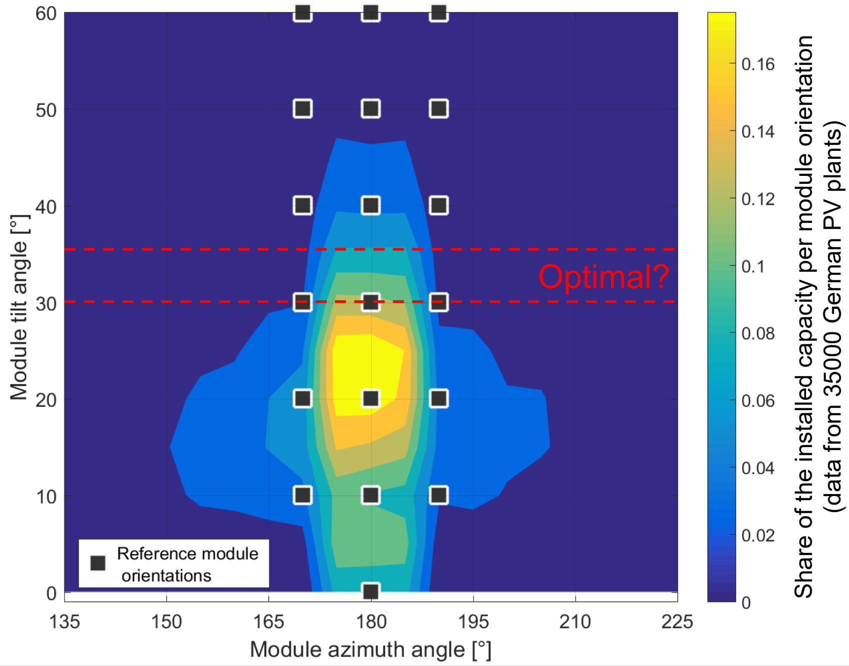
- However, very good performance (>80%) still achieved even for some east- and west-oriented PV systems



Source: http://www.renewable-energy-concepts.com/solarenergy/solar-basics/tilt-angle-pv-array.html

Orientation of PV modules

- E.g. analysis of 35000 German PV systems (2% of total) shows that many modules tilted at ~20-25°, which is much flatter than would normally be anticipated
- Possibly because this was simply the roof angle of the house
- Can be uneconomic to alter this, plus also unaesthetic



Source: Adv. Sci. Res. 15 (2018) 51–62

Examples of PV Systems

- 5.3kW grid connected PV system (Boston, USA)

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

- Building integrated photovoltaic (BIPV) balcony (Helsinki, Finland)

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

- Community owned solar- and wind-farm (Westmill, England)

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

- Photovoltaic power station at Mt. Komekura (Japan)

Source: *http://en.wikipedia.org/wiki/Photovoltaic_system*

Examples of PV Systems

- Solar array at National Solar Energy Center (Negev Desert, Israel)

Source: *http://en.wikipedia.org/wiki/Photovoltaic_system*

Examples of PV Systems

- ~30-year old, ground mounted PV system on a island in north Germany

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

- An isolated mountain hut in Catalonia (Spain)

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

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- A farming village in Germany (solar thermal and PV)

Source: https://insideclimatenews.org/news/20121113/germany-energiewende-clean-energy-economy-renewables-solar-wind-biomass-nuclear-renewable-energy-transformation

Examples of PV Systems

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- The Japanese winner of 2009 World Solar Challenge (Australia) – 3022km

Source: http://en.wikipedia.org/wiki/Photovoltaic_system ; https://www.worldsolarchallenge.org/event-information/route_map

Examples of PV Systems

- Photovoltaic powered water pumping system for stock watering (India)

Source: http://regentsolar.com/swp.html

Examples of PV Systems

- Small hybrid wind-PV system on a yacht

Source: http://www.micamalecharter.com/barca_en.html

Examples of PV Systems

- Early electric vehicle charging station (France)

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

- A solar-powered community satellite phone in Western Australia

Source: blog.activ8me.net.au

Examples of PV Systems

- Solar powered electric fence in Northumberland (U.K.)

