GREEN POWER FOR RURAL COMMUNICATIONS

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13.1 DEFINITIONS AND BACKGROUND

Power - in the sense of electrical power - remains one of the key challenges in improving living conditions in rural and remote parts of the planet. In 2012, "nearly 1.3 billion people remain without access to electricity and 2.6 billion do not have access to clean cooking facilities. Ten countries - four in developing Asia and six in sub-Saharan Africa - account for two-thirds of those people without electricity" [1]. In sub-saharan Africa, 57% of the population have no access to electricity [2]. Lack of electricity affects many areas, some of these arguably even more fundamental than communications - light, cooking, cooling/heating, water purification, to name a few.

For the scope of this article, we will define green or sustainable energy as *any form of electrical energy not based on fossil or nuclear fuel, but on fully renewable resources such as hydroelectricity, solar energy, wind energy, wave power, geothermal energy, artificial photosynthesis, and tidal power* (see [3] for alternative definitions).

A key characteristic of sustainable energy is abundance rather than scarcity:

- Fossil energy draws on limited resources, resources that will be depleted within the foreseeable future and that surge in price as more people demand access to them.

- While estimates about oil and coal reserves are well outside the scope of this paper, current best estimates assume about 1,500 billion barrels of proven sources left, which would make for about

1. IEA World Energy Outlook http://www.worldenergyoutlook.org/publications/weo-2012/

2. IEA World Energy Outlook http://www.worldenergyoutlook.org/resources/energydevelopment/globalstatusofmodernenergyaccess/

3. https://en.wikipedia.org/wiki/Sustainable_energy

50 years of oil even if consumption could be frozen at its current level [4].

4. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm

- The primary sources of green energy however are unlimited within timeframes of human imagination, and access to them becomes more affordable rather than more expensive with growing demand, due to mainstreaming and growth in production capacity.

There are of course limits to this simplified view - one river will not be able to host an unlimited number of hydroelectricity dams. The principle of abundance is particularly strong in solar energy. The total solar energy absorbed in the earth's atmosphere in one hour is larger than the whole world's energy consumption in one year. [5]The total solar irradiance, measured in watts per sqm, to the earth's atmosphere is around 1365 W/m^2 [6] . With the surface of the earth's disk as seen from the sun being 128 million square kilometers, the earth receives a total of about 174 petawatts, about 80,000 times its current total electricity consumption (18,466.459 billion kWh/year in 2010) [7]. About a quarter of this energy gets absorbed or reflected by the atmosphere. Each square meter of earth surface, facing directly in the sun's direction, thus receives an average 1000 W per square meter. The details of what part of this energy can be successfully harvested depend on many factors to be discussed later - but the key finding is: *even with today's soaring energy hunger, the sun supplies tens of thousands of times the total human consumption.* Access to solar energy is essentially limited only by access to a receiving surface, i.e. land or building mass, and the availability of technology to convert sunlight into electricity. This technology, called photovoltaics, is available and currently realistically reaches conversion efficiencies of about 20%.

5. https://en.wikipedia.org/wiki/Sun_energy#Energy_from_the_Sun

6. http://phys.org/news/2012-01-earth-energy-unusually-solar.html

7. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm

In what follows, we will focus mainly on solar power as our choice of sustainable energy.

While the term "developing countries" should not be mistaken as a synonym for "southern countries", the global statistics for rural population and access to electricity cited above put special focus on developing Asia, Sub-Sahara Africa and South America, all of which are among the truly rich regions on this planet, when it comes to solar light. Looking at the second part of Green Power for Rural Communications, we will define rural communications as any form of data transmission - whether these data are text, numbers, moving or still pictures - between humans or machines, and we will not define rural any more precisely than denoting the absence of typically urban infrastructure. A defintion based on population density, as typically used to define rural, is less meaningful in the context of our topic. Already at this point, it is worth noting that there are significant differences in requirements and approaches to communication technology, depending on whether one is looking at human communications or machine-to-machine communications. In what follows, we will narrow down the term communications to denote digital communications via networks, or more specifically, TCP/IP networks.

13.2 THE CASE FOR SOLAR POWERED ICT

Electrical power or its absence or instability remains one of the main challenges in building communication networks. Significant progress has been made in the energy efficiency of end user devices such as laptops, pads and tablets, which today can run on battery for 5, 10, even 20 hours without depending on any external backup. However, these devices to a growing extent depend on network connectivity, requiring extra energy to power the additional infrastructure. Most network infrastructure depends on grid electricity, often complemented by backup mechanisms such as grid charged UPS (uninterrupted power supply) or diesel generators. However, in most places in e.g. developing Asia and sub-saharan Africa, a stable grid is nothing but an assumption, a myth rather than a reality. Even where utility grids exist, these are often unstable or subject to brown outs and load shedding.

