Solar-DC: L1
Powering Residential and Business Sectors

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L1: Introduction

Are we pushing the world backwards with DC Power?

By the middle of 2017

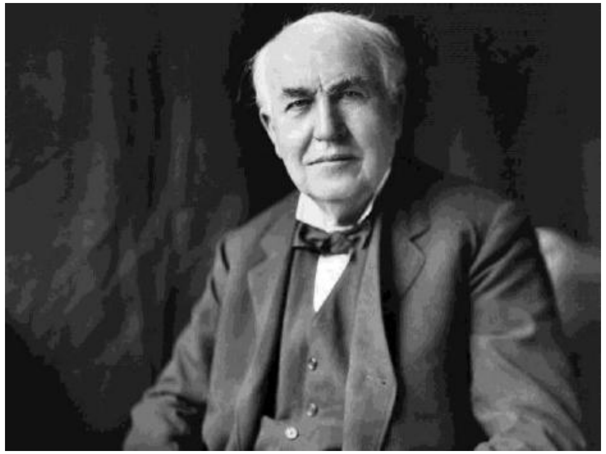
- ***Sasaram (Bihar, India)*** *will be the "**First DC City**" in the world with DC Power line in all Homes*
  - *In next few decades, all homes in the world will follow. Every home will have a DC power line*

- Is this really true? Why?
- Is DC not pushing us back by a century?
- What has changed? And why Now?

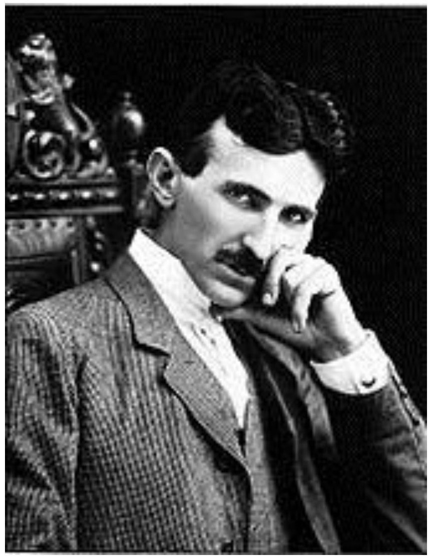
Before we answer these questions, let us look back at the history

The War of the Currents: AC vs. DC Power

- In late 1880s, Thomas Edison and Nikola Tesla were embroiled in a battle now known as the War of Currents [http://energy.gov/articles/war-currents-ac-vs-dc-power]
  - Edison developed direct current (DC) - standard in US in early years of electricity: but DC was not easily converted to higher or lower voltages
  - Tesla believed that alternating current (or AC) was solution -- can be converted to different voltages relatively easily using a transformer



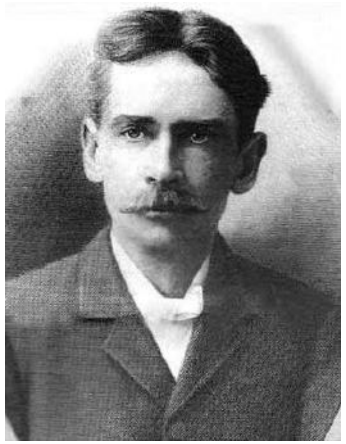
American inventor and businessman Thomas Edison established the first investor-owned electric utility in 1882, basing its infrastructure on DC power



Nikola Tesla's induction motor patent was acquired by Westinghouse in July 1888 with plans to incorporate it in a completely integrated AC system

Transformer gave the edge to AC transmission

William Stanley developed first practical AC transformer for Westinghouse and helped build the first AC transmission

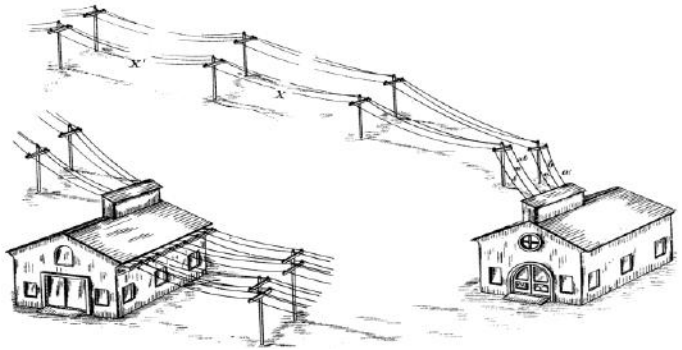


Hungarian "ZBD" Team (Károly Zipernowsky, Ottó Bláthy, Miksa Déri) were inventors of first high efficiency, closed core shunt connection transformer and also invented the modern power distribution system: Instead of former series connection they connect transformers that supply appliances in parallel to the line.

- DC at low voltage (110V) had small transmission range (1 km or so), or would require much thicker and expensive copper conductor
  - If power doubles at same voltage, wire cross-section needs to be increased 4 times as current will double and losses are I2R
- AC transmit voltage could be increased by transformer and stepped down at load end
  - Required much thinner wire
  - Westinghouse in USA took patent for the Hungarian transformer and pushed for AC line

AC development started thereon

- AC for long-distance transmission
- AC for power distribution grid
- AC at homes and offices and industries
- AC appliances
  - Lights, fans, motors (fans, refrigerators, air-conditioners, mixers, washing machine), as well as early Television and displays
- AC protection was perfected: MCB (Miniature circuit breaker) made homes safe
- On the other hand, very little development took place on DC, despite some rumblings



In the beginning of 20th Century

- Diffusion of technology and Innovations: highly dependent on the market as well as Government policies in regulating the market
  - Government order objected to conversion from DC to AC on the grounds that, "Calculation showed that an AC fan consumed about twice as much energy as DC fan." [Notes to Madras GO 756 (W), 11 April 1913, available at Tamil Nadu Archives, Madras]
  - Government also feared that a mixed system of AC and DC "would produce endless trouble and inconvenience to consumers and owners of the buildings in which electric apparatus is installed." [Notes from Electric Inspector, E.J.B. Greenwood, to Madras Electric Supply Corporation, dated 29 May 1913, available at Tamil Nadu Archives, Madras]
- Even as late as middle of 20th century, some remnants of DC power had remained: but they all disappeared

Late 20th Century: when DC was considered dead, DC creeps in

- A **high-voltage, direct current** (**HVDC**) electric power transmission system used for bulk transmission of electrical power for long-distance transmission https://en.wikipedia.org/wiki/High-voltage_direct_current
  - Less expensive and suffer lower electrical losses
    - Power travels in core in DC rather than on surface as in AC (due to skin effect)
  - For underwater power cables, avoids heavy currents to charge / discharge of cable capacitance each cycle
  - Even for shorter distances, the higher cost of DC conversion equipment may still be warranted, due to other benefits of direct current links
  - Allows power transmission between unsynchronized AC transmission systems: can stabilize a network against disturbances due to rapid changes in power
    - Improves stability and economy of each grid, by allowing exchange of power between incompatible networks

Late 80s, Electronics entered and started to dominate home-life

- Discreet electronics before 80's: expensive and less-reliable
- Integrated Circuits came in late 70s
  - More like printing of circuits using masks
  - High volume ICs ride on Moore's Law: cost and size halves every 18 months
    - So does the power-consumption
  - Programmable processors and Circuits leveraged ICs
    - Software is one time effort : Indian engineering talent gains dominance
  - Electronics permeates into every aspect of our lives: TVs, cell-phones, computers, sensors

- But electronics is all DC-powered: uses AC-DC converters with each device / appliance: *have losses, adds costs and impacts reliability*

Then came the DC lighting

- LED lighting came into being a few years back
  - Almost 2.5 times more energy efficient as compare to the CFL lighting
    - CFL itself was several times more energy efficient than incandescent lighting used till 90's
  - Price is much higher, but dropping rapidly
    - And the life of LED is about eight to nine years, as compared to 18 months for CFL
    - Is available in several colours

- But LED lighting requires only DC-powering
  - With AC home-grid, an AC-DC converter has to be associated with each light
    - Adds Costs and impacts reliability

Displays changed more recently

- In 90's display used mostly Cathode Ray Tube (CRT)
  - High voltage and power required to drive it
- Plasma display was better quality, but required high power

- Then came LCD display
  - Power consumption came down and quality improved
- LED display followed: power consumption further came down
  - Today most TVs have LCD / LED displays
- But LCD / LED display only needs DC-power

DC was slowly creeping into Homes

- And with each such DC appliance, one had to use AC-DC converter
  - Converter have losses and costs
  - Are mostly less reliable as compared to rest of the systems
  - Poor-quality converters could impact power-factor on power lines
  - Stage was slowly being set for DC power-line

- But bigger things were still to come
  - Especially in countries like India
  - And it had to wait till this decade
  - India uses 72% of its domestic power on lighting and fans!

And these fans

- A ceiling fan is a life-saver in hot country like India
- These fans use hub-mounted AC induction motor
  - Typical home fans consume 72W
  - Speed is varied by reducing voltage by inserting a resistance in series
    - Some motors, such as shaded pole motors, have a torque capability curve that allows the motor speed to be controlled by reducing the applied voltage. This technique works best when the load torque requirement rises as speed increases (as in a fan). Power is wasted as speeds reduce
- Now we can get these fans with BLDC Motor: consumes only 30W
  - And they are driven by DC
  - Same is the case with SR Motors

How has this happened?

- Brushless DC (BLDC) Motors
  - This is not new
  - Was always known to be far more energy efficient as compared to AC induction motor
  - Also speed control is easier and power consumed falls rapidly with motor-speed

- But why are they getting into fans today?

The magic lies in Power Electronics IC

- Electronics devices did not take off so widely till ICs came in
  - But ICs only handled low-voltage and low-current applications
  - Power-electronics was getting developed, but it remained discreet
- Change happened at the turn of the century
  - Driven quite a bit by Indian researchers in USA
    - IITM alumni like Jayant Baliga and Krishna Shenoy were amongst the lead contributors
- Power-Electronics Integrated Circuits kicked in

And with Power-Electronics IC came

- Power-Electronics Integrated Circuits kicked in
  - And Moore's law kicked into Power-electronics
  - High currents & voltages can be switched thousands of times / second at low cost and losses
- An example
  - as current-switching moved from 50 Hz to 500 Hz and to 5000 Hz, the coil-turns required in a transformer reduced by 10 times and 100 times respectively
    - Tiny magnetics came into being
- Everything became smaller
    - More reliable
    - And much less expensive: with volumes the costs drops rapidly
  - BLDC Motors, SR Motors and Variable Frequency Drives (VFDs) are a result of this new Power-electronics revolution

BLDC Motors in Indian homes

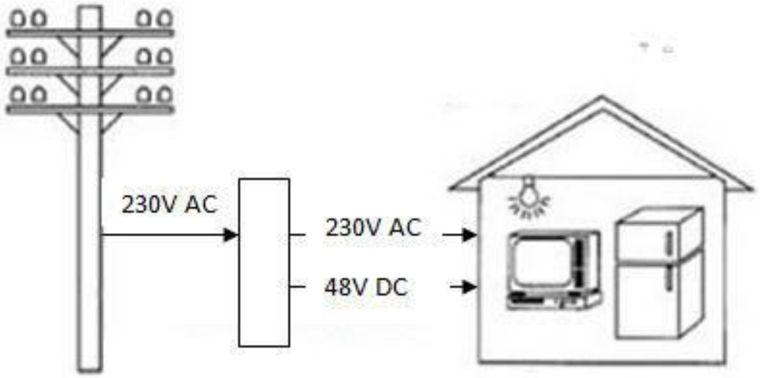
- As mentioned earlier
  - BLDC motor based ceiling fans consumes only 40% of power as compared to that for AC induction motor ceiling fan at full speeds
    - Advantage gets more pronounced at lower speed
- And BLDC motors are DC-power driven
  - An AC-DC converter is required if one has only AC power-lines

- Refrigerator power consumptions is primarily in motors
- Air-conditioners consume power in motor
- Mixer, washing machine, grinders are all motors
  - Use of BLDC motor can substantially enhance efficiencies of these devices

Net, Net: there is a strong case for "DC power-line at each home"

- To drive all the DC-powered devices of the present and the future
  - And all sensors use only DC power
    - AC appliances will slowly fade away
    - No need of multiple AC-DC converters
- And, there is more
  - Solar PV panel produces only DC power: If decentralised solar is to be used at home roof-top, a AC-DC converter is needed
  - Also, along with solar PV, battery storage is used
    - And battery is charged only by DC power and outputs only DC power
    - AC-DC converter and DC-AC converter is needed if AC power-line is used
      - Each of these converters have 15% power loss when power handled is of the order of 100 Watts
- With DC power-line at home, solar and batteries can be directly plugged in

Has time come to switch back?

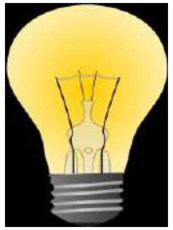
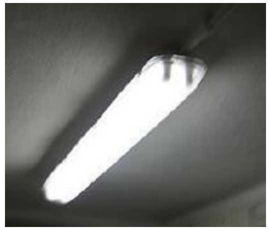


- To a DC power-line at homes and offices…
- The future appears to be there
  - And huge power savings even today
  - *But the legacy and the mind-set would be the bottleneck*
- Yet, little doubt that all homes will have DC power-line tomorrow
- May be in transition phase, one may have dual lines
  - A DC power line
  - And an AC power-line

L2: Appliances, Solar Panels and Batteries

- *Driving the case for DC Power-lines at homes and offices*
  - *Use of direct DC power replacing AC power*
  - *Choice of DC Voltage*
  - *Efficiencies, Availability, Costs*

Lighting

	Incandescent bulb	Florescent tubelight	CFL Bulb	LED Bulb/ tube-light
Wattage	60W	32W	11W	5W / 15W
Lumens/Watt	12	63	52	88
Life span (hrs) Approx.	1200	15000	10000	36000

Data is from our Lab tests/ estimations from specifications of some brands in market / internet

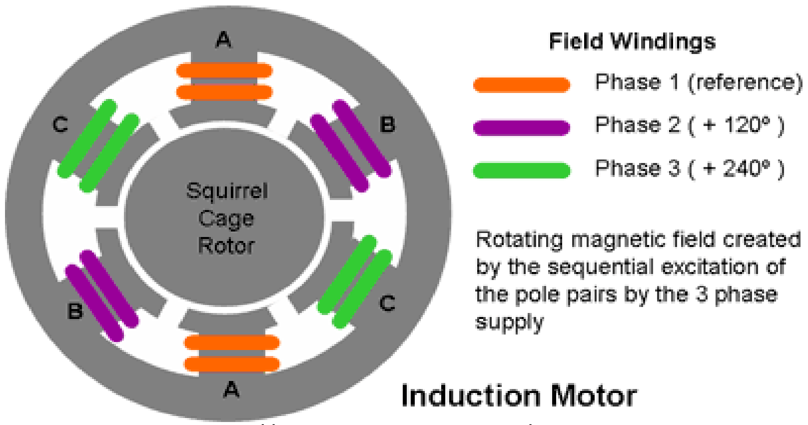
- LED bulbs and tube-lights need only DC power
    - Will need a AC-DC converter if AC power-line is used

Motored Loads is the next biggest load

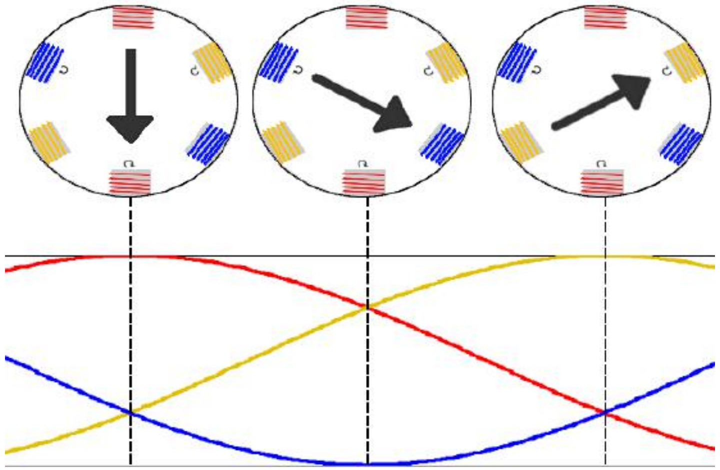
- Which are the motorized Loads?
  - Fans
  - Air Conditioner
  - Washing Machine
  - Water Pumps
  - Mixers and Grinders

- The Energy consumption and Efficiency of these appliances depend largely on the type of motor used