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

- “Solar Sailor” passenger ferry in Darling Harbour (Sydney, Aust.)

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

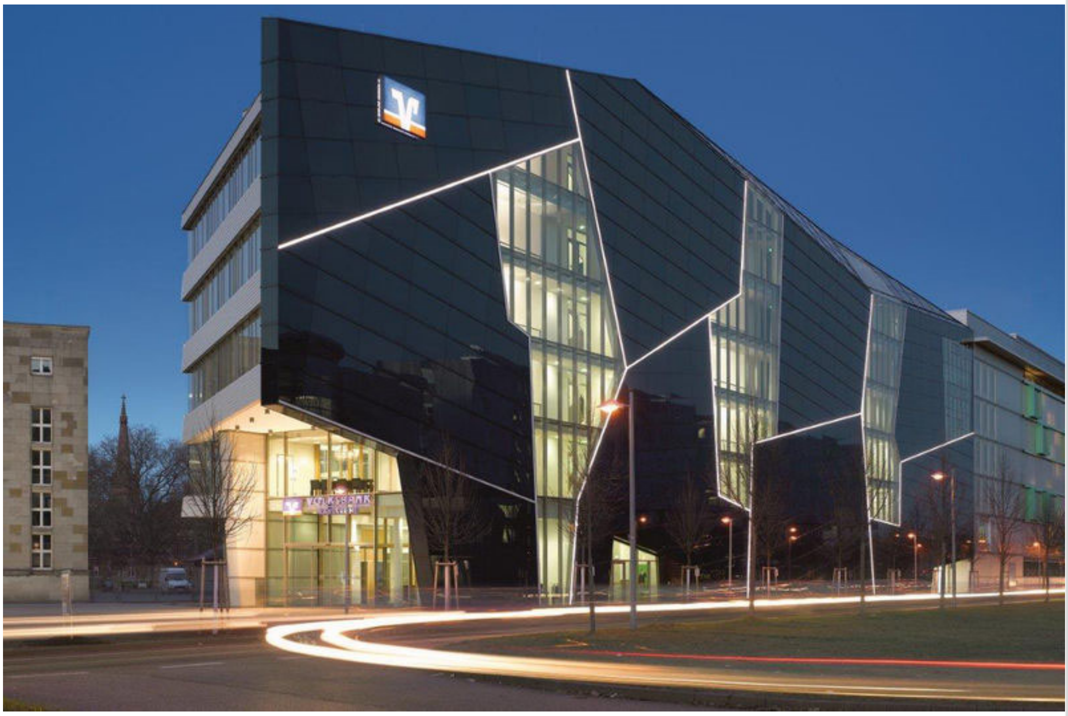
Examples of PV Systems

- Solar power for a yurt (Mongolia)

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

- Volksbank Karlsruhe, zero energy building (ZEB)



Source: https://www.schwarzwald-tourismus.info/Media/Attraktionen/Volksbank-Karlsruhe-eG

Examples of PV Systems

- 17MW O’MEGA 1 floating PV plant (Vaucluse, France)

Source: https://www.nsenergybusiness.com/news/trina-solar-supplies-17mw-modules-to-omega-1-floating-pv-plant/

Examples of PV Systems

- 46MW solar farm in Amareleja (Portugal) with 2-axis solar trackers
- Was largest in world in 2008

Source: http://www.solarserver.de/solarmagazin/newsa2009m01.html#news9993
https://www.acciona.com.au/projects/energy/solar-photovoltaic/amareleja-solar-park/

Examples of PV Systems

Karlsruher Institut für Technologie

- 35MW 2-axis tracked solar farm in Alamosa (Colorado, USA) ⇒ sunlight concentrated using Fresnel lenses

Source: http://en.wikipedia.org/wiki/Photovoltaic_system

Examples of PV Systems

Karlsruher Institut für Technologie

- The future of flight? Solar-powered plane – first circumnavigation of Earth in 2016 (Solar Impulse 2)…