Even in highly developed regions with grid power currently seen as stable, this might change as fossil fuel in all its forms will become more and more difficult to source and to pay for. Unstable grid power not only causes services disruptions, it also destroys equipment and thereby investments. Strangely though, and partly explainable by the fact that ICT capacity and knowledge is driven by those in privileged environments, network professionals keep working with a base assumption of stable grid electricity, which only is complemented with backup or UPS solutions, often based on diesel generators or grid charged batteries, in case of grid failure.

While obviously, solar power - and other forms of sustainable power - offer suitable alternatives in this field, they are not just a backup solution for the time period until conventional large scale grids reach stability. In developing as well as highly developed regions, such as the strong economies of Asia, the USA, or Europe, conventional large scale grids are entering a phase of transformation - transformation of conventional centralized demand-driven grids towards decentralized grid fabrics, driven by complex negotiation of demand, opportunity and production, and consisting of micro-grids of all sizes and sources. Solar, wind and hydro power generation become part of these decentralized structures that will replace the conventional large scale grids, in the post-fossil-fuel era. It is thus more likely that today's grids will develop in the direction of the decentralized autonomous structures that we are proposing for wireless networks, rather than centralized in the foreseeable future growing to offer the reliability that our networks require.

The benefits of getting started with solar power for networks and other infrastructure include:

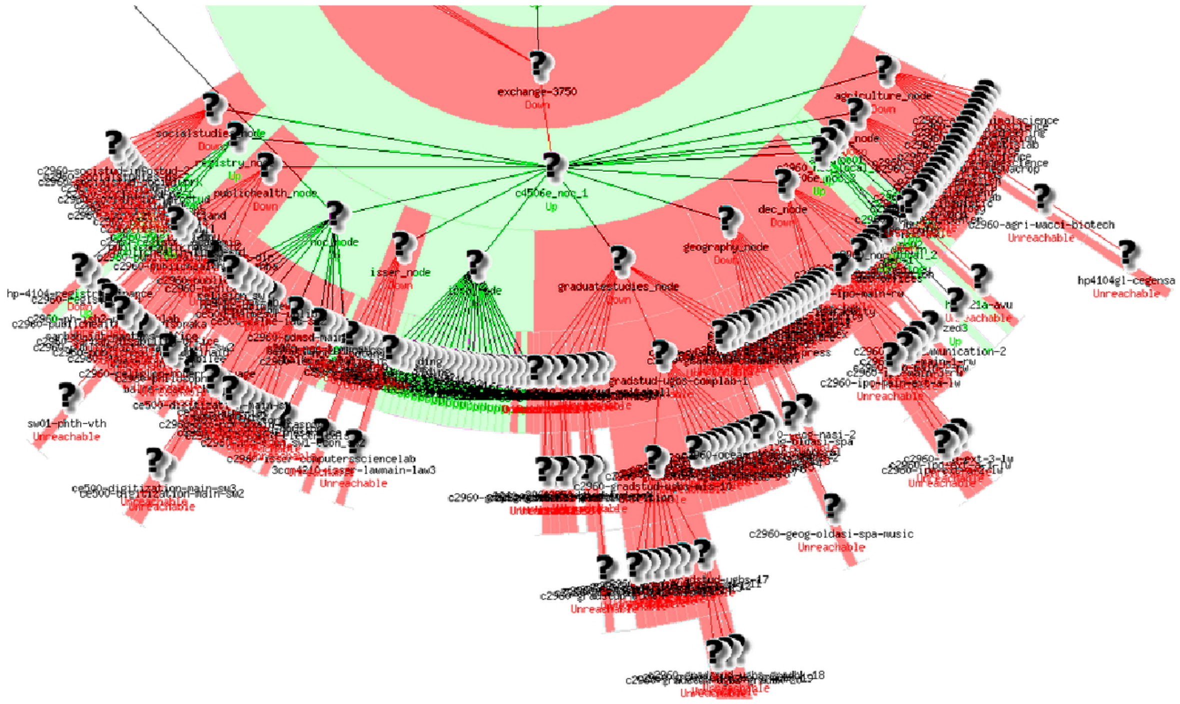

Figure 13.1: Power failure as seen by a typical network management tool (Nagios network monitoring at the University of Ghana).

- Stability
- Protection against hardware failure caused by grid instability
- Price
- Independence from political, financial changes, e.g. changes in grid energy or fuel pricing
- Sustainability
- Future readiness
- Local ownership and control

8. http://9to5mac.com/2011/12/07/at-around-5mw-apples-new-solar-roof-could-make-it-the-biggest-in-the-us-power-a-million-appletvs/

Leading technology companies have begun to understand these benefits, and like most other businesses in the developed world are establishing their own, partly grid-independent power generation: Google's current solar allocation is about 1.6 MW and Apple is planning for about 5 MW at their new headquarters in Cupertino [8].