3 phase AC Induction Motor



Source: http://www.mpoweruk.com/motorsac.htm



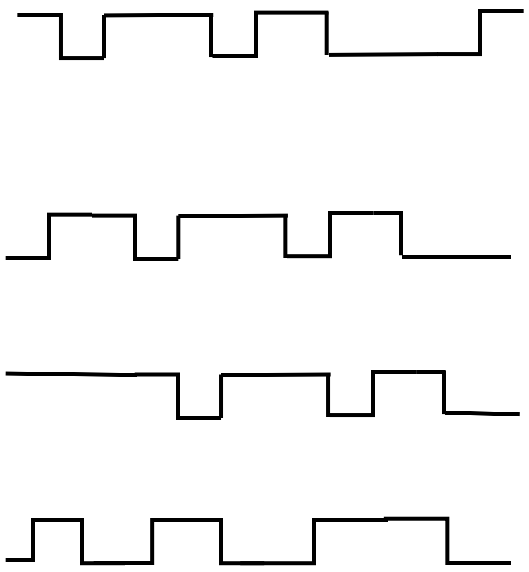
Source: https://en.wikipedia.org/wiki/Induction_motor

Working Principle

- 3 phase winding circuit on stator (with offset electrical angle of 120 deg) connected to 3 phase AC source: will make rotation smooth
  - establishes a rotating magnetic field in Rotor (with coil forming closed loop), rotates at a fixed synchronous speed
  - Speed of motor, Motor RPM = (120 X f) /P, where f = supply frequency (in cycles/sec), P = Number of motor windings pole

New Generation Motors: Enabled by Power Electronics

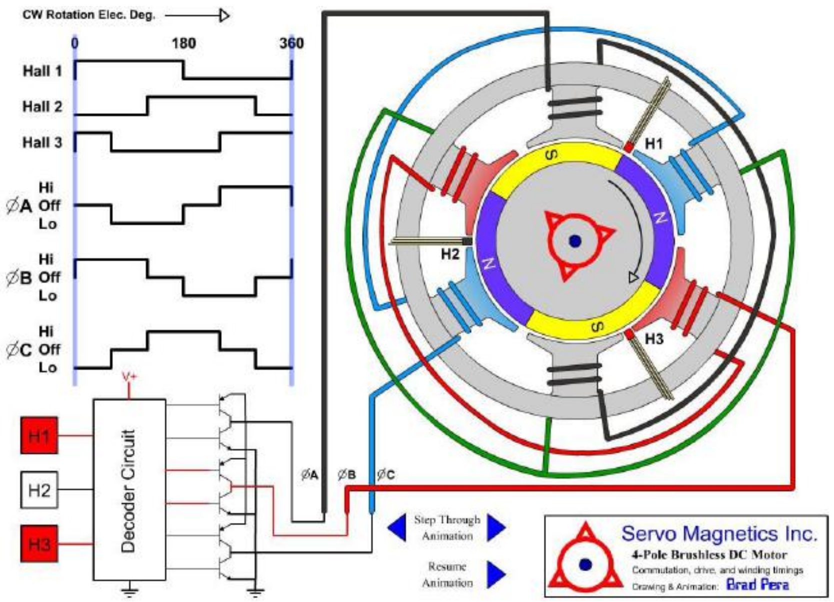
- Power Electronics gives us ability to design pulse shape for power signals
  - Signals with different pulse-widths, switching on and off at different times can create varying Magnetic field
  - Start with DC power Signals (if only AC is available, convert first to DC)
    - Create multiple signals (three or six or whatever) with frequency varying in time



BLDC Motor

Working Principle

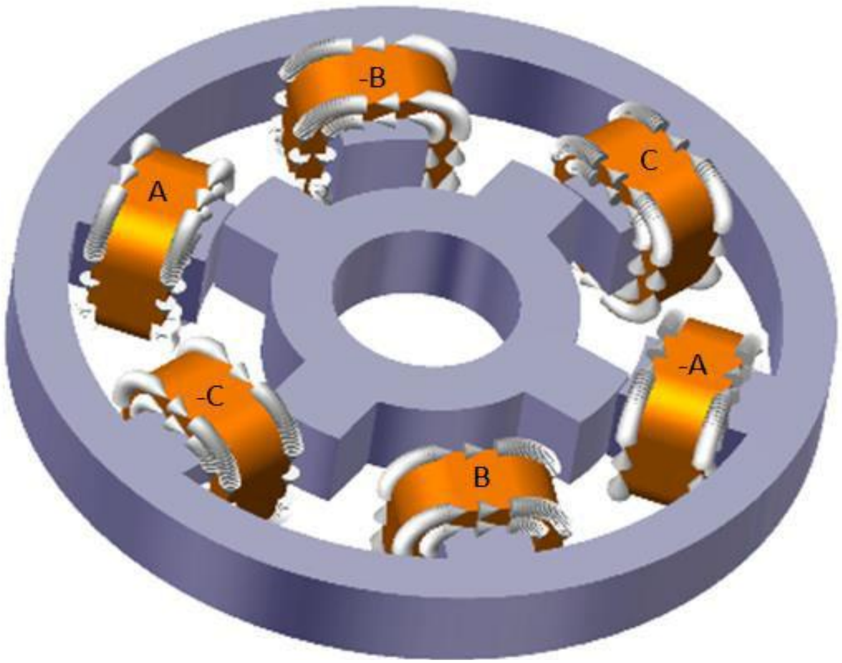
- Stator windings are supplied with varying current to produce magnetic field
- Power Electronics control the currents through the windings
- Rotor magnetic field created by permanent magnet
- Opposing magnetic field causes motor to rotate.



Highlights

1. Core and Rotor losses are nil so efficiency increased by 10 %
2. Mostly uses powerful Neodymium magnet
3. With speed change, efficiency remains constant
4. Very low power factor
5. Limitation: Dependency on permanent magnet and presently expensive

SRM Motor



China has 90% of rare-earth materials (like Nb) used in permanent magnet

- may control prices tomorrow
- SR Motors use only steel produced by SAIL

Working Principle

- Power applied to stator windings (6 poles) induce rotor magnetic reluctance: creates force that attempts to align the rotor pole with nearest stator pole
- Number of stator / rotor poles can be varied: 6/4 SR motor has 6 stator and 4 rotor poles
- Electronics used to switch on the windings of successive stator pole in sequence

Highlights

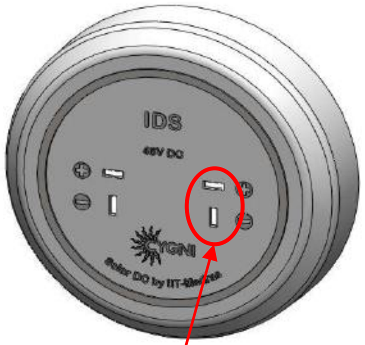
- No permanent magnets required
- Have torque ripple and noise: can be controlled by large number of poles and signal design

DC power-line for homes: will require Standardisation of Voltage

- Various Forums in India and the world are engaged in this exercise
  - IEEE Standards Association in India launched a LVDC Forum in April 2014, for micro-grids, commercial buildings and homes: recommended 48V DC
  - Bureau of Indian standards (BIS) set up a technical committee of academicians, industry personnel and researchers to look into the best voltages suitable for DC and the panel has recently recommended to use 48 V DC wiring at homes/offices premises
  - Central Electricity Authority (CEA), MoP, GoI set up a committee to study DC standards and have concluded that 48 V DC is most suited for use at homes
- While 48V DC voltage is becoming the de-facto standard for power up to 500W in each loop
  - 380V DC is being suggested for higher power appliances and systems (of the order of 1 to 10 kW per loop)
    - Will require special protection

DC power-line for homes and small offices

- 48V DC chosen due to
  - SAFE voltage: world-wide, 60V or less defined as Safe Extra Low Voltage (SELV) limit for deployment inside buildings without any specific protection for low-power appliances
    - 48V DC even with ripples and voltage variation will not cross 60V
  - Lower cable losses compared to 12V/24V DC systems
    - If cable resistance is R, losses are I^2R
    - For 100W, the losses will be approximately 4R for 48V, 16R for 24V and 64R for 12V respectively



- 48V DC is highest possible SELV voltage and gives minimum cable loss
  - Also used at homes with telephone lines, in telecom, electric vehicles, power over Ethernet etc.
  - Would require a polarised plug and socket to prevent reverse polarity connection

48V DC Appliances being made in India

LED Bulb
- 5W instead of 30W bulb


Phone Charger/Socket
- charger with USB port

DC-powered TV
- Consumes 30W along

LED Tube light
- 15W - dimmable to 4W, instead of 36W fluorescent tube

BLDC Fan
- 30W instead of 72W AC fan
- 9W at lowest speed

DC Desert Cooler
- Consumes 80W instead of 180W AC cooler

Remote Control for Fan & Tube light
- ON/OFF and for dimming

DC Mixer
- Consumes 150W, whereas AC Mixers consume 350W

Speed-control for existing AC Motor Appliances

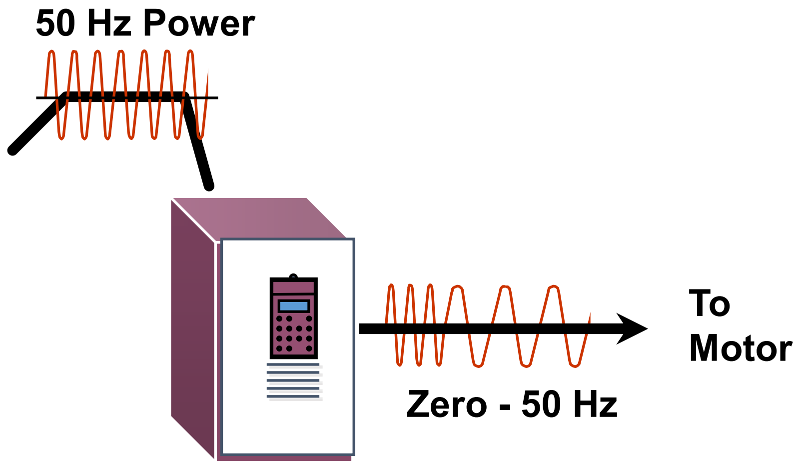
- Speed Control of AC Induction Motor enabled by a Variable Frequency Drive (VFD): can be retro-fitted
  - Huge amount of power saving
  - Low starting current
  - Controlled power factor

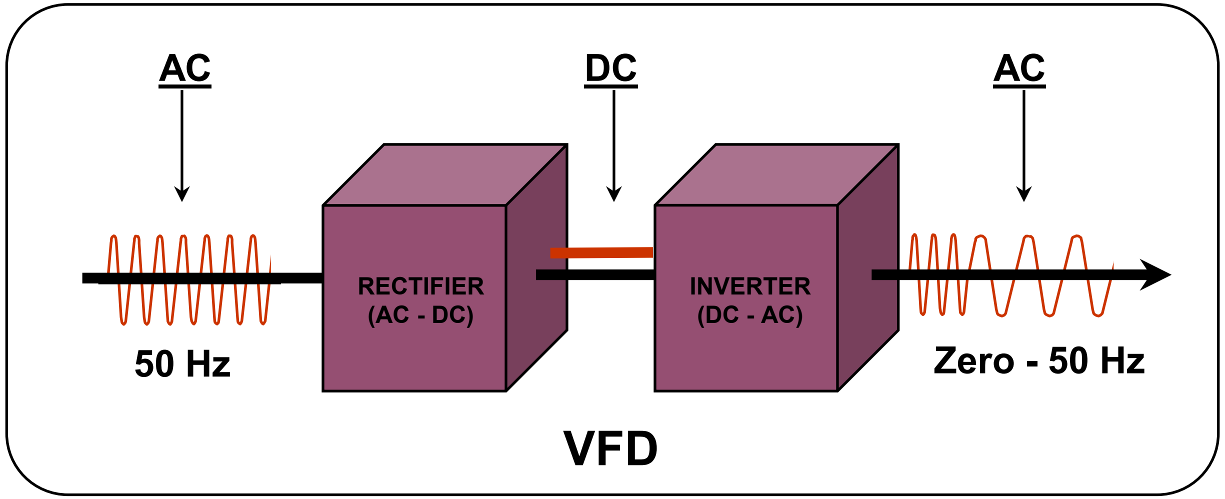
- Applications
  - Electric Vehicles
  - Air conditioning systems
  - Most industrial machinery
  - Lifts and pumps
  - Domestic appliances, fans, cooler etc.

Variable Frequency Drive

Ideally Powered by DC

- A variable frequency drive converts 50 Hz utility power into DC, then converts to a variable voltage, variable frequency output
  - By switching the inverter device on and off many times per half cycle, a pseudo-sinusoidal current waveform generated at desired frequency
  - Efficiency can improve at lower speeds

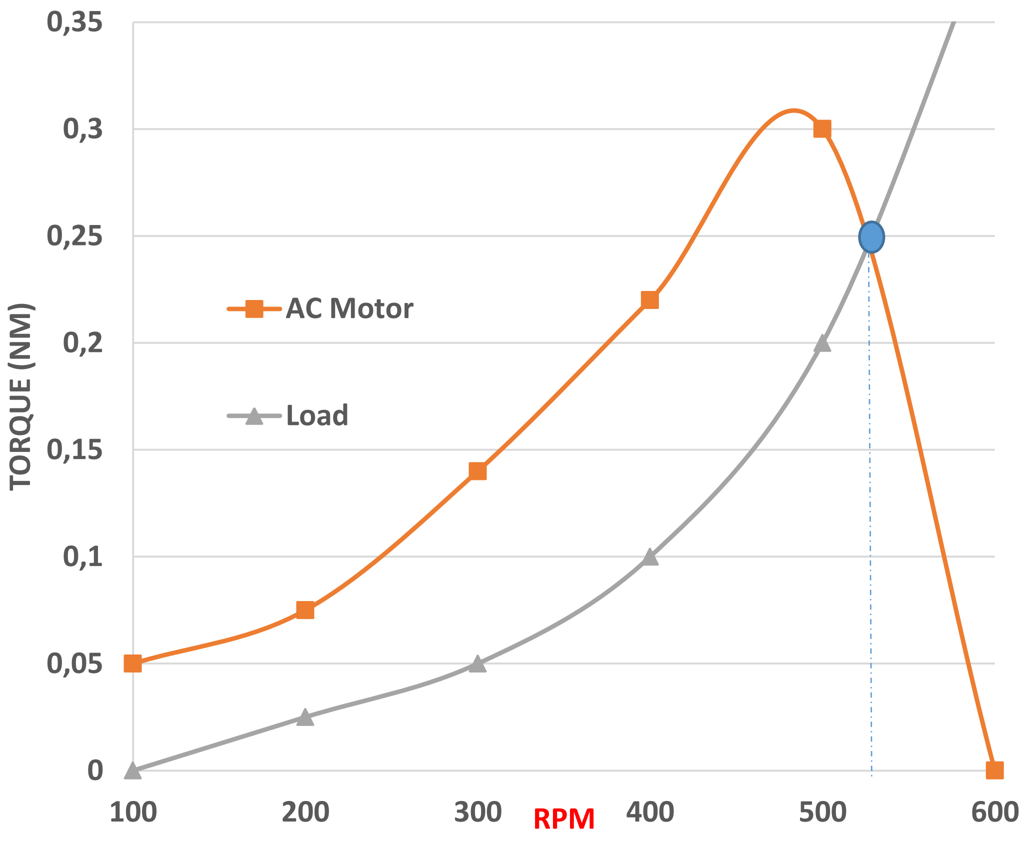




When Motors drive a fan

Air flow takes place: ceiling fans, blower fans, AHU

- Input Power Pi = Voltage x Current
- Mechanical Power, P_{out} = Torque(gen) x rpm
- Load curve for fan $\tau_L \propto (rpm)^2$
- Voltage ∞ RPM
- Current ∞ Torque
- Elect Power consumed ∞ (RPM)^3
- AC Induction Motor Torque (gen) Vs rpm meet load curve at rpm = 520



Solar PV Panels and cells

- India is endowed with vast solar energy potential
  - about 5,000 trillion kWh per year energy incident over India's land area
  - Distributed: most parts receiving 4-7 kWh per sqm per day
    - solar energy most secure of all sources and distributed
- Solar Cell efficiency: % of incident solar energy converted into electric
  - For example: 16.5% efficiency implies that 6 sqm of panels will produce power equal to solar insolation on 1 sqm
    - For 5000 Wh energy incident per sqm in a day would require 6 sqm of such panels to produce 5 kWh a day
      - On the other hand, 20% efficiency cells would need only 5 sqm panel to produce 5 kWh a day
    - Efficiency only affects the land area used, and not what a solar panel can produce
      - As solar panel is purchased for a certain peak W and its priced per W(p)

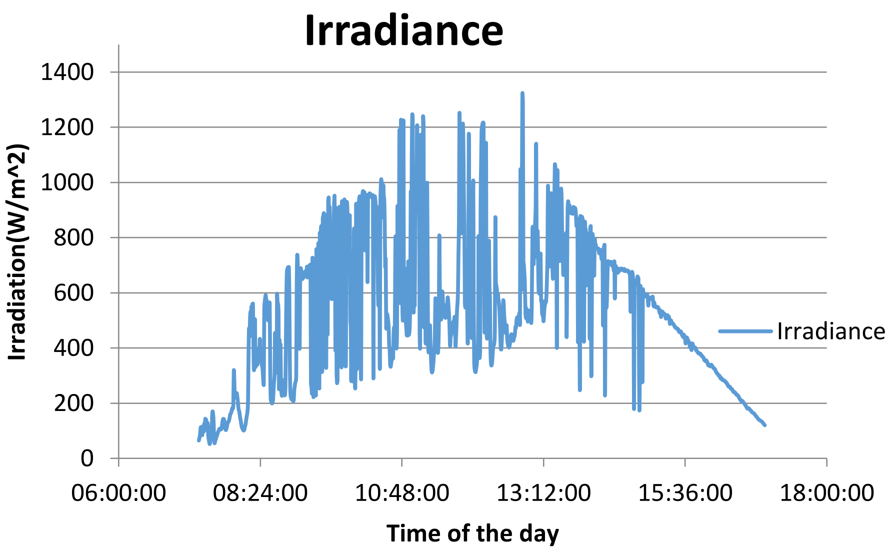
So how much will a solar panel produce?