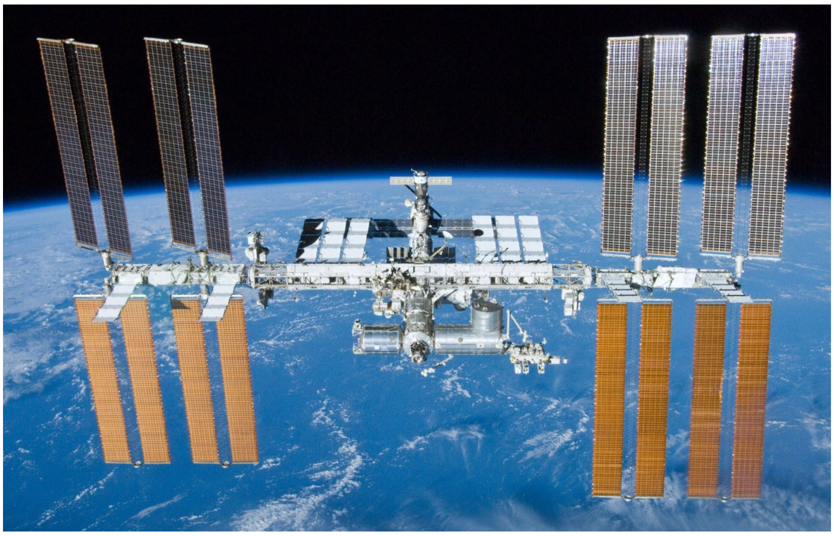
Source: http://www.powerclouds.com/index.php/photovoltaics-that-make-you-fly-the-solar-impulse-venture/

Examples of PV Systems

- … 1-2 pilots, wingspan similar to Airbus A340 (63m,~350 people)!

Source: http://www.aerospace-technology.com/projects/solar-impluse/solar-impluse2.html

Examples of PV Systems



262,400 solar cells power the International Space Station, which orbits the earth at 4.76 miles/s. The solar arrays cover more than half a football field, and can generate **120 kW** of power. While in sunlight, the station diverts 60% of the electricity generated to the **batteries, which must support the station while its not in view of the sun ⇒ super-critical load!!**

Source: https://electrek.co/2018/01/29/10-really-cool-solar-power-installations/

Topaz Solar Farm

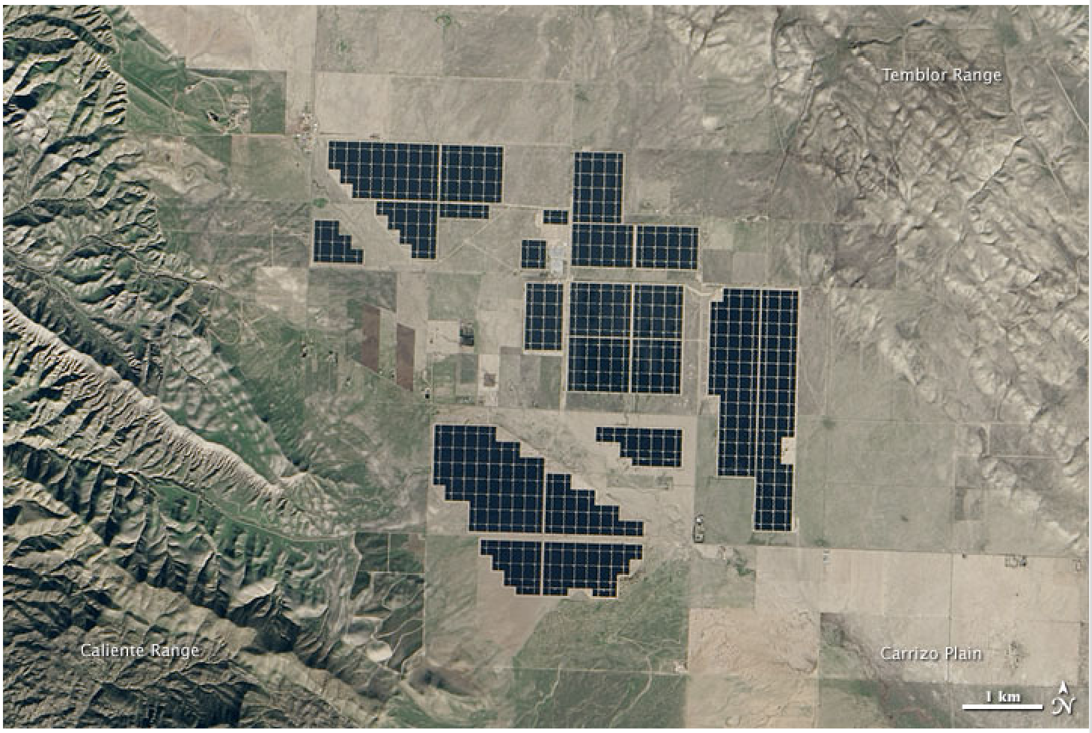
- Topaz Solar Farm is a 550MW PV power station in California (USA)
- Construction began Nov 2011, ended in Nov 2014
- U$2.5 billion project
- 25 km^2 area
- 9 million CdTe PV modules from First Solar
- 400 construction jobs created
- Annual generation is expected to be 1,096 GWh
- A utility (Pacific Gas and Electric) have 25 year contract to buy the electricity