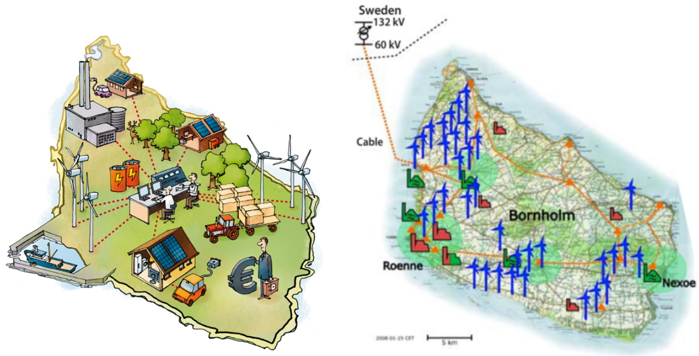

Figure 13.2: Smart Grid Bornholm, source: EcoGrid EU.

13.3 THE CASE FOR SOLAR POWERED NETWORKS

Having narrowed down communications to digital network communications earlier, we will now look at wireless networking, and at TVWS in particular. With the emergence of 802.11 WiFi networking and its huge success in infrastructure over the last 15 years, solar powering has been a popular choice from day one, both for networks and general IT infrastructure.

Likewise, mobile networks (GSM, GPRS, etc) especially in rural areas, often depend on solar powering. For basics of solar powering of IT infrastructures, see [9] and [10].

One needs to be very careful not to compare technologies beyond what they are comparable in: 802.11 WiFi is different from mobile in both its purposes and underlying technology, and the same is true for any other pair of technologies we are mentioning here. While it is tempting to work towards a "performance per power consumption" rating, such a rating does not make a lot of sense: the requirements for different kinds of networking are too different from one another. Speed, reach/coverage, availability, ease of roaming, energy efficiency - all of these and more are valid performance parameters.

When looking at networks for rural communications, however, we can isolate a few key requirements:

- long distance reach and NLOS is more important than ultra high bandwidth - despite sometimes being coined "super WiFi", TVWS will not be able to compete with 802.11n, 802.11ac and proprietary TDMA extensions at 2.4/5 GHz, in terms of bandwidth
- availability and stability are more important than seamless roaming

TVWS lends itself very well to reaching both of these, at low input and output power, for two main reasons:

9. Wireless Networking in the Developing World, http://WNDW.net

10. Amos Nungu, Robert Olsson, Björn Pehrson, "Powering Communication Networks in Developing Regions", 16th IEEE International Symposium on Computers and Communications (ISCC 2011), Corfu, Greece, June 2011.

Figure 13.3: Powering teachers' computer room at the Kopan monastery school, Nepal.

- Working at low frequencies (470-860 MHz, depending on region), compared to WiFi's 2.4 and 5 GHz and mobile networks 1.8 GHz, TVWS is better suited for long distance and non-line-of-sight (NLOS) links. A first order estimate leads to the result that TVWS will cover an area four times larger than WiFi at 2.4 GHz, at the same output power [11].

11. http://www.newamerica.net/files/nafmigration/Rural_Broadband_and_TV_WhiteSpace.pdf

- Emerging TVWS protocols put a lot of focus on minimizing protocol overhead, so that energy efficient operations become feasible.

At this point we need to remind ourselves that, within TVWS proponents there are radically different ideas of how it is going to be used. The potential for extreme low power TVWS is significant especially for sensor networks, devices, rather than human communications, as sleep modes can come into full effect [12].

12. http://www.weightless.org/benefits-battery

13.4 ELEMENTS OF A PHOTOVOLTAIC SYSTEM

While a full introduction to photovoltaics is beyond the scope of this booklet (see [13] and links therein for this), we introduce the main elements of a photovoltaic system:

13. Wireless Networking in the Developing World, http://WNDW.net

- Solar panel, the heart of the system, turning light intro DC electricity, typically at 5 or 12 volts or multiples thereof
- Battery (of a type suitable for solar operations)