- When one obtain a solar panel, one buys in terms of W(p) of solar panel
  - For example, a 125 W(p) of solar panel implies 125W will be produced, assuming 1000 W/sqm of solar insolation at 25°C Standard Test Condition (STC)
  - It will produce 125 Wh of solar energy per hour assuming that 1000 W/ sqm (1 SUN) is the solar incident during that hour: say from 12 PM to 1 am
    - Efficiency of cells does not matter, except it affects the land-area used

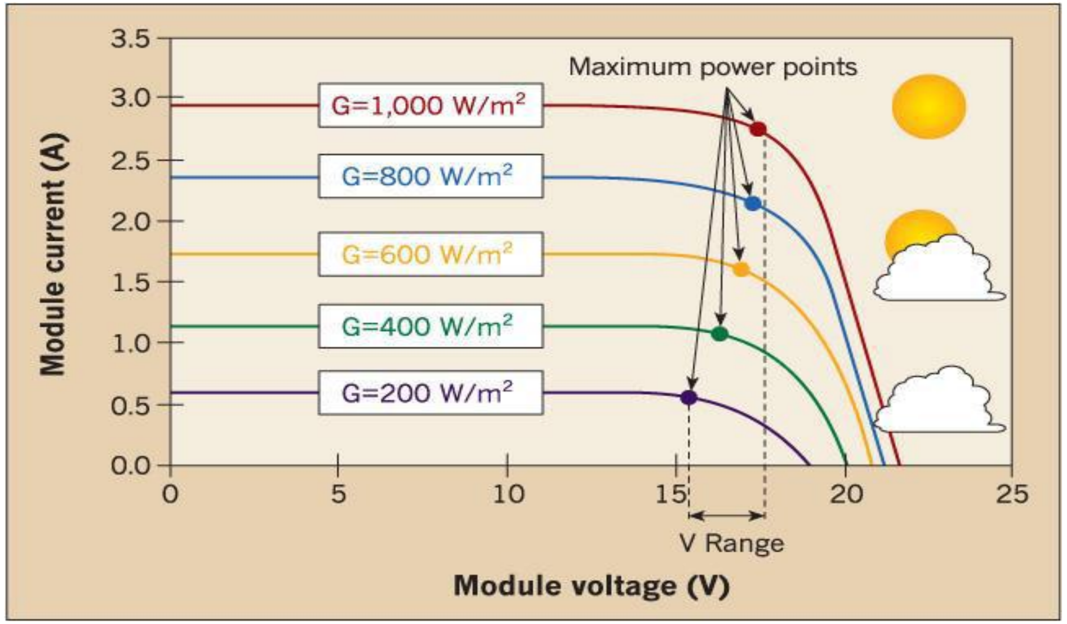
- But the solar power produced is DC
  - and the actual power produced at any time depends on
    - Actual solar incidence at the time (and the angle at which solar is incident)
    - Temperature of the panel
    - Circuit used: Is power drawn at MPP?

Power produce by a Solar Cell / Module

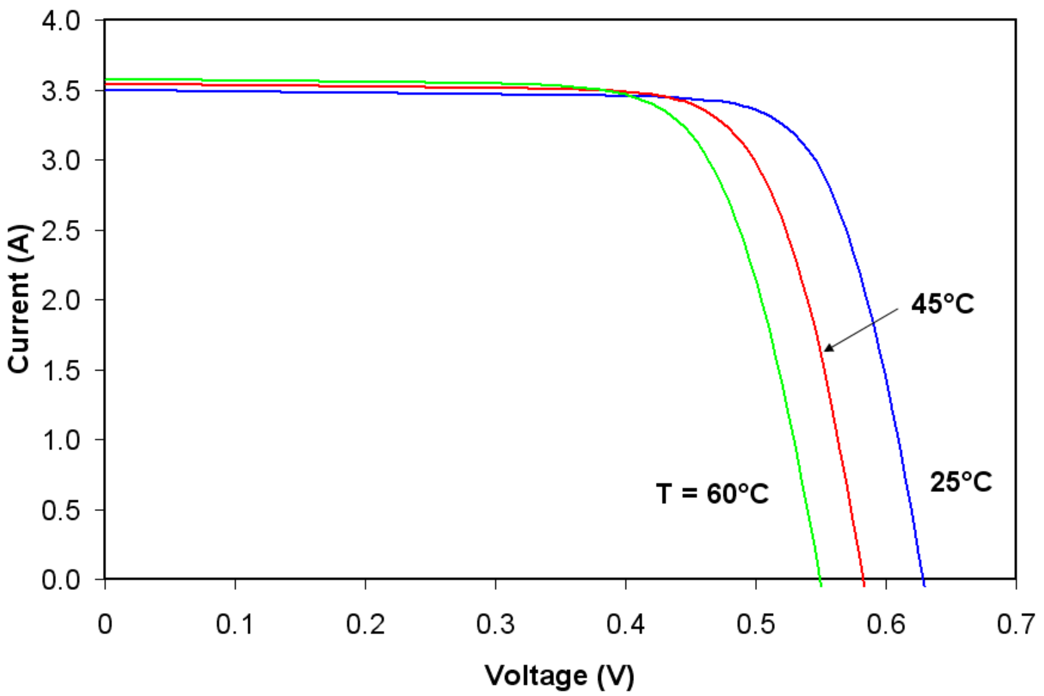
- Solar insolation increases gradually, reaches a peak and then decreases
  - can vary drastically in cloudy weather



- IV curve variation with change in insolation (G Watts/m^2)
  - Circuit to be designed so that operating point is Maximum Power Point (MPP)



Effect of Temperature



- Module operating temperature higher than ambient temperature
  - typically by 25°C to 30°C
  - if noon ambient temperature is 35°C, module operating temperature can go upto 60°C
- IV characteristics and MPP varies with temperature
- Variation in cell parameters
  - Isc: 30 to 35 mA/cm^2 → +0.06 to 0.1 % per ^{o}C
  - Voc: 0.5 to 0.6V → -2 to +2.3 mV per ^{o}C
  - Pmp: 10 to 15 mW/cm^2 → -0.4 to -0.5 % per ^{o}C

Angle of incidence matter

- As sun moves from morning to evening, actual solar insolation on the solar panel will vary
  - Tracking: ensuring that solar-cells face the sun and the full insolation falls vertically
    - Two-axis tracking will increase total solar incident in a day by 15 to 20%
  - Fixed tilt: orienting so as to give optimum power through the year
  - Manual tracking (seasonal): 5 to 6% gain over fixed tilt

Other factors impacting output

- Age of cells and defect of cells
- Cell matching in a module / panel
- Cable losses
- Losses due to connectors, switches and diodes
- DC to AC Conversion Losses
- Tilt used
  - Chennai 11° south facing
  - Hyderabad: 18° south facing
  - Gujarat 24° south facing

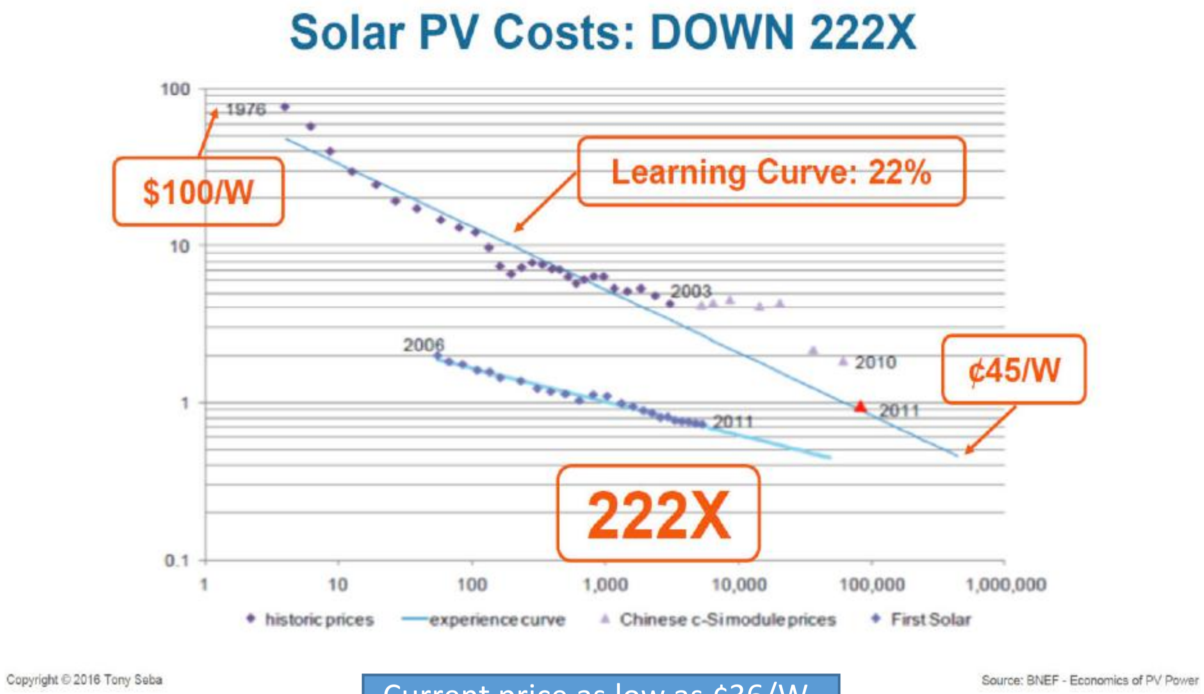
From Cells to strings to modules/ panels

- Solar cells can be connected in series to form a string
  - each cell = 1.6V nominal : MPP voltage is higher *(12V string may operate at around 15V)*
- Multiple strings connected in parallel to form a module (or panel)
  - If any cell in a string is partially/ fully shaded, it produces less / zero current : the whole string will generate only that much current
    - Even with one fully shaded cell, the full string will add zero current to module
  - If a cell is shorted, the string voltage goes down: module voltage will be equal to minimum voltage on all its strings
- Modules / panels can be connected in series and parallel
  - Current for modules in series is equal to that for module with minimum current
  - Voltage for parallel connected modules is equal to that of module with least voltage

Typical Economics as solar PV costs tumbles

- Assuming 300 days a year, 5.5 peak hours a day, a fixed tilt system may give 1650 kWh for 1 kW(p) solar
  - With about 12% losses due to panel temperature, cables and others
  - Net delivered 1452 kWh per year
- Cost (assuming 40% on BoS) per kW(p) = 0.36*68/0.6 = ₹40.8K
  - With 10% average interest and 25 year depreciation, and 2% OMC, cost per year = ₹40800* 0.16 = ₹6530
  - Per unit cost = ₹6530/1452 = ₹4.50

BOS includes mounting structure, Inverter, protection



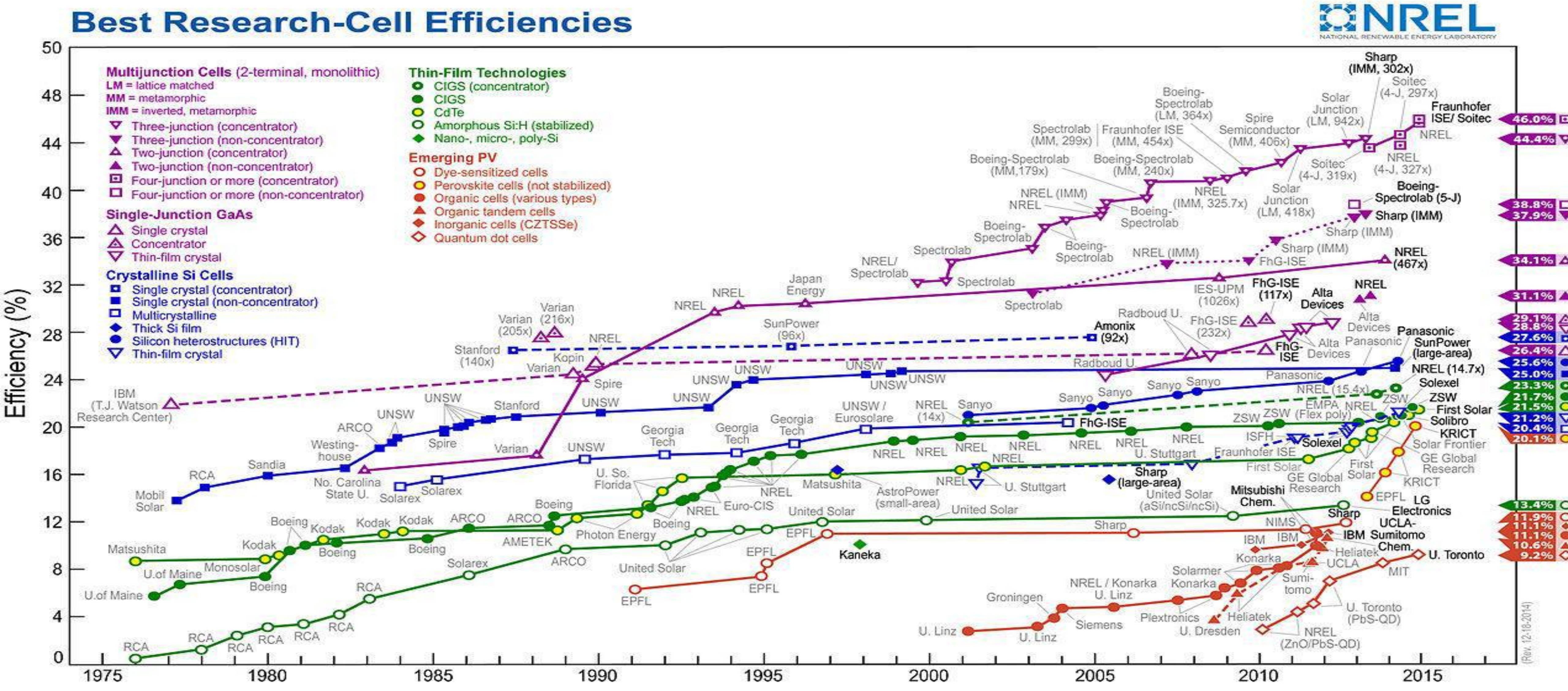
Current price as low as ¢36/W_p

Decentralised solar panel at roof-top

- Can produce power depending upon sunlight availability
  - In most parts of India, sun shines brightly between 300 to 325 days an year
  - Average power produced per W(peak) of solar panel varies from 1450 to 1650 Watt hours per year
    - Equivalent to 4 to 4.5 hours of equivalent peak power in a day
      - Sun is available almost 12 hours on most days
  - Solar panel need to be mounted at specific south facing angle depending on location longitude for maximum power

- Solar efficiency corresponds to area needed to produce a Watt (p) of power
  - 1 sun = $1000W/m^2$
  - 16% efficient solar cell (costs about ₹25 per Wp) produces peak power of $150W/m^2$
    - Or 1 kW(p) would require about $6.5m^2$ solar panel
  - R&D on for improving efficiency; as high at 46% in labs -- very expensive

Cell efficiencies



Why Batteries?

- When solar is used to drive some electrical load
  - Supply has to match load at every instant of time
  - As solar power fluctuates (as sunlight fluctuates), exact matching to load not possible
  - Need some balancing source / sink equal to (Load – solar power)
    - Electrical Grid can be used as source of balance of power or sink to excess power (net-metering)
    - Electrical Batteries can be used as source (battery is discharged) or sink (battery is charged)
- Solar power available only in day-time
  - Batteries can store power for usage when sun is not available
- Other applications: portables
  - Surrounded by batteries all around us for most of our common usage
    - Laptops, Mobile phones, Inverters, Watches, calculators and what not !!