Location of Topaz Solar Farm

Country	United States
Location	Carrizo Plain, San Luis Obispo County, California
Coordinates	35°23′N 120°4′W
Status	Operational
Construction began	2011
Commission date	2014
Owner(s)	MidAmerican Renewables
Solar farm	
Type	Flat-panel PV
Site area	9.5 sq mi (25 km^2)
Power generation	
Nameplate capacity	550 MW_p
Annual generation	1,096 GWh (125 MW avg)
Website	topazsolar.com

Source: http://en.wikipedia.org/wiki/Topaz_Solar_Farm

Topaz Solar Farm



Source: https://en.wikipedia.org/wiki/List_of_photovoltaic_power_stations

Topaz Solar Farm

Was world's largest in 2014
*(now small c.f. 2.7GW Bhadla
Solar Park, India ⇒ US 3.2¢ per kWh)*

Source: http://papichco.com/construction/project/topaz-solar-farm/

World's cutest PV system?

Panda Green Energy PV Park (50 MW) - to raise awareness about sustainable development in China, a new novel approach has been taken: cute panda-shaped solar parks

Source: https://www.pv-magazine.com/2017/06/30/panda-green-energy-finishes-50-mw-in-china/

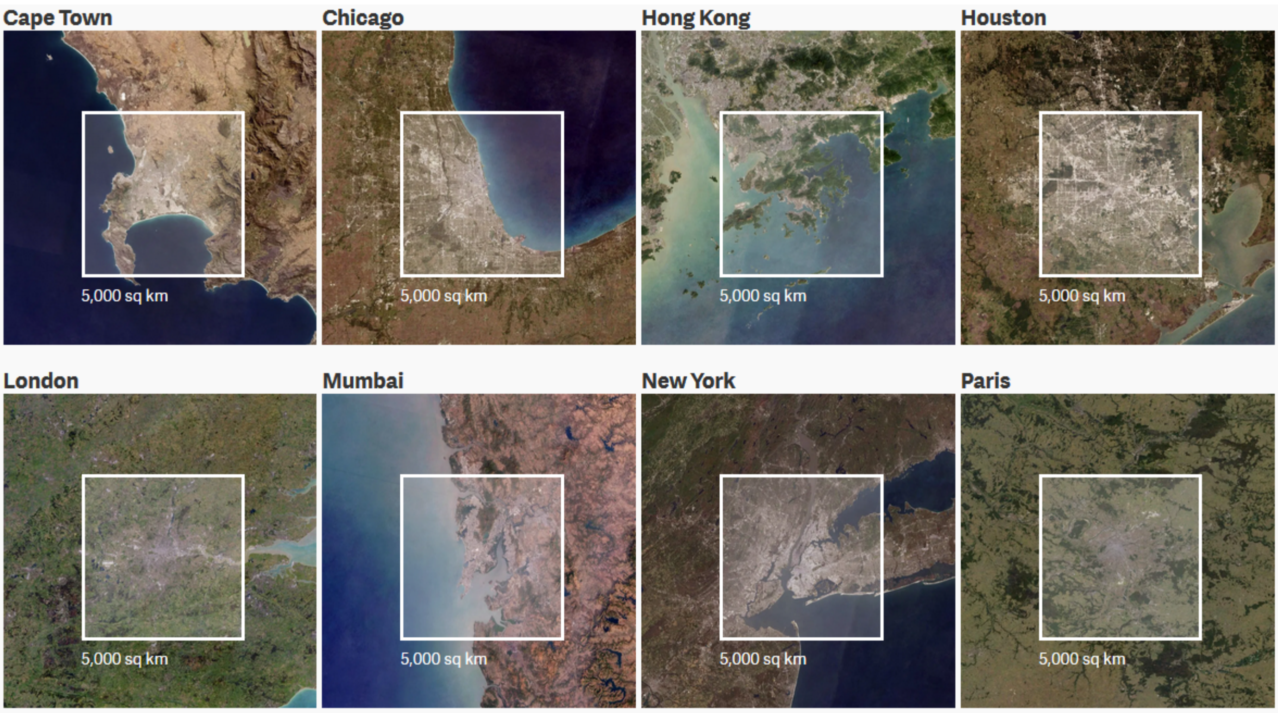
200GW PV System?