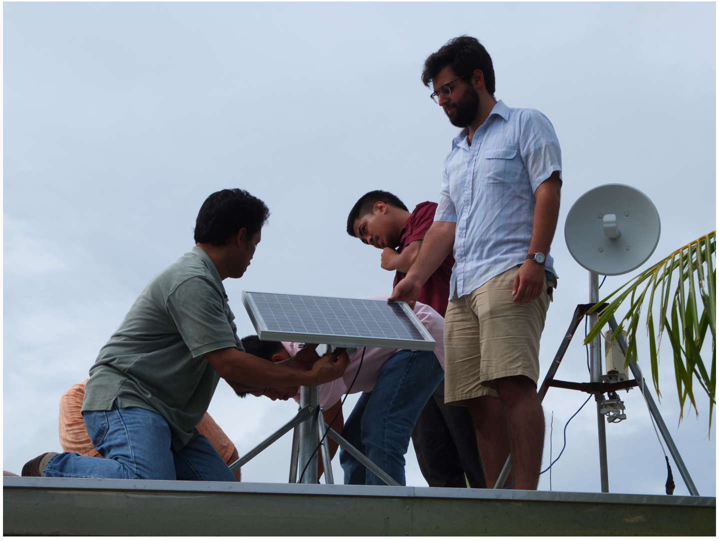

Figure 13.4: Solar powered WiFi networks in Guam.

- Charge controller
- Inverter, if conversion to AC and/ or connection to an AC grid is needed.

plus cabling and mechanical installation

13.5 TYPES AND EFFICIENCIES OF SOLAR PANELS

The main types of commercially available solar cells are:

- mono- and polychrystalline silicon
- amorphous silicon
- thin film cells, made from Cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (A-Si) have significantly lower efficiency, but allow for the production of flexible bendable panels, which are well suited for mobile applications, solar tents, solar wrappings on existing building structures and so forth, and are considerable cheaper in production than silicon cells

There are numerous other approaches, e.g. based on organic polymers, (organic) dyes or advanced quantum structures. While most of these have not reached market maturity yet, the diversity of technologies promises access to the principal abundance of solar energy, even if one or the other of the raw materials should become short in supply. In most cases, we will look to maximize efficiency, and at this point in time, monochrystalline SI cells remain unrivalled in this regard. Commercially available monochrystalline panels are available with about 15% (-20%) efficiency, and a 25-30 year guarantee on 80% of that rating.

13.6 DIMENSIONING OF PHOTOVOLTAIC SYSTEMS

The dimensioning of a photovoltaic powering system depends on three key input parameters:

1. insolation or peak sun hours at the given location
2. total power consumption or load
3. maximum time of autonomy (i.e. time of operation without recharge, time without sun)

plus a number of supportive system parameters, such as area available, panel efficiencies, etc.

Based on these three input parameters, different views and approaches may be chosen in order to calculate solar panel and battery sizes. The solar panels of course are the source of all energy within the system. For the sake of dimensioning, however, it is helpful to look at the battery system as the primary entity: the batteries are powering the load constantly, while the input power from the panels varies, e.g. in day/night cycles. The accumulated input from the panels obviously needs to be in balance with the overall energy consumption, and capable of keeping the batteries at a high charge state. Batteries should never to be discharged to below 50% of their capacity. Ultimately, regardless of what view one chooses, the model has to be critically tested against real life experience, and adjusted where necessary.

But first of all, let us look at where to get the input parameters from:

- Insolation or peak sun hours at the given location may be looked up from databases and tools [14], [15], [16].
- Total power consumption or load may be derived from data sheets or trusted technical information. Measuring and confirming these under realistic operation conditions is always recommended.
- Autonomy expectations ultimately depend on the network engineers' and users' educated opinion. While it might be acceptable for a computer classroom to run out of power during the night or on weekends, for networks we should generally design for near 100% uptime.

14. http://www.wunderground.com/calculators/solar.html

15. http://www.altestore.com/howto/Solar-Electric-Power/Reference-Materials/Solar-Insolation-Map-World/a43/

16. Photovoltaic Geographical Information System (PVGIS) http://re.jrc.ec.europa.eu/pvgis/

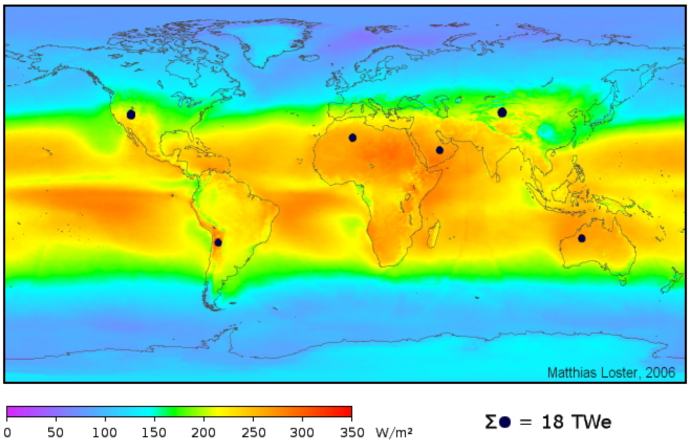

Figure 13.5: World insolation map.[17]