Battery Performance Parameters

- Battery Capacity [C] defined either in Wh or in terms of Ah (voltage x Ah will give Wh)
  - For example, 1 kWh (more exactly 0.96 kWh) battery could be
    - 48V 20Ah battery or
    - 24V 40 Ah battery or even 12V 80Ah
    - Cells are 2V (Lead Acid) or 3.7V (Li Ion)

- Rate of Charge/discharge
  - 0.1C charge / discharge rate for 1 kWh battery implies rate of 100W
      - or 2A charge / discharge rate for 48V battery
    - 10 hours to charge from empty to full
  - 0.2C rate implies charge / discharge rate of 200W
  - 1C rate implies charge / discharge rate of 1000W: in 1 hour battery can be fully charged
  - 2C rate implies charge / discharge rate of 2000W: full-battery charge in 30 minutes

Some More performance parameters

- State of Charge (SoC): percentage of total charge at which the battery is currently at
  - 70% SoC implies that battery is 30% empty and 70% full

- Depth of Discharge (DoD): percentage of battery full capacity to which battery will be utilised in a normal discharge – charge cycle
  - Depth of discharge of 40% implies that battery can be discharged to 60% of its capacity
  - It is the extent a battery can be used to power the load
  - Batteries when operated beyond rated DOD, have their lifetime reduced

Battery Life

- Maximum number of Charge-Discharge cycles before its capacity degrades such that it can not be used further (say its capacity degrades to 80% of its original capacity)
  - It is number of times the batteries are charged and then reused
  - Is a function of DoD as well as Charge/ Discharge rate used as well as temperature
- Example: For a specified battery lifetime of 1000 cycles
  - Battery will come to an end in 100 days if it is charged 10 times a day
  - Or It will last for 1000 days, if it is charged once in a day
  - Further, if DOD exceeds the rated DOD, it will decay much faster
  - Also if charge / discharge rate is higher than specified, it will decay faster
- Battery life also impacted by temperature and age: age impacts typically beyond 5 years

Some Typical Battery Parameters

Battery type	Cycles(max.)/ DOD	Charge time	Discharge per month	Density	Cell voltage	Peak Drain	Optimal Drain
NiCd	~1500 / 80%	1h	20%	41	1.25	20C	1C
NiMH	~500 /80%	2-4h	30%	51	1.25	5C	< 0.5C
Lead Acid	~1000 /50%	8-16h	5%	30	2	0.2C	0.2C
Li-Ion	~3000 / 80%	2-4h	5%	100	3.6	2C	1C

Battery Costs

- Battery Costs depends on energy stored (capacity in kWh), chemistry and life-cycles, DoD and rate of charge -discharge
  - Not on voltage used: 1 kWh battery at 12V or 24V or 48V will typically cost same
- Example
  - 1 kWh Lead Acid battery costs ₹6000 (all at 25°C)
    - 800 cycles with 50% DoD (only half capacity used) and 0.1C charge / discharge
    - 400 cycles with 80% DoD or even with 50% DoD but 0.5C charge /discharge
  - 1 kWh Li Ion Battery may cost ₹20000 (less impacted by temperature)
    - 2000 cycles with 90% DoD and 1C charge / discharge
    - Costs may be ₹15000 for 1000 cycles with 90% DoD with 1 C charge / discharge
    - Costs may ₹25000 for 3000 cycles with 90% DoD and 1 C charge / discharge

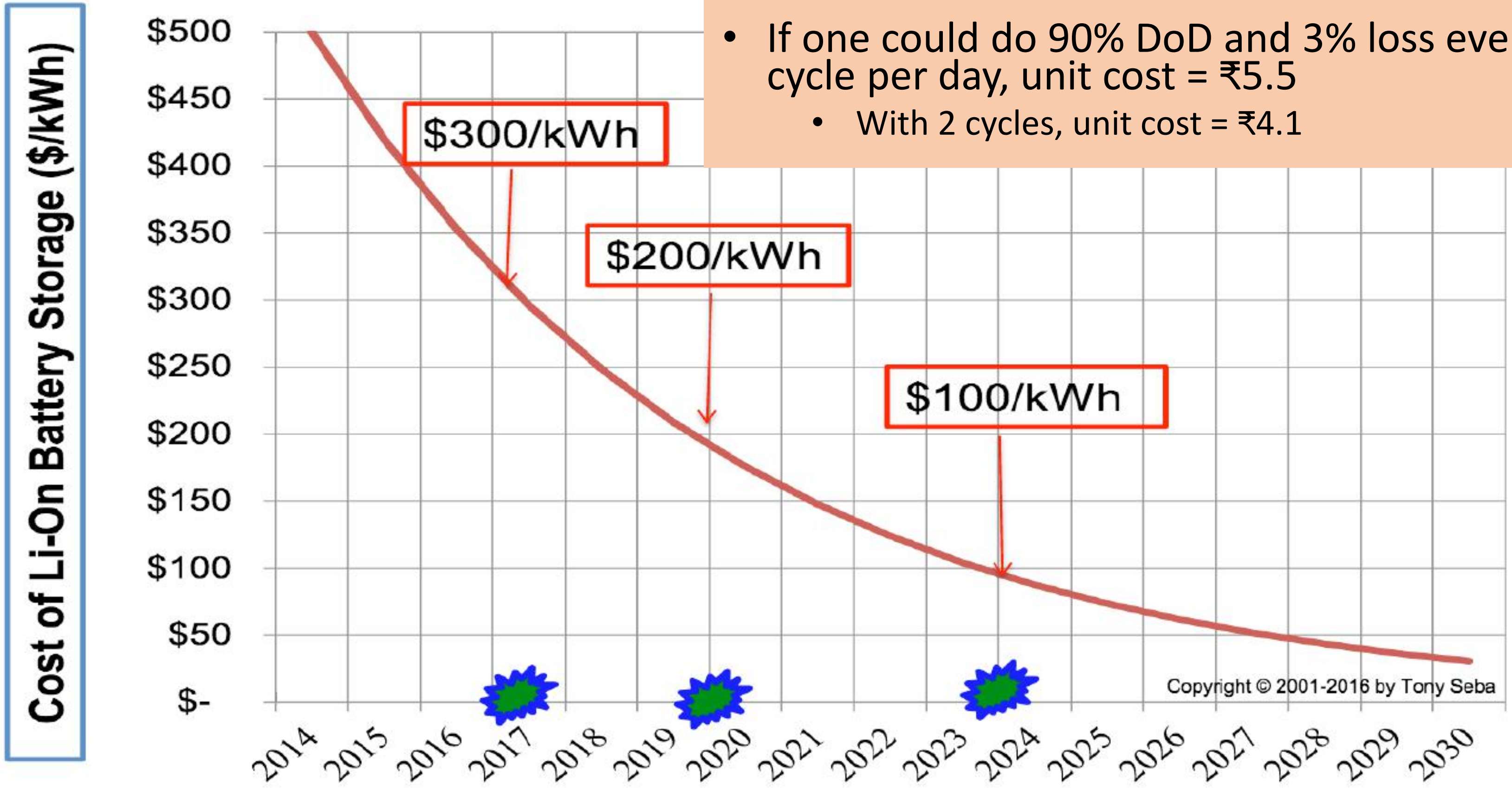
Amaraja and IITM have innovated

- To come up with hi-performance Le
  - 1 kWh battery at ₹7200 (48V 24 AH)
  - 1600 charge –discharge cycles
  - At 50% DoD and assuming 0.1C charg
- Probably the best available current
  - See sample calculation in Indian cont

- 1 kWh with 50% DoD, 1600 cycles assuming 1 cycle per day (4.4 years lifetime)
  - Total usable energy per year (assuming 10% losses) = 1000 Wh *0.5 *365 * 0.9 = 164 units
  - Cost per year = depreciation + interest at 12% (not including charging costs) = ₹7200* [(365/1600) + 0.12] = ₹2506
  - Cost per unit = ₹2506/ 164 = ₹15.3 (plus charging)
- If 2 cycles per day, cost per unit = ₹12.6 per unit plus charging costs

LI Ion Battery Costs falling very rapidly

- Assuming 3000 cycles, for $100 cost
- If one could do 90% DoD and 3% loss even with 1 cycle per day, unit cost = ₹5.5
    - With 2 cycles, unit cost = ₹4.1



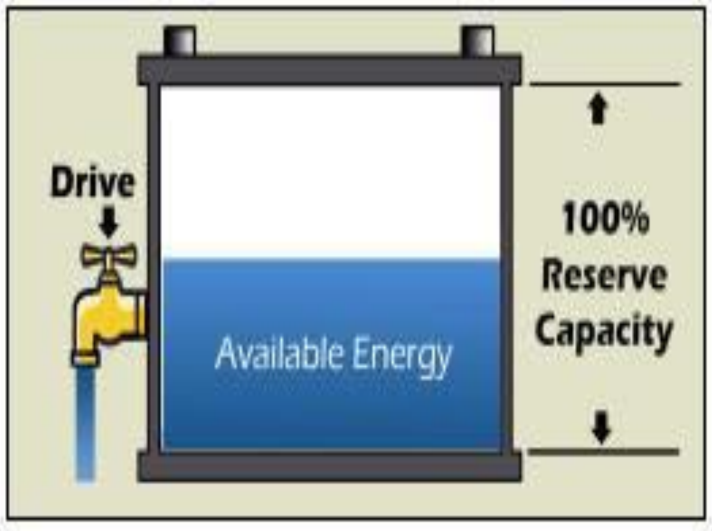
Battery charging and impact on Lifetime

- Is it good to keep charging the batteries (always on power, if possible for certain applications) to avoid their discharging?
  - No, overcharging of Batteries is equally or even more damaging
  - Extra current flowing through the batteries drain its electrolytes. Batteries decay faster even without usage
- Charging the Batteries with right amount and for right duration becomes critical in determining the Battery lifetime [BMS]
  - Equally important is to keep monitoring the status of batteries to know the right charge-discharge status of the battery

- Thus, careful designing of Battery Chargers is crucial, taking care of battery status and amount of charge needed for right duration

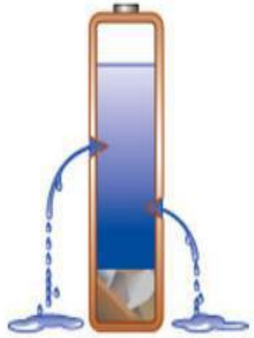
Beyond SOC

- Can we determine the Age of battery, i.e. the cycles/lifetime remaining in the battery?
  - Not very accurately, but we can estimate !!
  - Referred to as age/health of a battery tells us “State of Health (SOH)”
    - represents the amount by which battery has deteriorated due to irreversible physical and chemical changes
- Periodically completely discharge and then charge the battery (track oc voltage) and then again discharge slowly and carry out the coulomb count
    - Give several hours rest after full charge
  - Indicates total amount of charge that the battery can hold currently
  - Compare it with past data
    - Gives an estimate of SoH

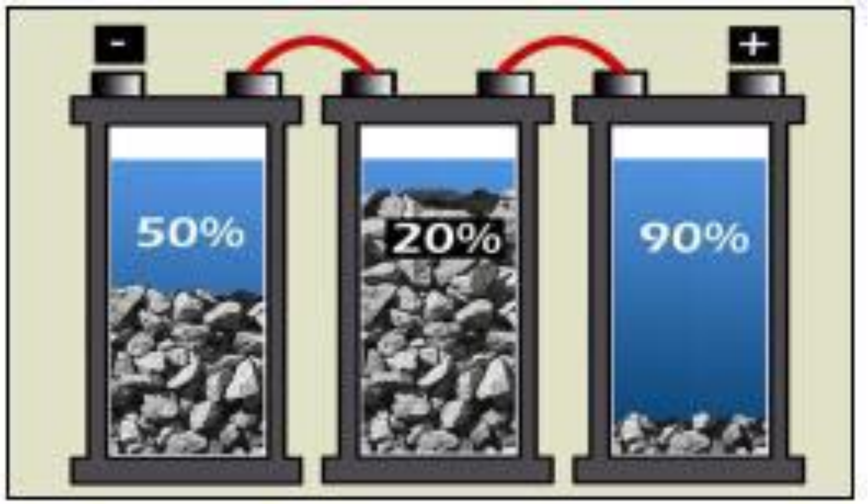


Self-discharge of battery

- Self discharge defines the rate at which the battery looses its energy while on shelf



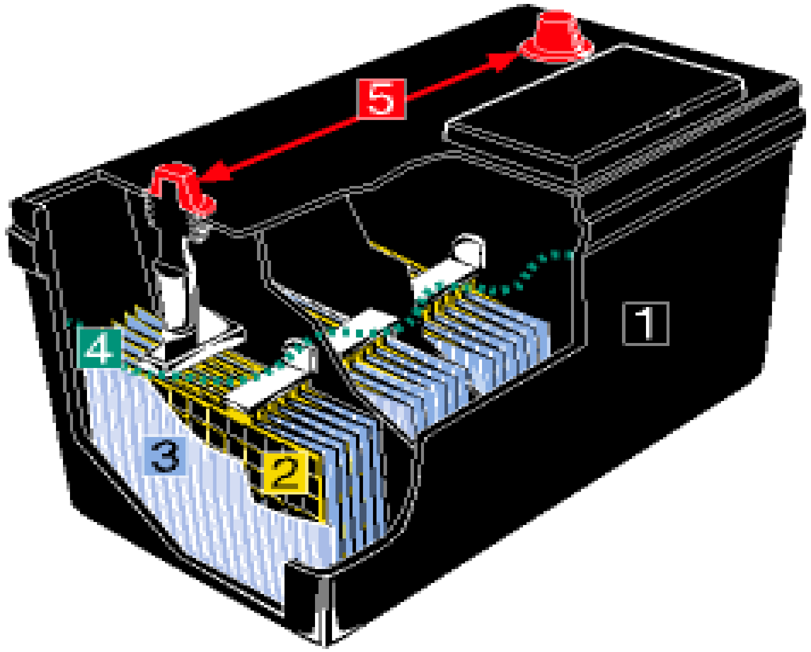
Battery System	Estimated Self-discharge
Primary lithium-metal	10% in 5 years
Alkaline	2-3% per year (7-10 years shelf life)
Lead-acid	5% per month
Nickel-based	10-15% in 24h, then 10-15% per month
Lithium-ion	5% in 24h, then 1-2% per month (plus 3% for safety circuit)

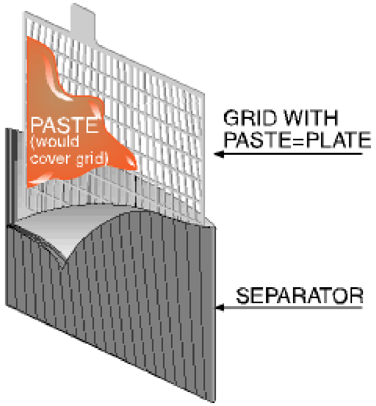


- If the test results in 30% self discharge per month, discard the battery

Lead Acid Battery components

- Every Cell (also called element) has
  - Plastic Container
  - Positive/Negative Lead Plates
    - Positive plates are made of antimony covered with active layer of lead di-oxide
    - Negative plates are made of lead covered with active layer of sponge lead (Pb)
  - Separator between set of Plates
  - Electrolyte in between two plates
  - Lead terminals

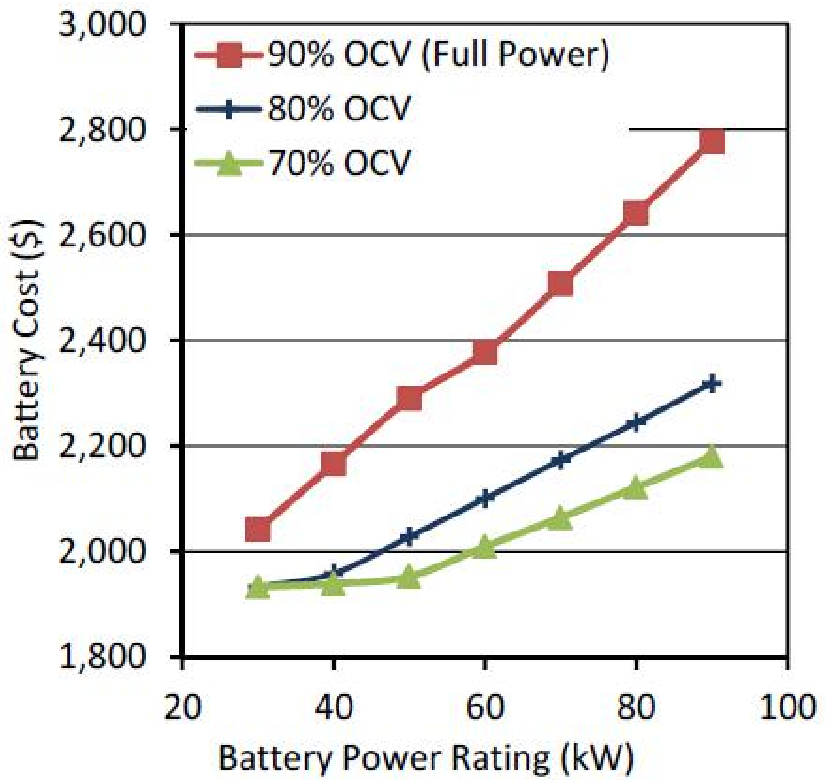




Cells to Module and Modules to Pack

- Multiple Cells packed in parallel to form a Module
  - Cells selected so that they are of same voltage
  - Cells are connected with a metal that conducts electricity
- Multiple Modules in series to form a battery Pack
- Battery Management System (BMS) a must to get optimal performance
  - Especially for Li Ion batteries
- Cell equalisation during Charging
  - Monitor voltages and temperature of each module and total pack current
- If a module is over-charged (impacts life), equalise by
  - Passive balancing: bleed module with higher charge through a resistor, so that it charges slower, or just drain it
  - Active balancing: stop charging module with higher voltage; instead, use its output to charge the rest of pack (using a DC-DC converter)
- BMS could limit temperature of each module if active cooling is done