- What will Saudi Arabia's 200GW PV system look like….?

Source: https://renewablesnow.com/news/lowest-bid-in-germanys-latest-solar-tender-at-eur-389mwh-616257/

200GW PV System?

- Size ~ 5000km^2

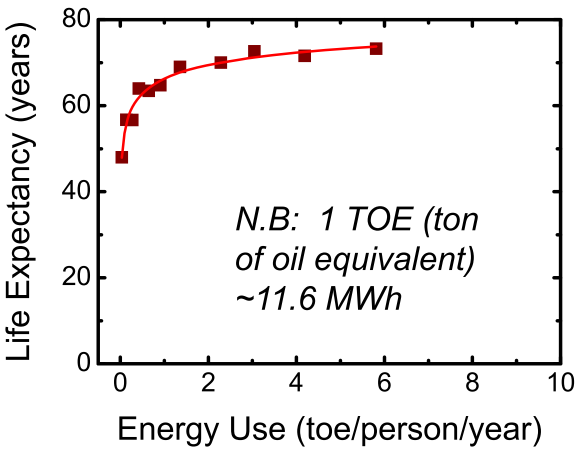


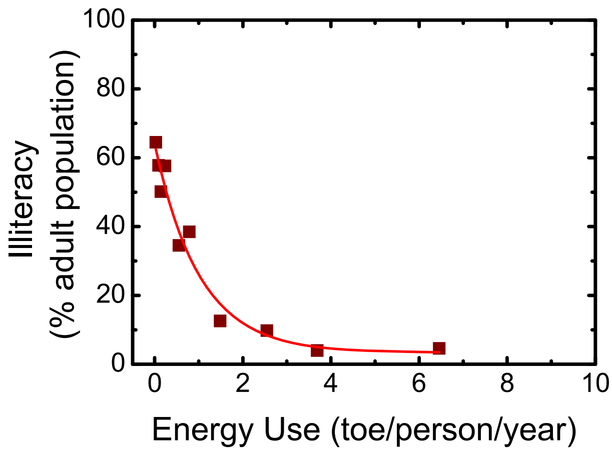
Source: https://qz.com/1240862/what-saudi-arabias-200-gw-solar-power-plant-would-look-like-from-space/

PV in Developing Countries

<u>Direct link between energy consumption & human poverty</u>

- Poverty and scarcity of energy go hand-in-hand, and exist in a synergistic relationship