17. http://commons.wikimedia.org/wiki/File:Solar_land_area.png

13.7 INSOLATION DATA AND PEAK SUN HOURS

We will be using the concept of Peak Sun Hours (PSH), which needs explaining. We mentioned earlier, that the earth's surface receives about 1 kW/sqm in full sunlight. Measuring the total insolation over one day, we can express the resulting value in its equivalent "hours of full sun". Peak Sun Hours thus is a measure of energy per surface area - the average daily solar insolation in units of kWh/m^2. A value of 6 PSH thus corresponds to an average power of 0.25 of the full 1 kW/sqm, i.e. 250 W/sqm.

While data on insolation or peak hours are readily available, the main challenge lies in taking into account all seasonal variations, or any variation that might occur at a given deployment site, whether it is due to special weather conditions (e.g. clouds, fog) or shading (by nearby trees or buildings) or, generally, anything that might have an impact on the amount of sun light that effectively reaches our solar panel. Seasonal variations of peak sun hours may be very strong, and it is clear that a system which is designed based on an all-year-average is very likely to run out of power in the worst part of the year. Even when choosing the worst-month approach, i.e. taking the month with the lowest PSH as base of our design, we might encounter particularly bad days where the total energy produced is not sufficient. In particular, the longest time without sun will be longer than simply assuming it to be 24 hours minus PSH. A more conservative approach - which we will call the battery approach - calculates the amount of energy the battery has to store to power the load during the period assumed to be the worst possible case, and then calculates the minimum size of the solar panels based on the requirement that the battery can be fully recharged during the peak sun hours. Note that this approach may lead to very high demands and thus

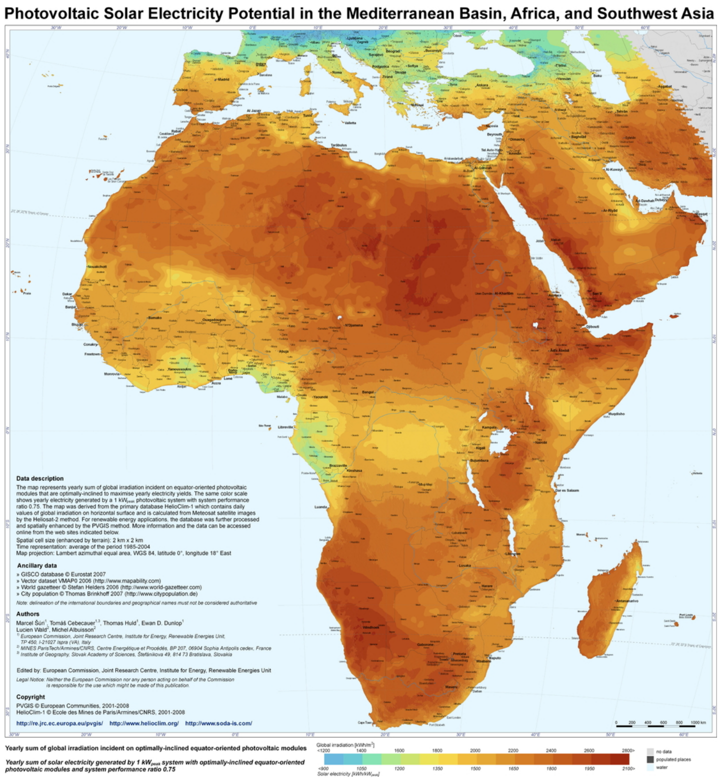

Figure 13.6: African insolation map.[18]

18. Solar Electricity Potential in Africa, South West Asia and the Mediterranean region , JRC's Institute for Energy and Transport - European Commission PVGIS http://re.jrc.ec.europa.eu/pvgis/

very expensive systems!

The differences between an all year average and a worst month model will naturally be small for places where seasonal variation is small, i.e. close to the equator. In the other extreme, both these PSH models become useless when working in the arctic or antarctic region, where polar nights might last for weeks and months. A battery approach is the only feasible model in these cases. There is no golden rule to solving this problem - ultimately we will have to make reasonable compromises between our expectations and the budgets available. The following formula provide the basis for dimensioning:

PSH peak sun hours (year average or worst month) [h]

$\mathbf{P_l}$ load [W]

$\mathbf{W_p}$ Power (watt peak) of solar panels [W]

$\mathbf{E_p}$ Energy produced by panels, in Wh/day.

$\mathbf{E_{ff}}$ Efficiency of solar panel [%]

$\mathbf{C_b}$ Capacity of battery [Wh], never be discharged to below 50%.