Secondary Use of batteries

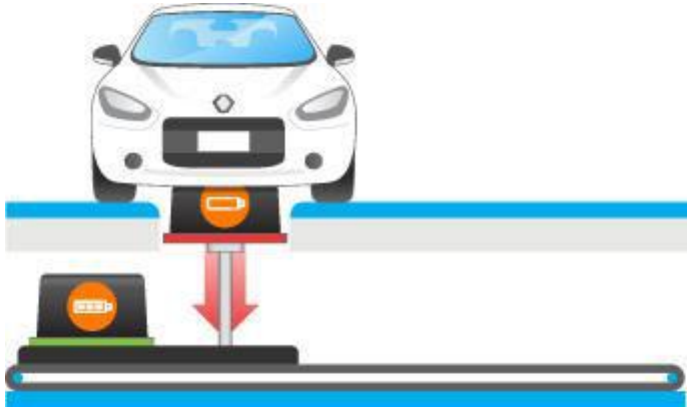


Source: Battery Testing and Analysis, Annual Progress Report. Argonn National Laboratory, 2013

- Even though a battery may not be usable in one application because of the required SoH, it may be usable in another
- Need to encourage Secondary usage?
  - Sound Retirement Policy
  - Alternative Use Cases

Battery Swapping

- Why Battery swapping is an option?
  - Easier replacement, time saving in refuelling
  - Avoiding big investment for replacing old batteries



- Where does this option find the best Use case?
  - In situations of high usage of batteries or high requirement of charge-discharge rates
  - Specially for heavy vehicles like buses or other transport vehicles
  - Fast charge is an option but frequent fast charge may damage the battery and reduce the life drastically

Car Battery Swapping station

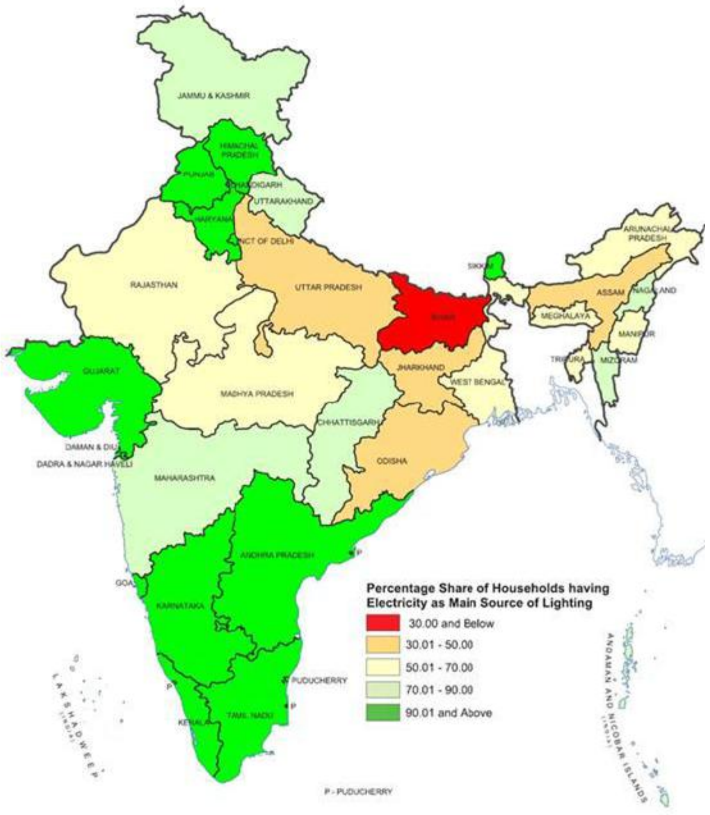
L3: Load-shedding and Solar-DC solution & UDC Innovation

Go Inverterless

Power for Indian Homes: Dilemmas

Even as India moves away from power-deficit situation

- Indian Power Scenario
  - 50 million homes not connected to grid
  - About 100 million homes have load-shedding between 2 hours a day to 12 hours a day
  - 50% of Indian homes can not afford power even at subsidized rates
    - At this tariff all DISCOMS lose money



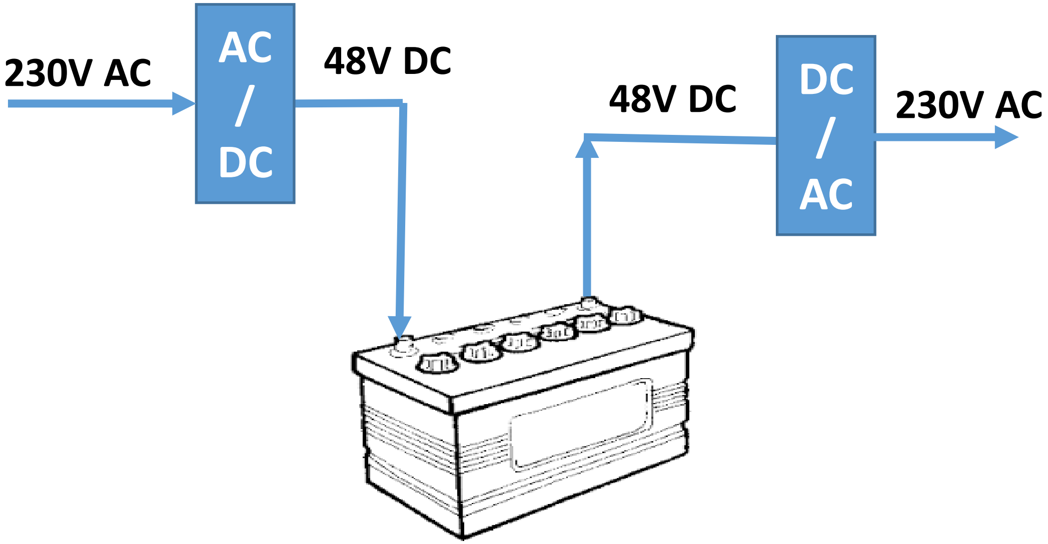
Low ability to pay and low Power consumption

- At the same time, a large section of Indian homes have low ability to pay
  - Tariff-hikes are socially resisted
  - Many homes can not afford to pay over ₹100 to ₹200
- And how much do the connected homes Consume?
  - Total domestic consumption: 200TWh per year for 1.25 billion people
    - An average of about 500Wh/day per person or 2.5 kW per home /day
    - Average power consumption for grid connected homes is only 4 kWh per day (33% homes do not have power)
    - 100W to 500W peak load
  - Most lower-income homes consume even lesser

What happens when power fails?

- Some upper income group home and multi-storied apartments use Diesel Generators
  - Cost of DG power per unit is five times the grid-tariff
- Some middle and lower-middle class homes use Inverters
  - Cost of Power still about 4 times that of grid-tariff
- Others just suffer without power

How are Inverters designed?



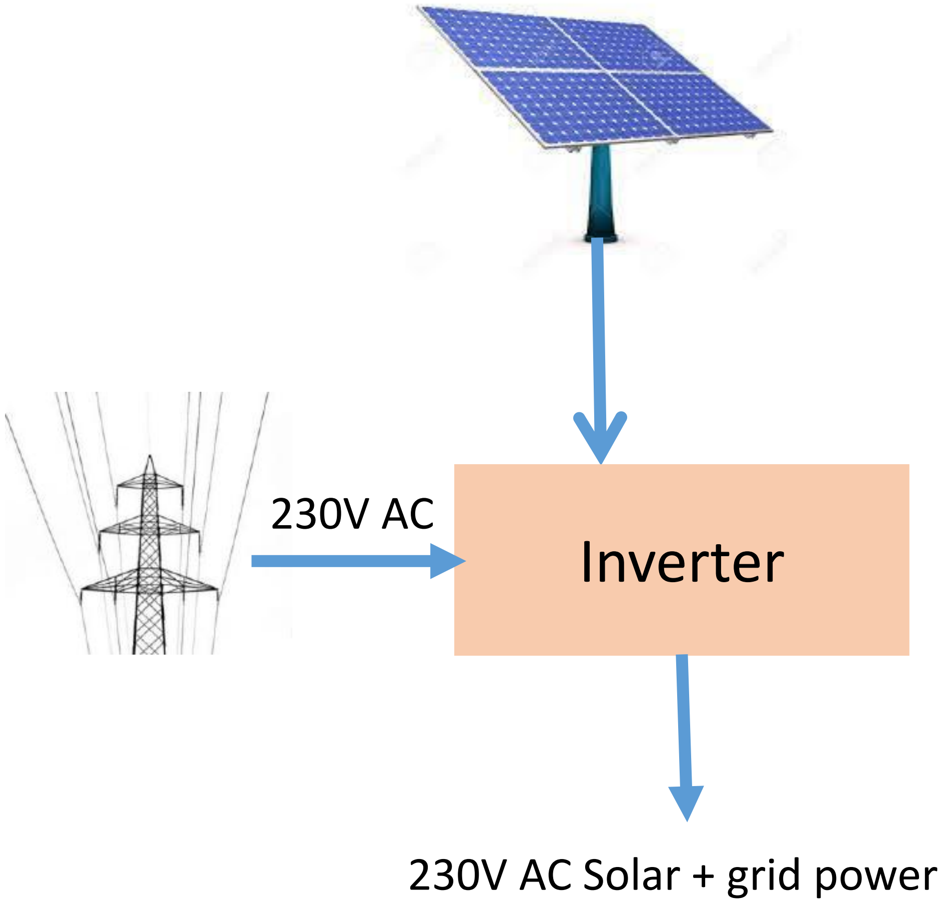
- AC from incoming grid is converted to DC, to charge battery
  - Typically 50 to 54V DC, for 48V battery depending upon SoC
  - Battery can also be 24V / 12V
- On power out
  - battery output is converted back into AC (230V) to drive load
- Battery charge / discharge rates limited to 10% of capacity (VRLA) for long battery life

- AC-DC and DC-AC converter losses can be less than 5% for each converter when charge / discharge rate of battery is 5kW or larger
  - But for charging / discharging rates of 100W to 500W batteries, losses can be 15% or higher for each conversion
  - Most home batteries less than 5 kWh, giving charge / discharge rates of less than 500W

Will roof-top Solar PV help?

- Grid-synchronised Inverters are commonly used with solar PV panels
  - They covert DC power from solar to AC
  - Synchronise it with AC grid
  - Outputs combined solar + grid power

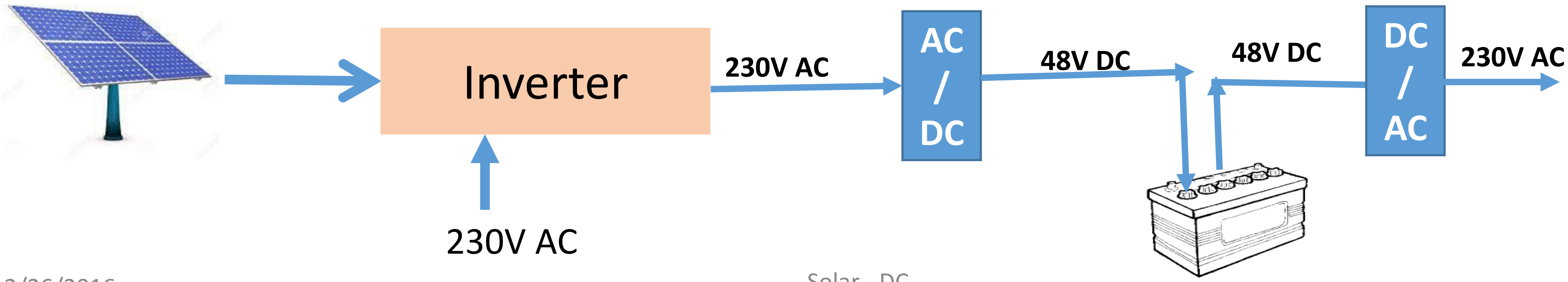
- Typical inverter has power efficiency of 97% for 10 kW power and costs small fraction of panel
  - But if solar panel is 200W
  - Losses are over 15% or higher if inverter cost is not very high: some fraction of panel costs



Will Solar PV help overcoming power-cuts?

- Not on its own!
  - Solar power is available only for certain hours
  - If grid-power fails when sun is not shining, one will be without power
    - Also, grid-synchronised Inverters shut down output when grid-fails, even if sun is shining
      - Otherwise solar power generated must exactly match the load at each instant of time!

- What is the solution?
  - Use battery back-up along with solar: provides back-up for solar + grid power!

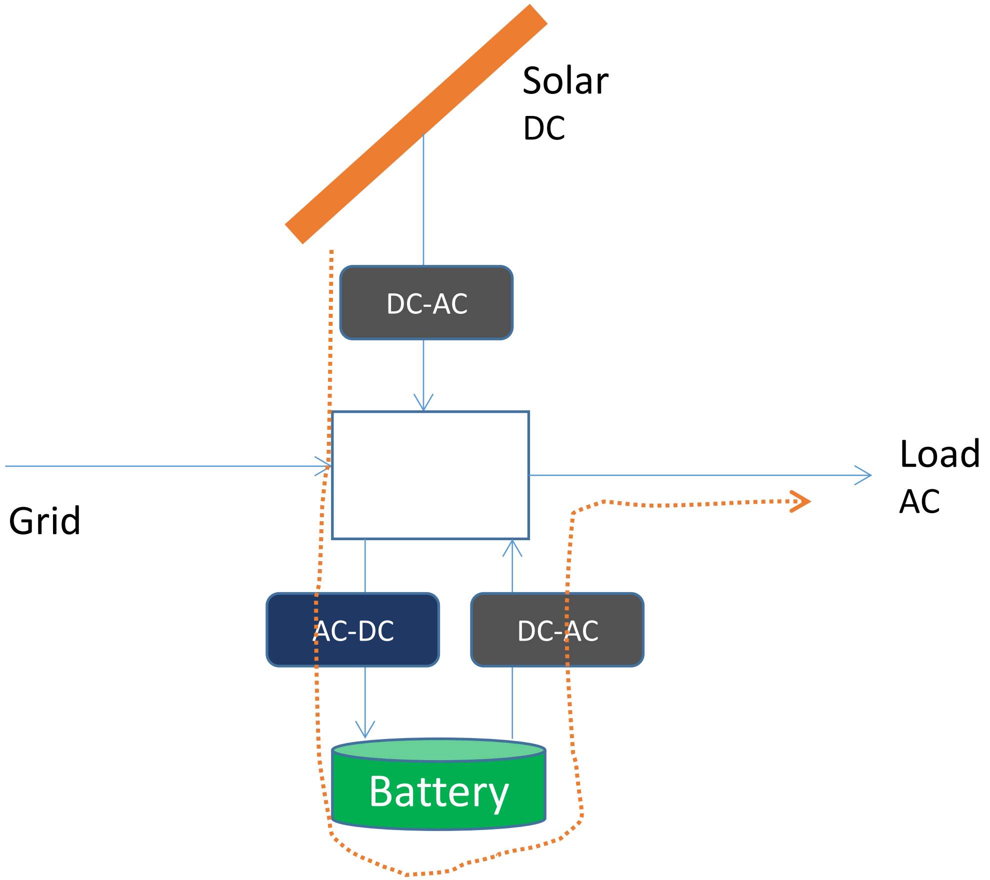


But the consequences!!!