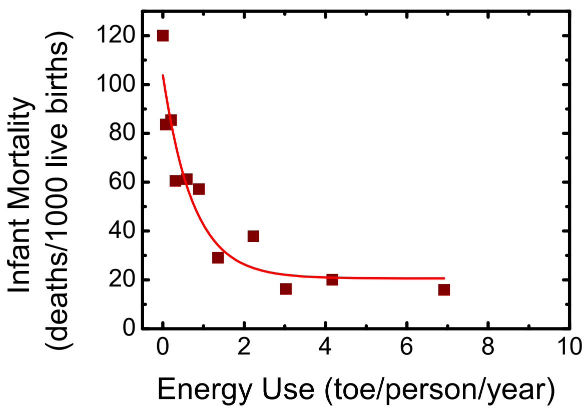




Source: World Energy Council, *Energy for Tomorrow's World*, Kogan Page Ltd, London 1993

PV in Developing Countries

<u>Direct link between energy consumption & human poverty</u>



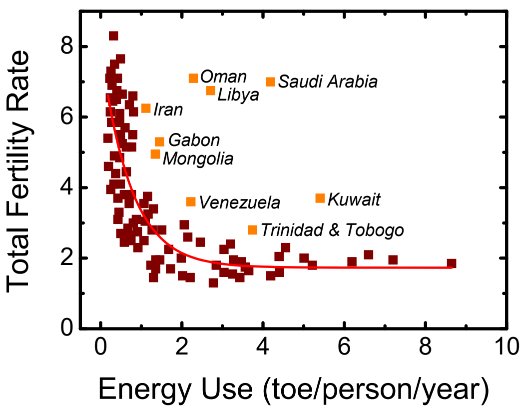


Table 3.8. Time Spent on Fetching Water and Collecting Firewood by Women and Men Engaged in the Activity (In hours and minutes)

		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

PV in Developing Countries

- Often, different financing mechanisms are needed

e.g. M-KOPA solar home systems (East Africa):

- Contains: PV panel, controller, USB phone-charger + 4 LED lights + radio + torch
- Control box contains a rechargeable battery, a GPS modem, LCD status screen, and connection to 8-watt PV module, LED lights, and USB port
- Each M-KOPA SHS has a unique customer ID number ⇒ used to add credit to user's account

Source: https://m-kopa.com/products/

PV in Developing Countries

M-KOPA solar home system:

- Innovative payment plan fits with pre-paid mobile culture in Africa (e.g. on-grid customers also buy electricity from utility via mobile)
- Retail "price" is ~US$30 ⇒ actually more like a deposit
- After that user pays US$0.50 per day to keep device operational ⇒ context: an estimated 3 million *households* (N.B. not people) spend US$0.70 daily on kerosene and phone charging
- Customers make payments directly from mobile phones ⇒ system 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 420 days worth of electricity customer owns the system outright ⇒ no more future payments ⇒ total cost US$240 (c.f. up-front cash price for system is US$190)

PV in Developing Countries

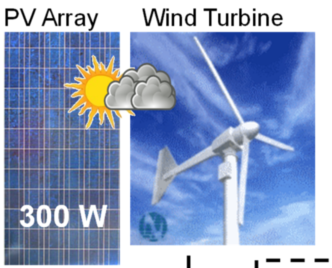
<u>No Clean Water and No Electricity</u>

- 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
- Further problems: dissolved contaminants (e.g. arsenic, fluoride,…) causing disease, disability and deaths

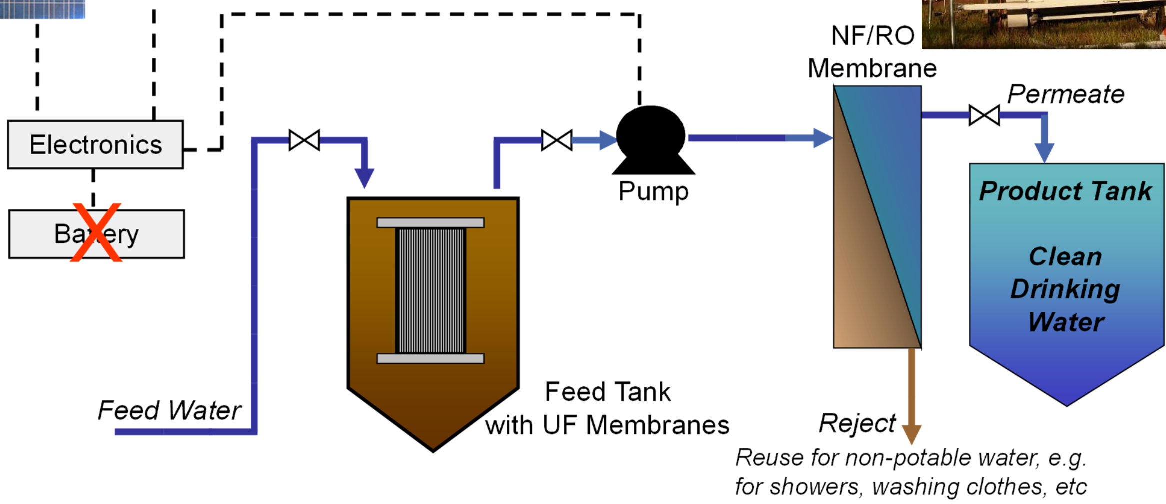
→ *Solution: development of small-scale decentralised water-treatment systems powered by solar and/or wind energy*