A Area of solar panel [sqm]

t_O time of operations without recharge [h]. t_O is at least (24 hrs - PSH), but likely significantly larger

t_C charge time for batteries [h]

Energy produced by a panel, in Wh/day:

$$E_p = 1000W * E_{ff} * A * PSH = W_p * PSH$$

At an efficiency of 15%, about 7 sqm of panels are needed for 1kW peak (about 150 Wp / sqm).

13.8 YEAR AVERAGE APPROACH

Minimum panel size, in watts peak = P_l * 24 / PSH (year average). The battery size in Wh may then (optimistically!) be deducted from:

$$C_b = 2 * P_l * (24 - PSH(year\ average))$$

Note the factor 2, due to the fact that batteries should never be discharged to below 50% of their capacity. This is a very optimistic calculation, that does not consider the power required to charge the battery, and by using the year average will fail to satisfy the demand those days in which the amount of sunlight is below average. It could be appropriate for non critical applications that can tolerate power outages.

13.9 WORST MONTH APPROACH

Minimum panel size = P_l * 24 / PSH (worst month) The battery size may then be deducted from:

$$C_b = 2 * P_l * t_o$$

This is again an optimistic calculation, that does not consider the power required to charge the battery, but by using the worst month can provide a more realistic result.

13.10 BATTERY APPROACH

Starting with a more conservative assumption:

$$BatteryCapacity C_b = 2 * P_l * t_o$$

we deduct optimistically, neglecting the power required to charge the battery:

$$MinimumPanelSize W_p = C_b/(2 * PSH)$$

Table 13.1: PSH in different locations.

Location	PSH Year Average [h]	PSH Worst Month [h]
Kenya, Nairobi	6.00	5.00
Germany, Berlin	3.00	1.00
South Africa, Cape Town	6.00	4.00
UK, Cambridge	3.00	1.00
Malawi, Lilongwe	6.00	5.00

Table 13.2: Minimum Panel Size in different locations.

Location	Minimum Panel Size Year Average Approach [W]	Minimum Panel Size Worst Month Approach [W]	Minimum Panel Size Battery Approach [W]
Kenya, Nairobi	400	480	380
Germany, Berlin	800	2400	2300
South Africa, Cape Town	400	600	500
UK, Cambridge	800	2400	2300
Malawi, Lilongwe	400	480	380

or more conservative, where we take into consideration the power required to charge the battery besides supping the load.

$$MinimumPanelSize W_p = C_b/(2 * t_c)$$

13.11 DIMENSIONING: AN EXAMPLE

With the preparation and examples above, let us look at an example task of powering a 100 watt load. This might for example be a TVWS base station plus some surrounding infrastructure, e.g. routers or switches, WiFi equipment. We make the following assumptions:

$$P_l = 100 W$$

Note that for locations with moderate seasonal changes, the three different approaches give comparable results (which also are in good agreeent with real life experience). The stronger the variations over the year, the more difficult the planning becomes.

Table 13.3: Battery Capacity in different locations.

Location	Battery Capacity Minimum Year Average Approach [Wh]	Battery Capacity Minimum Worst Month Approach [Wh]	Battery Capacity Minimum For 3 Days Operation [Wh]
Kenya, Nairobi	3600	3800	7200
Germany, Berlin	4200	4600	7200
South Africa, Cape Town	3600	4000	7200
UK, Cambridge	4200	4600	7200
Malawi, Lilongwe	3600	3800	7200

13.12 POWER CONSUMPTION OF TVWS EQUIPMENT

Both the pilot in Malawi (started June 2013) and the trial in Cape Town, South Africa (started February 2013, [19]) are using TVWS equipment by Carlson. The Carlson RuralConnect Base Station is specified to have a power consumption of about 30 watts.

19. http://www.tenet.ac.za/about-us/the-cape-town-tv-white-spaces-trial

For a June 2013 Malawi pilot, a photovoltaic system with 150 W_p is tentatively planned to be powering this base station [20]. Note how this size is in accordance with the dimensioning example above.

20. Private communications, Ermanno Pietrosemoli

The South African (Cape Town) pilot, being located in an urban area with privileged infrastructure, relies on grid power.

The Windfi pilot in Scotland uses a different approach, in that it combines solar and wind to take advantage of the varying seasons of a northern european country. A battery approach for dimensioning the combined wind and solar system is used to dimension for a total load of 50 W. A battery bank of 600Ah at 12 V allows the system to run for 3 days without recharge. Batteries are charged by the combination of solar panels with 480 watt peak, later reduced to 320 W), and a 200 watt wind turbine. Another significant difference to systems discussed above is the fact that a tracking system is used, i.e. the solar panels are motorized to follow the sun. While this wins another 20-35% in power, most photovoltaic systems deployed in remote areas avoid the use of tracking system, as moving parts are seen as potential source of failure, ot at least demanding regular maintenance.