- Grid and solar would now charge the battery and also supply AC power to loads
  - During load shedding, solar and battery will feed load
  - When solar is not there, grid alone will supply the loads
    - And if now grid fails, battery will supply the loads

- But the solution has serious limitations
  - Solar PV power costs similar to grid-tariff, but introduction of battery quadruple the per unit costs
  - Solar PV power has losses at inverter and then at battery charger and again when battery output is converted from DC to AC
    - For 100 to 200W solar panel, each conversion will contribute to about 15% losses
    - amounting to a total of 45% in addition to battery losses

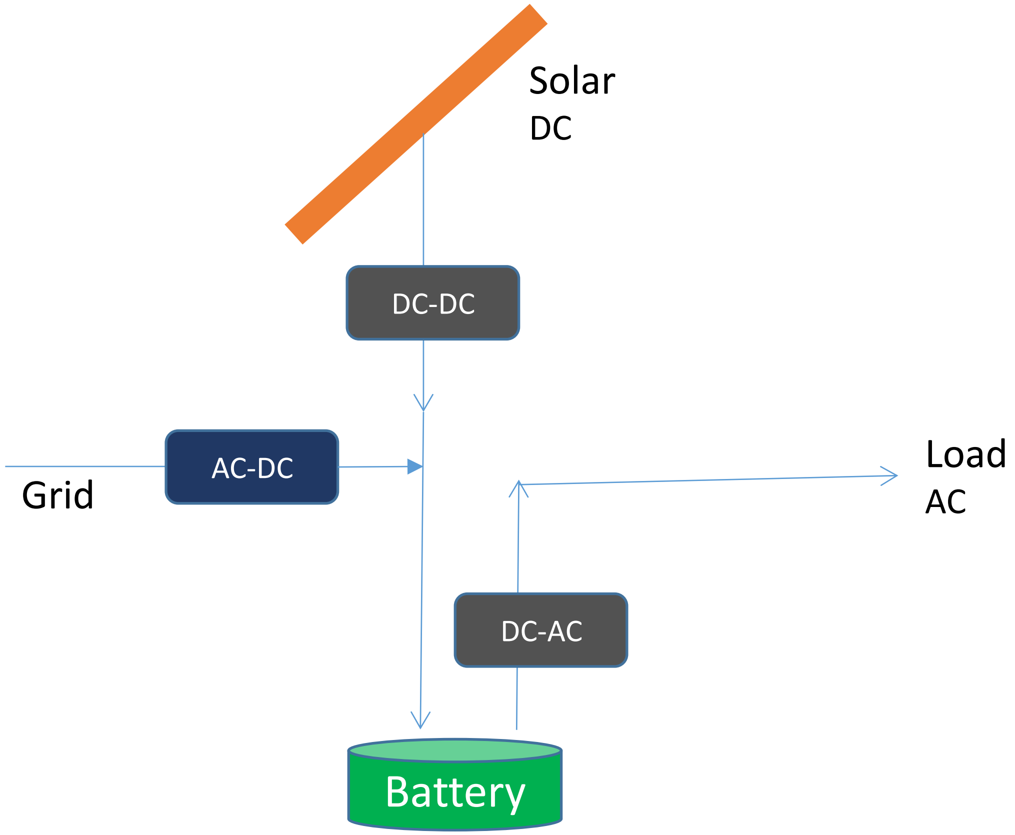
To Recap: Decentralised Solar Power at Homes



- Solar PV gives DC Power
  - But load is AC
  - Needs a DC-AC convertor
- Now if we add a battery
  - Battery stores only DC
    - Require a AC-DC convertor for charging
    - Require a DC-AC convertor during discharging
- For low power, each convertor can have up to 15% loss
  - Solar with battery may have up to 45% loss

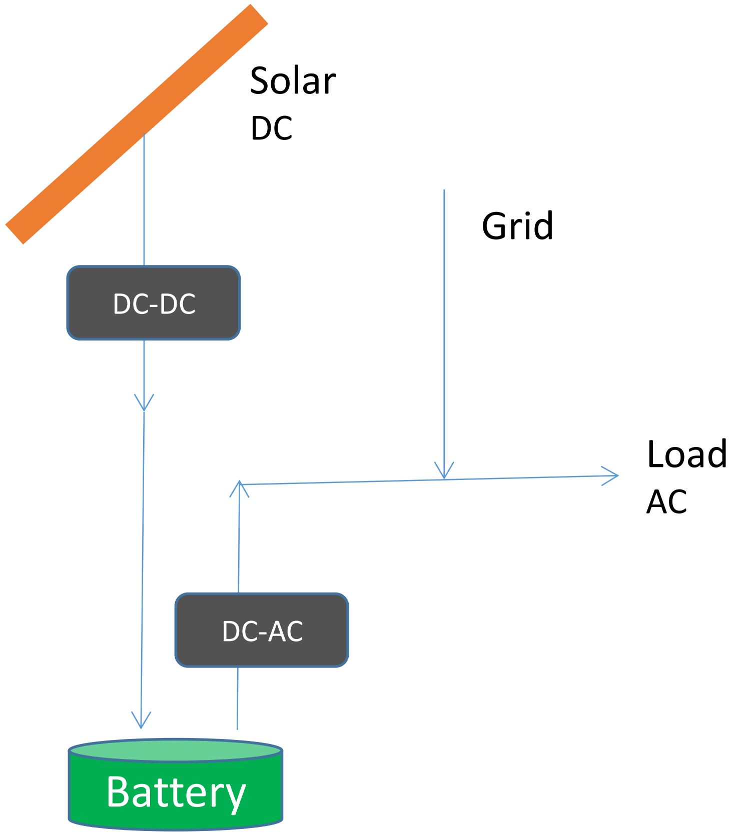
Can we do something better?

- Why cant solar DC directly charge battery?
  - It can; but now solar power always reaches load though battery
  - Even grid goes through battery
  - Solar and grid can not be used to directly power the load (by passing battery), even though solar + grid power > Load many times
    - Additional losses



Another Alternative

- One can connect grid directly to load at the output of battery
  - But then grid power can never be used to charge the battery!
    - On rainy days, battery will be discharged
  - Solar still always goes through battery, even when it could have directly drive load
    - Additional losses



Decentralised Solar-AC system

- Do Western countries face this problem when they use decentralised solar AC system? NO
  - Typical home deployment of solar is 5 kW to 10 kW, if not larger
  - For 10 kW solar panel, losses at each converter can be reduced to under 5%

  - Also, most of them rarely have load-shedding: So may not use battery at all
  - Normally solar power generation is less than required by load: Infinite grid will supply power so that solar + grid power = power required by load at each instant of time
  - If solar power generated is higher than the needed load, excess power (solar – Load) is fed back to the grid (grid feed-through with net-metering)

Our mid-income and lower-income homes

- Would rarely install solar panel greater than 1 kW
  - Mostly lower (average home consumption in India is 2.5 kW in 24 hours)
  - Losses at each converter will be 15%
  - Solar-AC with battery implies loss of 45% of expensive solar power
  - Grid feed-through makes little sense

- We need something different!

And it gets Worse as home-loads move to DC

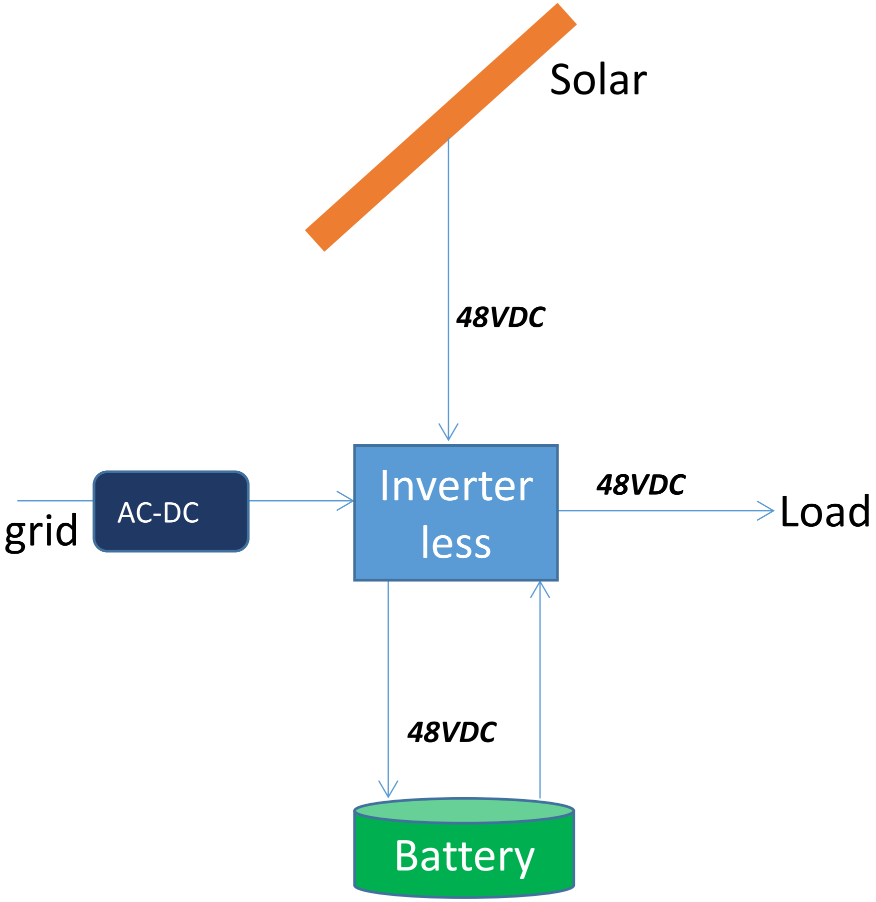
AC fan	72W	BLDC fan	30W
at speed 1	60W		9W
CFL tube	36W	LED tube	15W
low intensity	na		4W

Volume prices similar for fans

LED tube life much longer (DC powering enhances reliability)

- All Electronics devices work on low-voltage DC
  - TV (LED/LCD), laptops. Cell-phones, speaker-phones, tablets, speakers
    - AC to DC conversion has losses from 20% to 50% in each device
- Even the refrigerators, air-conditioners, grinders, mixers, washing machine in future is with BLDC or SR motors
- Use of DC-powered and energy-efficient devices
  - Consumption down by 50%

Inverterless: A Solar-DC battery back-up

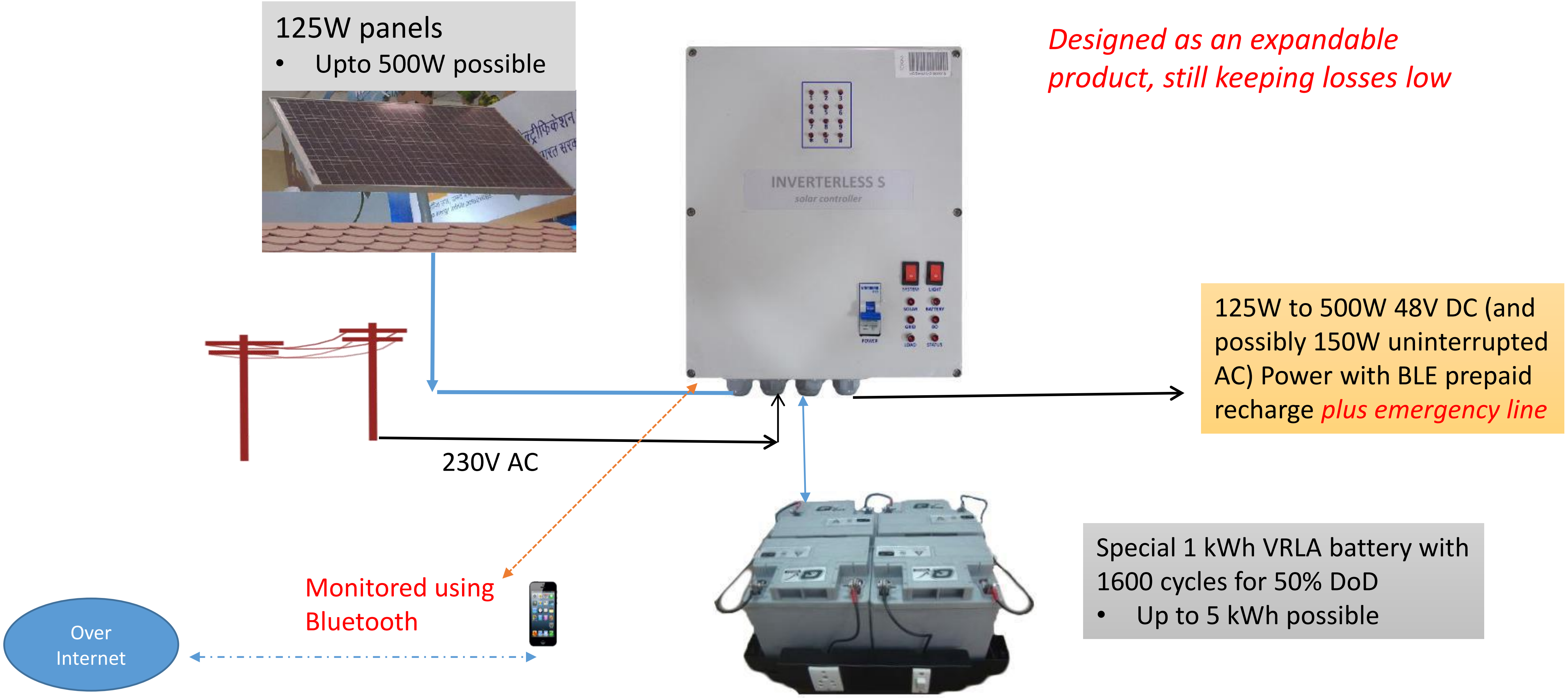


- 48V DC Home Micro-grid connecting
  - Solar Panel
  - Battery
  - DC Appliances
- Highly efficient usage of Power
  - Grid-power alone converted from AC-DC
    - Designed to have minimal loss
    - 7% instead of 45% (for solar-AC) + battery loss
- Design complex because
  - Solar MPPT voltage varies
  - Battery needs independent charge voltage
  - Load is at some fixed voltage
  - DC-DC converters will add similar losses

Solar-DC advantages

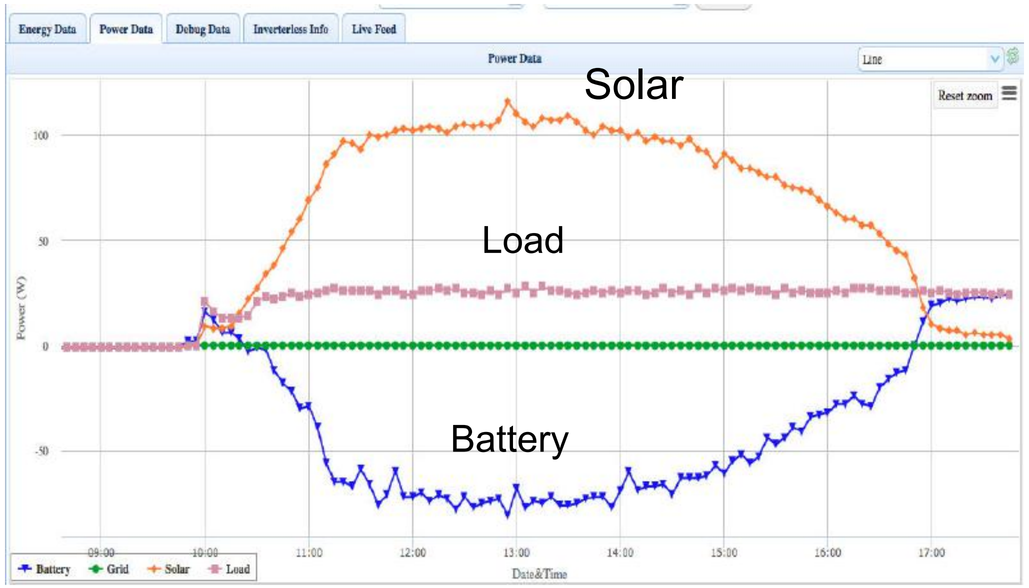
- Solar and DC-converted grid power can directly power DC load when grid is available (battery is not used)
- Both grid and solar can charge battery if battery is not full
- During load-shedding Solar power and battery will power Loads
  - Only excess solar power (solar power – load) will charge battery
- Highly efficient
  - Solar power delivered to load through battery has low loss (less than 7%) even for 100W solar panel (battery loss is on top of it)
  - DC appliances contribute to huge energy-savings

Solar-DC Inverterless has made DC-home a reality



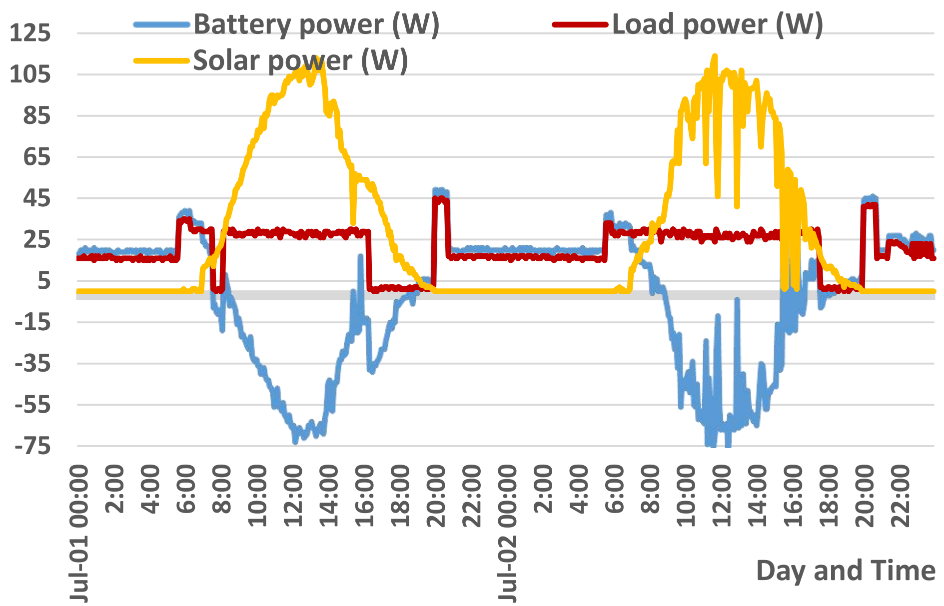
Large Scale Deployments ongoing

- Electrified 4000 off-grid homes in Rajasthan
  - Tough terrain, no road connectivity, sandstorms, lack of local resources
- 7500 homes in Assam being taken up in hills
  - Some More in other states: Orissa, Jharkhand, Karnataka
  - villages of 50-300 homes and small hamlets
- 105K DC deployments with UDC