PV in Developing Countries

<u>Renewable Energy Powered Membrane Systems</u>



Hybrid filtration approach:
- Ultrafiltration (UF) – remove particles, viruses, bacteria
- Nanofiltration/reverse osmosis (NF/RO) – achieve desalination



PV in Developing Countries

RE-Powered Membrane Systems in Tanzania

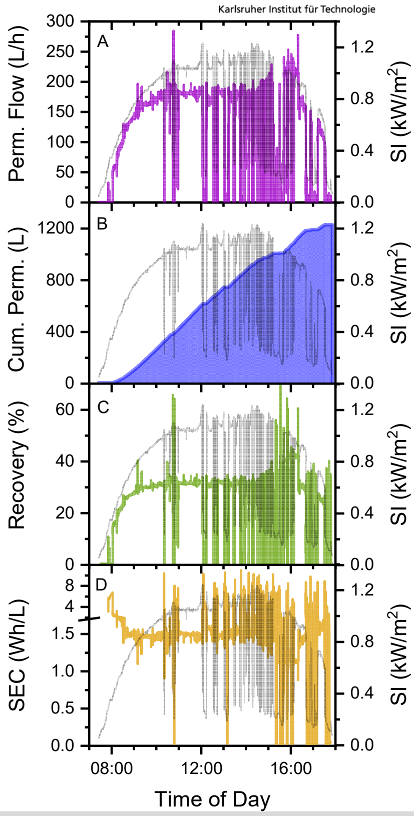
- Extreme amounts of organic matter in water – looks nearly black
- Able to remove these organics using UF membrane
- Many local school groups came to visit us and learn about our research
- Some villagers did not want to drink the water
  (they did not believe what we were doing was possible, thus it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

Source: Schäfer, Shen, Richards, npj Clean Water 1 (2018): 24.

PV in Developing Countries

RE-Powered Membrane Systems in Tanzania

- In Rift Valley, extreme fluoride concentrations of 60 mg/L (40x World Health Organisation limits) and highly brackish (salty) feed water
- Very arid environment with no electricity grid
- Overall F concentration after treating within WHO limit (<1.5 mg/L)
- Producing ~1000 L over one solar day (~10 hrs)
- Specific energy consumption (SEC) ~1-2 kWh/m^3



Source: Schäfer, Shen, Richards, npj Clean Water 1 (2018): 24.
N.B. SI = solar irradiance

PV in Developing Countries

Ongoing Research: PV-Powered Membrane Systems

- Re-evaluating energy storage options:
  - Li-ion batteries (10000 charge cycles)
  - Supercapacitors (1M charge cycles!)
- Control system and algorithms to maximise energy usage throughout the day
- Targeting permanent installation of 10 systems in Gambia and/or Senegal
- Development of integrated systems for provision of clean water & solar electricity
- Design and engineering of a suitcase version of system, e.g.
  - 100W of PV integrated into the walls of the suitcase
  - Pump and membrane filtration system inside
  - Clean water wherever you go ☺

Source: Schäfer, Shen, Richards, npj Clean Water 1 (2018): 24.
N.B. SI = solar irradiance