Closeness to service personnel obviously is a key factor here - with people nearby, one can take the risk of using moving parts, which might be unacceptable in a truly isolated location, e.g. a repeater station.

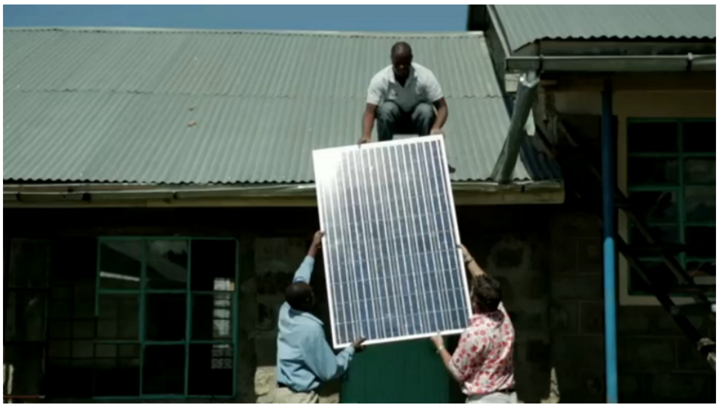

Figure 13.7: Deploying solar panels in the Kenya Mawingu project. [21]

21. Mawingu project, http://www.microsoft.com/africa/4afrika/white_spaces_project.aspx

Figure 13.8: TVWS project in Scotland. [22]

22. HopScotch project, http://jwcn.eurasipjournals.com/content/2012/1/112

13.13 ECONOMICS OF SOLAR POWER

While environmental considerations strongly point at using solar power, the economic advantages of solar power are far less obvious.

At the time of writing, solar power still has the reputation of being relatively expensive - despite the fact that it has reached grid parity in many countries, i.e. it is cheaper than grid electricity. This reputation is largely due to the fact that capital expenses at startup are high, while the benefits of not having to buy fuel or pay any electricity bill only show over time. The life time of a photovoltaic system - indicated by solar panel performance warranties of 25 or 30 years - often are beyond the scope of day-to-day planning. This fact, in combination with a very limited availability of loans to finance the upfront expenses, still constitutes a major hurdle for solar power in developing countries. Network developers willing to look at sustainable power need to have arguments at hand to convince management and financial departments. In what follows, we will give these.

In order to understand that solar power is competitive, we need to calculate its price per unit of energy over time. Reliable statistics and calculations for the de-facto price of energy by source are not hard to find, but they often contain assumptions about tax subsidies or penalties, tariffs for grid integration, and local, national or regional market conditions. Therefore, we choose a very direct case study - the comparison of solar power vs diesel generator for an off-grid system, for the conditions of Kenya. We calculate the cost of a kWh, a common measure for energy produced and consumed, as produced by a solar power system, for systems of sizes in the range 1 kWp up to a few tens kWp. These are systems that a household, a network node, a university NOC or a small company realistically could require. We will be making very conservative assumptions, and we will allow enough budget for the calculation to be valid for a standalone system as well as for a grid-tie system.

At the time of writing (May 2013), the cost of quality solar panels is about $500 to $1000 per kWp. A price of $3000 per kWp for a whole system, including controllers, cabling, batteries, inverters etc is realistic. Note that these are global market prices - some countries might put high taxes on imported systems. In many places, prices will be significantly lower. For a regularly updated list of solar price indices, see [23].

23. Solar price indices http://wireless.dk/?page_id=103

How many kWh does a system of a size of one kWp produce in one year? This primarily depends on the amount of peak sun hours at the given location.

With

CAPEX initial capital expenses

PSH peak sun hours (year average) [h]

$\mathbf{Y_{OP}}$ years of operation

Table 13.4: Cost per kWh [$], in year of operation.

			1	5	10	20	30
Solar	PSH	Accumulated CAPEX	3000	4200	5700	8700	11700
DK	2	Cost/kWh	4.11	1.15	0.78	0.60	0.53
KE	5	Cost/kWh	1.64	0.46	0.31	0.24	0.21
Diesel	Price/Liter [$]	Accumulated CAPEX	500	700	950	1450	1950
DK	1.8	Cost/kWh	0.60	0.56	0.55	0.44	0.55
KE	1	Cost/kWh	0.36	0.32	0.31	0.31	0.31

MF annual maintenance factor for replacement of equipment, etc.