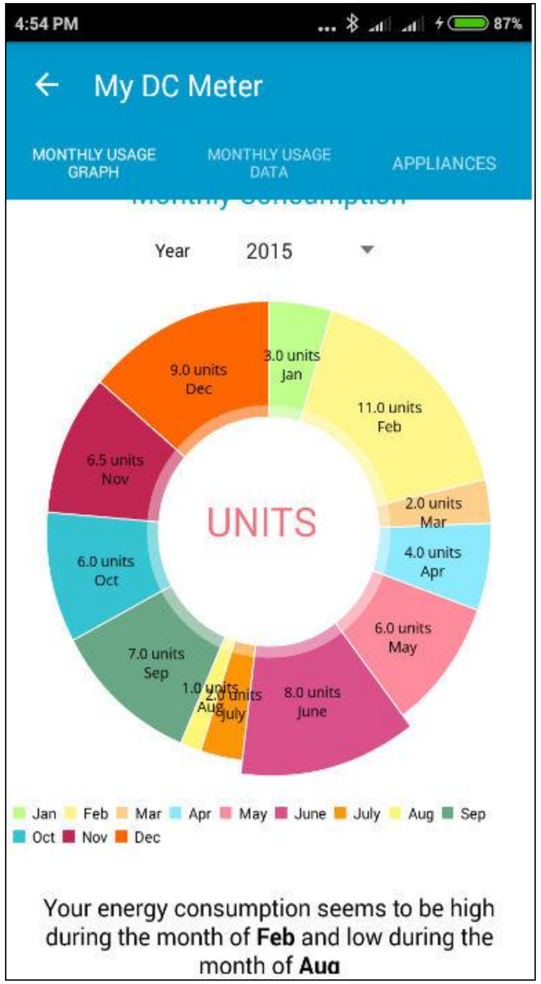


Monitoring Usage

- Understanding use of solar Power and losses: performance evaluation
- Is customer using more than what solar power provides?
  - Is she using less? Is power being wasted?
- In Grid-connected system (no reverse feeding for small system), grid-usage can be optimized to use all of solar power



Measurements from a home in Bhom Ji ka Gaon, Jodhpur from 9am to 5pm



Deployments in difficult terrains: some snapshots

Deserts in Rajasthan, India

Villagers Speak

- *"Apne Vidyarthiyon ko ghar ka kaam dene laga hu. Khush hu ki is baar garmiyon mein bhi bachhe mann laga kar padhai karenge." [now I give my students home-work. Happy that even in summer they will now be able to study]*

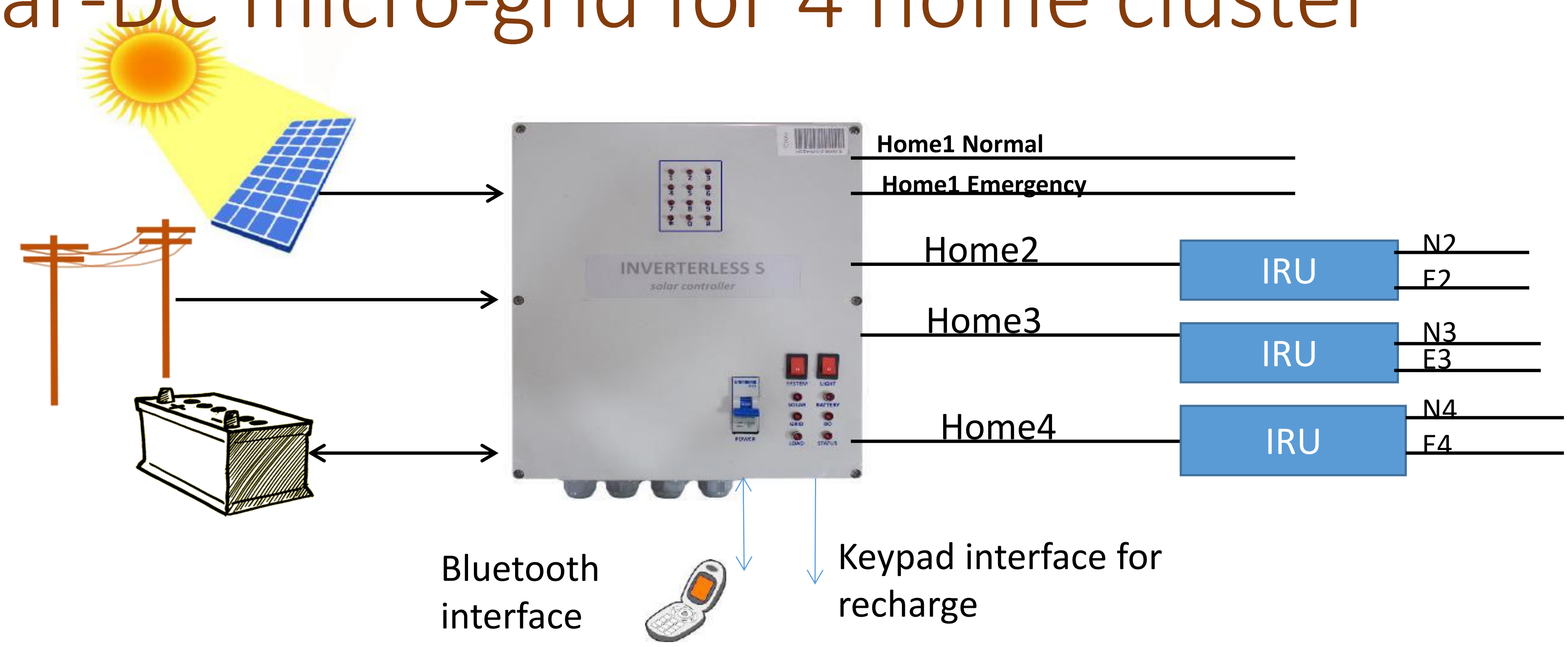
  \- Masterji

- *"Sab ko utshah se apne ghar ka Solar system dikhata hu ji, hamare ghar mein bhi pankha, light aur remote hai" [show my solar system to everyone at home. Have fan, light and remote]*

  \- Dunga Ram

- feedback: https://youtu.be/NF6EgdRsBXk

Solar-DC micro-grid for 4 home cluster



- Enables sharing of Solar and Battery Resources amongst multiple homes
  - Taking advantage of non-concurrent and unequal usage; each home metered and cut-off
- Inverterless2500 can power 12 / 24 home clusters and some industries

Solar-DC: Equally important for grid-connected homes

- Solar-DC Inverterless + DC power line + DC appliances: huge cost savings
  - Draws less from grid: reduces power-bill
- Provides back-up power: frees homes from load-shedding, grid-fault
- 500W solar power (50 sqft) with DC appliances can take care of most essential loads in middle class homes
    - Except washing machines, air-conditioners
  - 240M homes with 500W solar panel produces close to total domestic consumption in India in a year
    - 240Mx0.5 kWx1550 solar hrs/year = 190,000 GWh /yr

INVERTERLESS

- In off-grid home: to provide power for DC appliances
  - Can add a 125W inverter to INVERTERLESS to provide back-up power for legacy AC appliances when 500Wp solar panel used
- In Grid connected homes: Provides back-up power for DC appliances in grid-connected homes
  - Replaces Inverter / UPS with high efficiency gains
  - Makes financial sense to replace AC lights and fans
  - 125W Inverter for legacy AC appliances
- Apartments and Clusters: 4 / 12 / 24 homes INVERTERLESS provides 100W to 500W DC back-up power line to each home / apartment/ commercial unit
  - Large financial gains vis-à-vis use of DG

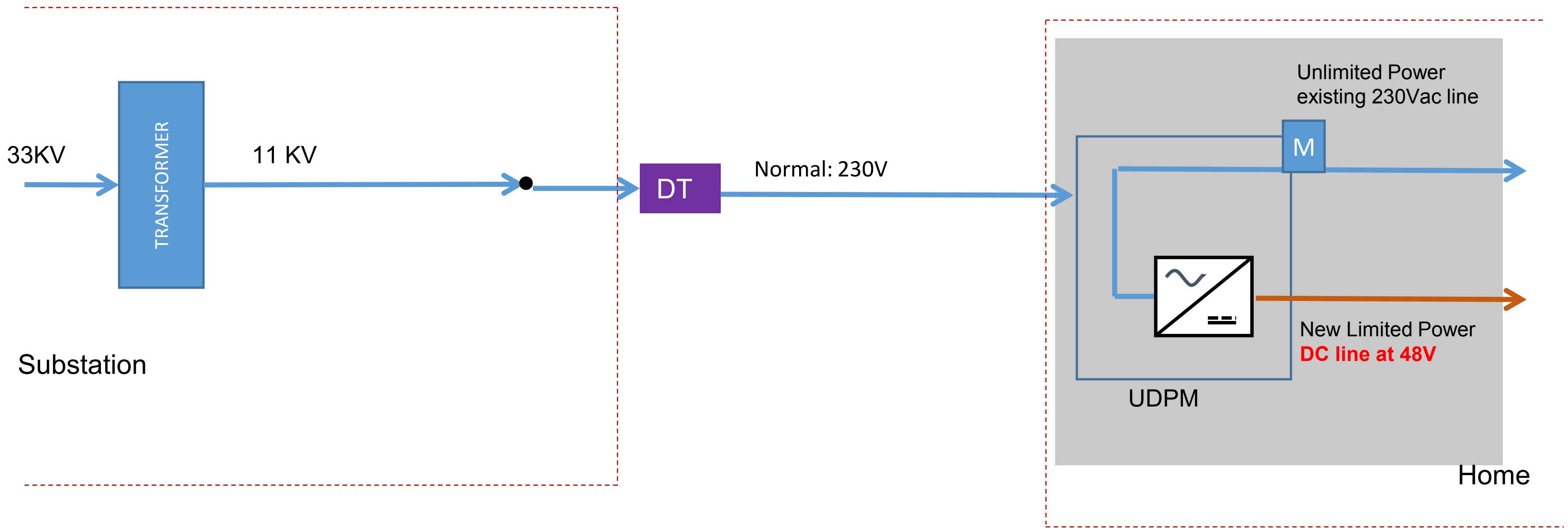
UDC Innovation

- Issues
  - Acceptance among people for technology and DC
  - Lack of standardization and availability of Home appliances

- What it Needs? Instead of Push $\rightarrow$ create a Market PULL

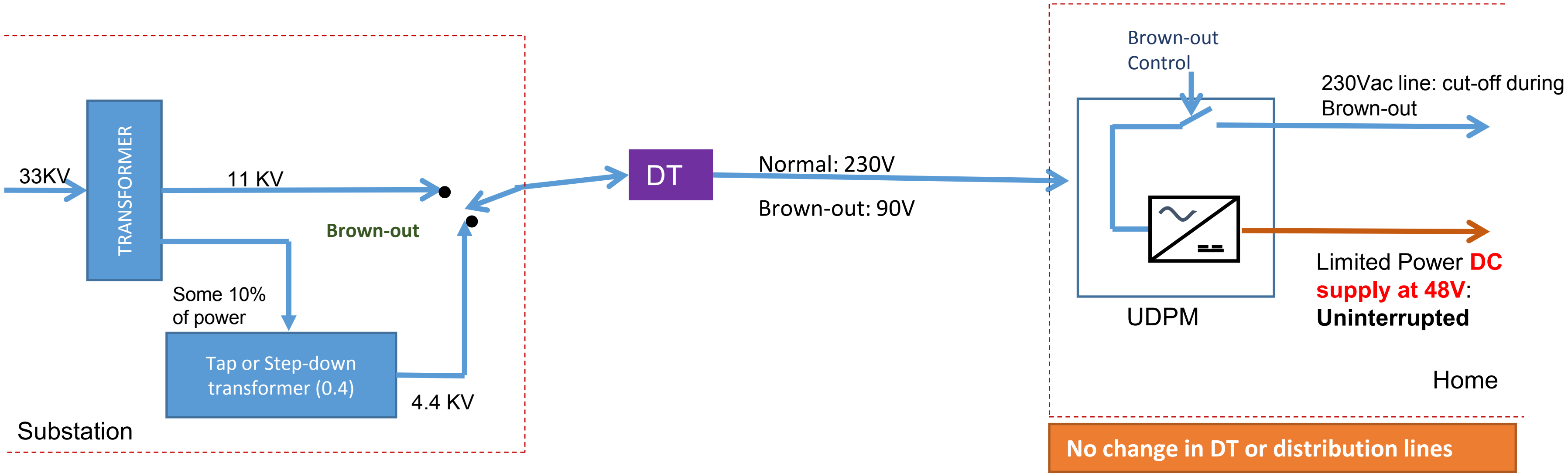
- UDC Innovation aimed to create such a market PULL by
  - Providing a limited Power DC line at each home from existing AC distribution grid in addition to existing AC line
  - During Load shedding, AC line is cut-off, but DC line is kept ON
    - Making the DC line free of Load-shedding

Addition of a DC Power line at each Home



- Substation charges feeders with 11kV Distribution Line
  - Distribution transformer steps down voltage to 230V in each of the three phases
- UDPM at home allows using present AC line and a limited power DC line

Load shedding: 90% power cut – **Brown-out**



- Brown-out: continue feeding 10% power to Distribution Line
  - Substation feeds 11kV in normal and with 4.4kV in brown-out condition (only 10%) on DL
  - Distribution transformer steps down voltage to 230V in normal / 90V in brown-out condition
- UDPM detects voltage drop to 90V: cuts off AC line but continues feeding 48V DC
- 10% BO Power small enough to be made available even during worst power-shortage

A free of Load Shedding line at homes

- Will now induce customers to use DC power line and appliances
  - As DC appliances become acceptable and customers see power-savings and reliability
    - Will add more and more appliances
  - When Limited power provided by UDC gets exhausted, will be willing to add solar-DC

To Sum up

- Solar-DC Inverterless is the future
  - For off-grid homes
  - For replacement of Inverters
- 48V DC power line at each home is the future

"The home of tomorrow will run on direct current" by: Lloyd Alter
In fact, the home of today primarily runs on DC. We just have all this AC stuff running between it**.**
http://www.mnn.com/green-tech/research-innovations/stories/the-home-of-tomorrow-will-run-on-direct-current

L4: INVERTERLESS Usage Economics

Tutorial

Outline

- New Installation in off-grid Homes
- New Installation in connected multi-storied Complex
  - Mid-Income Housing
  - High Income Housing
- Retrofitting Existing Mid-Income Homes having load-shedding
  - Changing Inverter to Inverterless

New Build using INVERTERLESS

- Economically Obvious for all new-builds
  - Replace 5A line with DC line and use DC appliances
    - Solar to the extent possible on roof-top is economical
    - Battery Back-up where load-shedding is likely
      - Far more economical than using Diesel Generator
    - Can have a small back-up AC power for legacy appliances
    - Small increment in CAPEX: Saves power-bill immensely
  - 15A line for AC line
    - Powering high power-consumption Appliances and also legacy AC appliances

Retrofitting Homes having Load-shedding

- Replacing INVERTER with INVERTERLESS
  - May be whenever the battery needs replacement

- Solar will always help
  - Better investment (in terms of return) than keeping money in bank
  - Appliance replacement costs recovered in a very short-time
    - By saving power-bills
      - Higher Load-shedding situation makes economics trivial
      - ZERO Load-shedding economics is a bit more long-term

Before we begin

- List Power Consumption of AC and DC Home Appliances
  - and the costs
- Understand typical appliance-usage per day
- Losses in different scenario
- Power-costs from different sources
- Load-shedding duration and usage

Power Consumption of AC and DC Home Appliances

Device		Power Consumption (W)					Costs (₹)
Fan	Speed/Intens	5	4	3	2	1	
	AC	72	69	66	63	60	1400
	DC	30	25	20	15	10	1600
Tubelight	CFL TL	36	-	-	-	-	225
	LED	18	14	11	8	4	700
Bulb	AC	40					60
	LED	5					110
TV	AC	40					
	DC	30					
Phone	AC	6.5					
	DC	5					
Laptop	AC	60					
	DC	45					
Aircooler	AC	250		230		210	
	DC	100		50		25	