P_D price of diesel per liter

H_{OP} hours of operation per year (for Diesel generator)

C_D Diesel consumption [Liter per kWh]

The total cost of a kWh produced is the total cost (capital and operational expenses) divided by the kWh produced. The price of a solar kWh is dominated by the initial capital expenses, while the "fuel" is free:

$$(CAPEX * (1 + (Y_{OP} - 1) * MF))/(PSH * 365 * Y_{OP})$$

The price of a diesel kWh is largely dominated by fuel cost:

$$(CAPEX * (1 + (Y_{OP} - 1) * MF) + Y_{OP} * H_{OP} * P_D * C_D)/(Y_{OP} * H_{OP})$$

The following results are based on the assumptions:

- 24 / 7 operations for both diesel and solar
- a diesel efficiency of 0.3 liters / kWh
- initial capital expenses of $3000 / kWh (solar) and $500 / kWh (diesel generator, a diesel friendly assumption taking the availability of used generators into account)
- a maintenance factor of 10% per year

In a simplified approach, assuming that both solar and diesel systems will require the same relative maintenance cost per year, and the diesel to run 24 / 7, we can calculate the year of operation in which solar power becomes cheaper than diesel power:

The year of break-even for solar power vs diesel is:

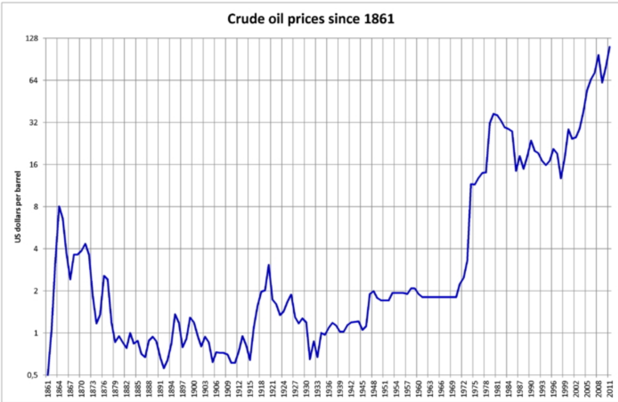

Figure 13.9: Crude oil prices development.[27]

27. http://en.wikipedia.org/wiki/File:Crude_oil_prices_since_1861_(log).png

$$CAPEXSOLAR/((PSH * 365)(CAPEXDIESEL/8760 + P_D * C_D))$$

This formula is easy to transfer to the respective conditions in a country, but should only be seen as a rough guideline.

For Kenya, the solar kWh becomes cheaper than the Diesel kWh after approximately ten years.

Calculations for high insolation belt (with a PSH of 5.5 and above) of the US lead to similar result, putting prices at .15 - .30 $/kWh for small to industrial size installations, over a 20 year lifespan [24].

24. http://www.solarbuzz.com/facts-and-figures/retail-price-environment/solar-electricity-prices

The strongest economical argument in support of solar power is difficult to quantify - it lies in the principle of abundance. While fossil fuel reserves are limited and prices bound to surge with growing demand and shrinking supply, more demand for solar power will lead to more panel production capacity, intensified research and continuous drop in prices. Swanson's Law - the observation that the price of solar photovoltaic cells tends to drop 20% for every doubling of industry capacity - so far seems to be valid: Crystalline silicon photovoltaic cell prices have fallen from $76.67/watt in 1977 to a forecast $0.74/watt for 2013 [25] [26].

25. http://www.economist.com/news/21566414-alternative-energy-will-no-longer-be-alternative-sunny-uplands

26. http://about.bnef.com/

Adding to all the economic reasons for a transition to solar power are the health and environmental damages caused by fossil fuels, with impact on human health especially when generators or stoves are used close to or inside homes and workplaces.

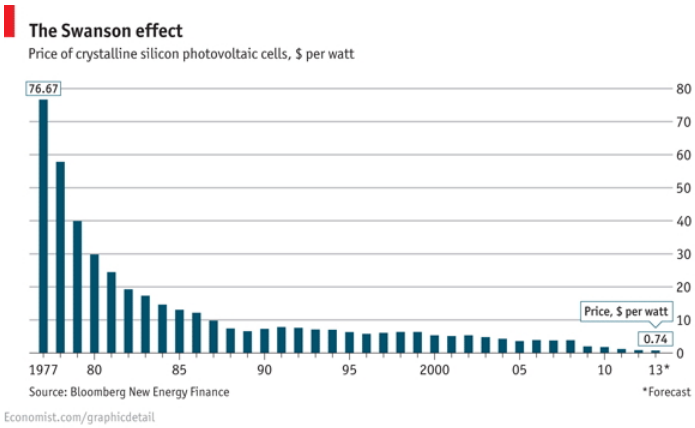

Figure 13.10: Swanson effect - price development for solar panel prices.[28]

28. http://www.economist.com/news/21566414-alternative-energy-will-no-longer-be-alternative-sunny-uplands