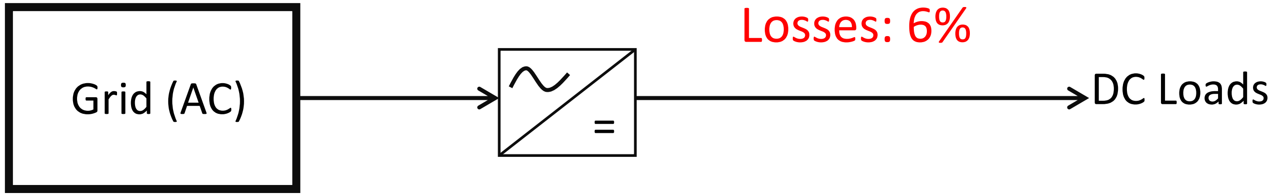
Typical Appliance Usage per day

Device	Numbers deployed			Operational hours per day
	Small House	Large House	Multi-storied small flat	
Tubelights	2	6	2	6
Fans	2	6	2	12
Bulbs	2	6	2	10
Air coolers	-	1	-	8
Phones	1	4	2	4
Laptops	-	2	1	5
TV	1	2	1	10

Mains without Solar and Battery

Powering DC loads

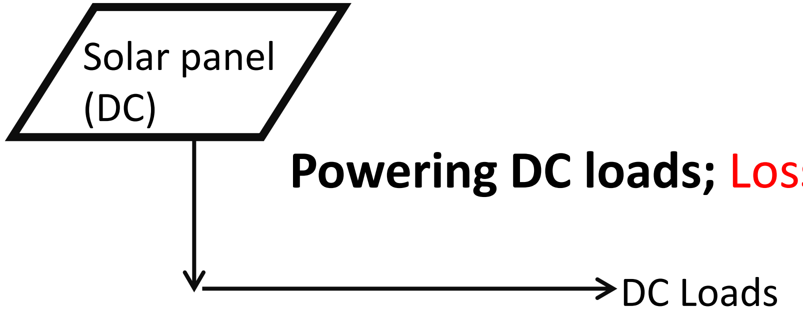
Losses: 6%



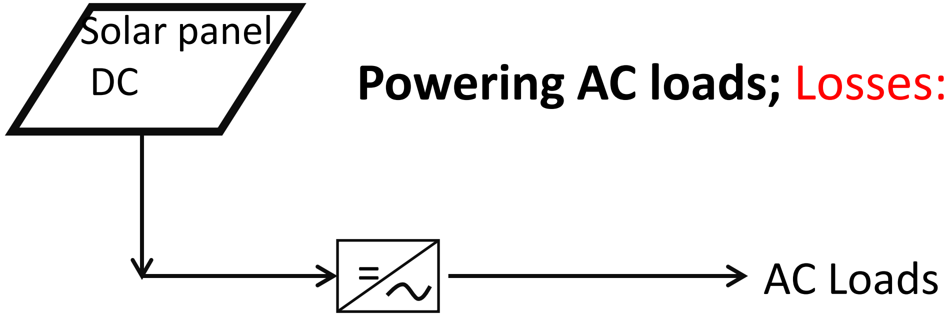
Powering AC loads

Losses: 0%

Solar without Mains and Battery



Powering DC loads; Losses: 3%

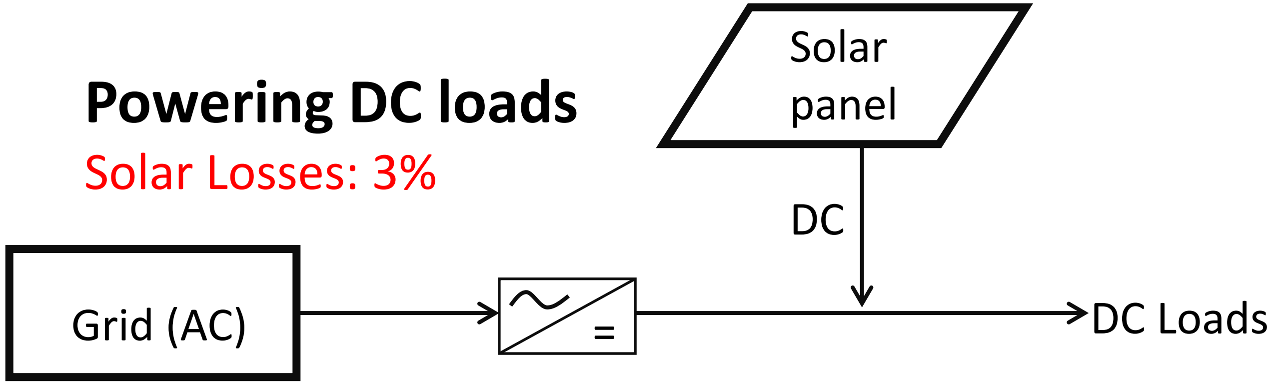


Powering AC loads; Losses: 18%

Solar and Mains without Battery

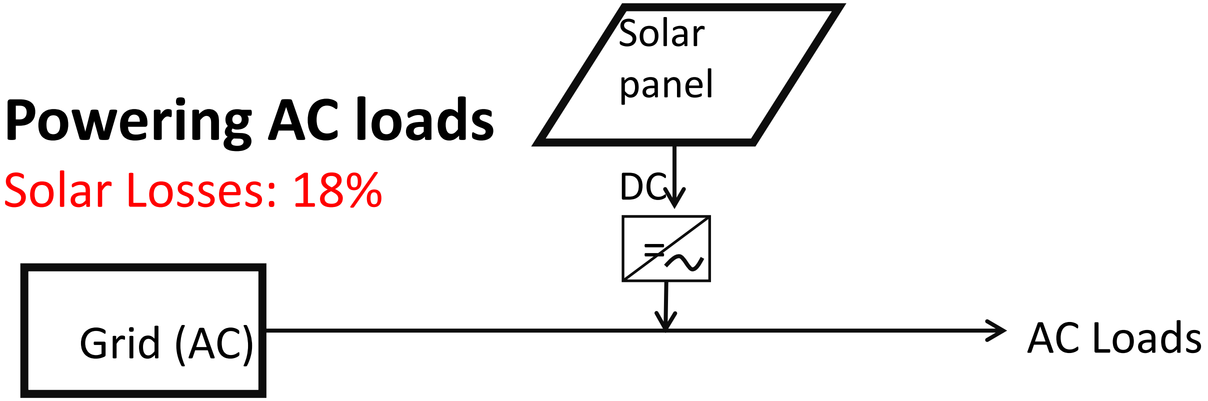
Powering DC loads

Solar Losses: 3%

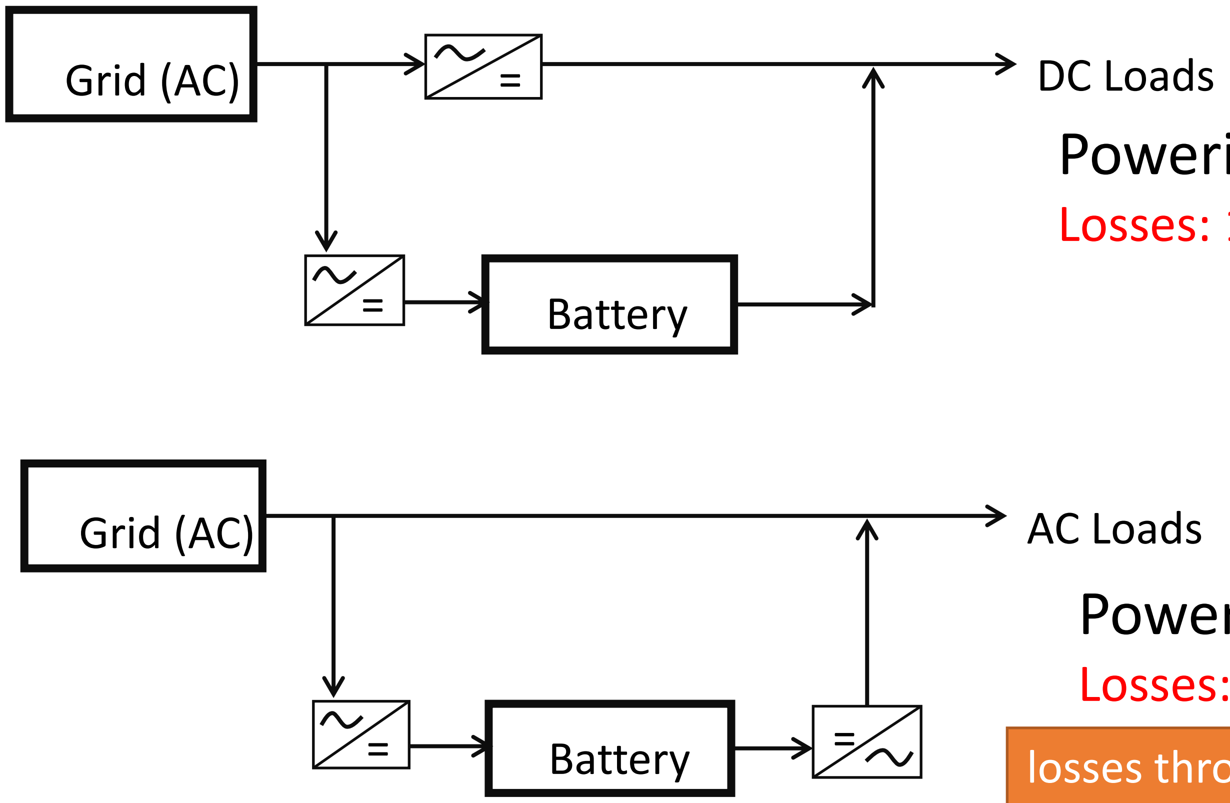


Powering AC loads

Solar Losses: 18%



Mains through Battery without Solar



Powering DC loads

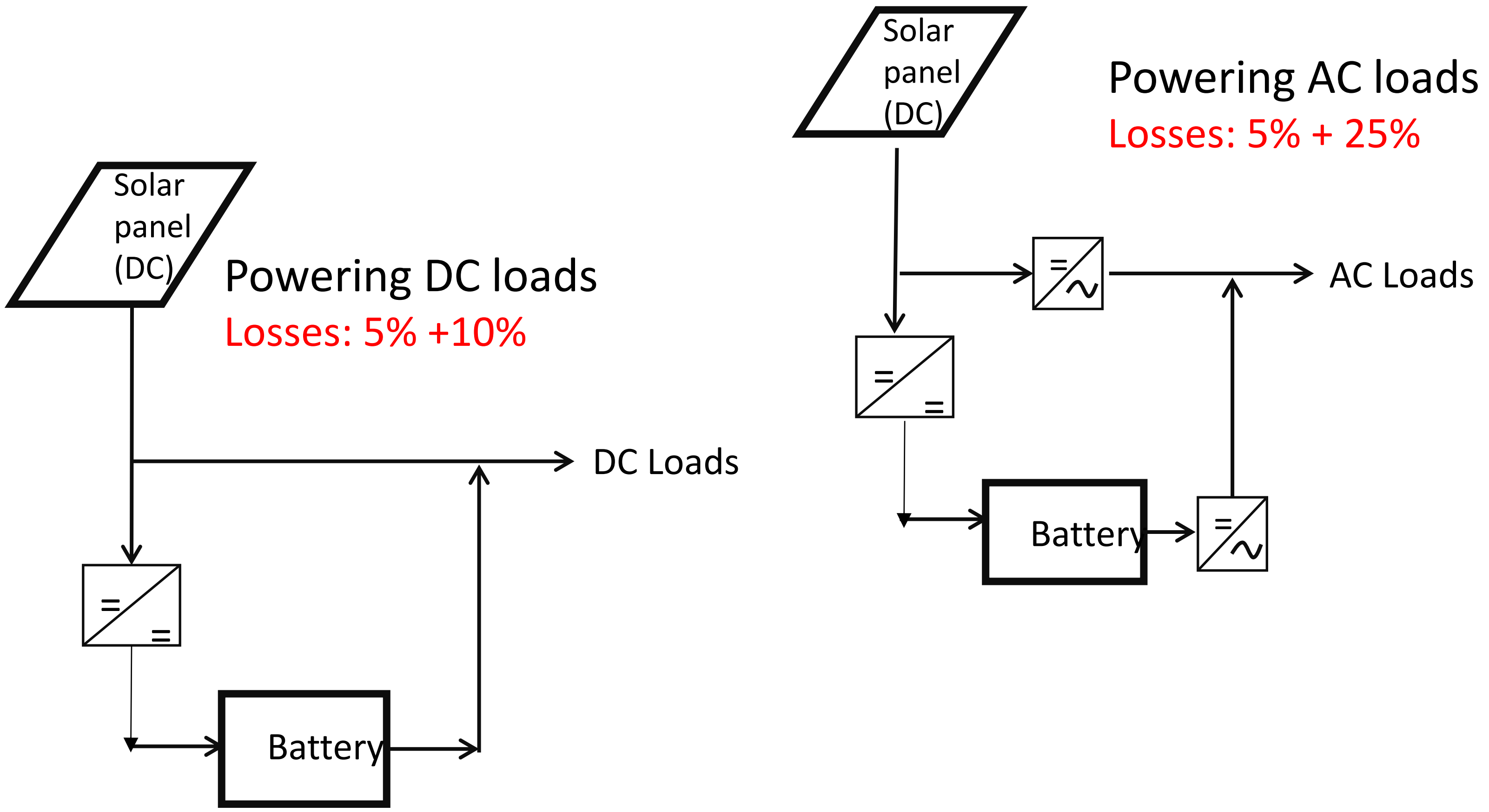
Losses: 15% + 10%

Powering AC loads

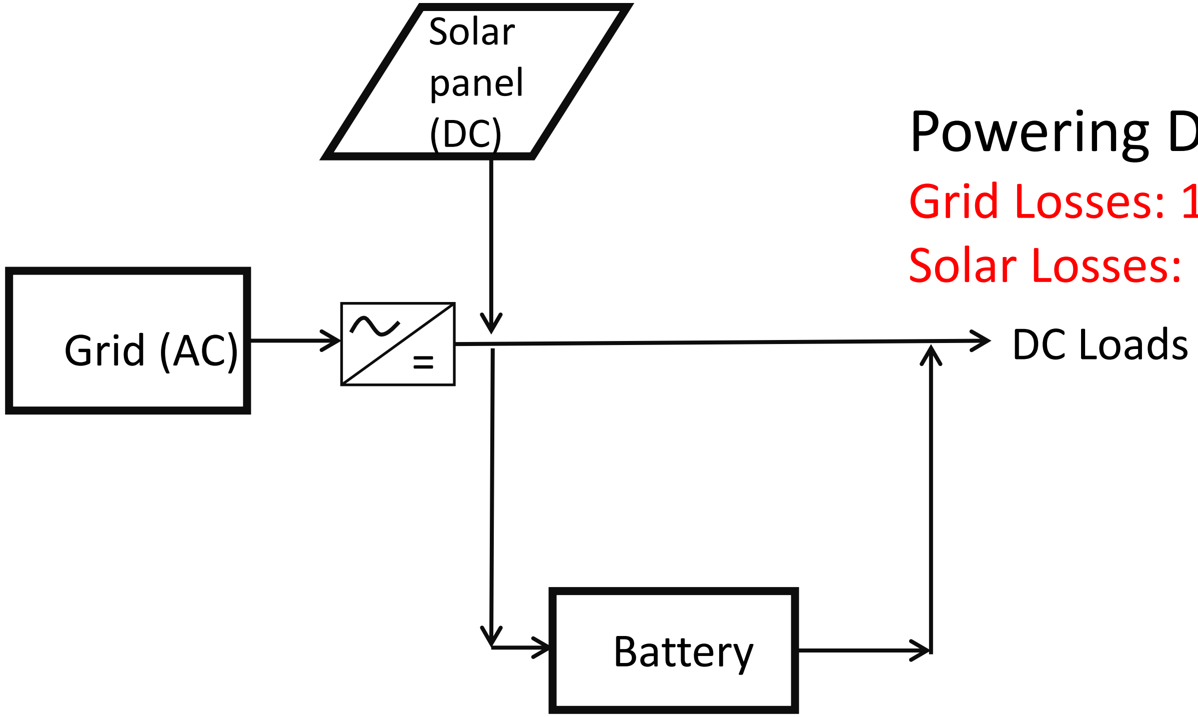
Losses: 15% + 25%

losses through battery x% + y%
StoBloss: x% for source to battery
BtoLloss: y% for battery to load
Assume B loss = 10% for Lead Acid

Solar through Battery without Mains



Solar and Mains through Battery

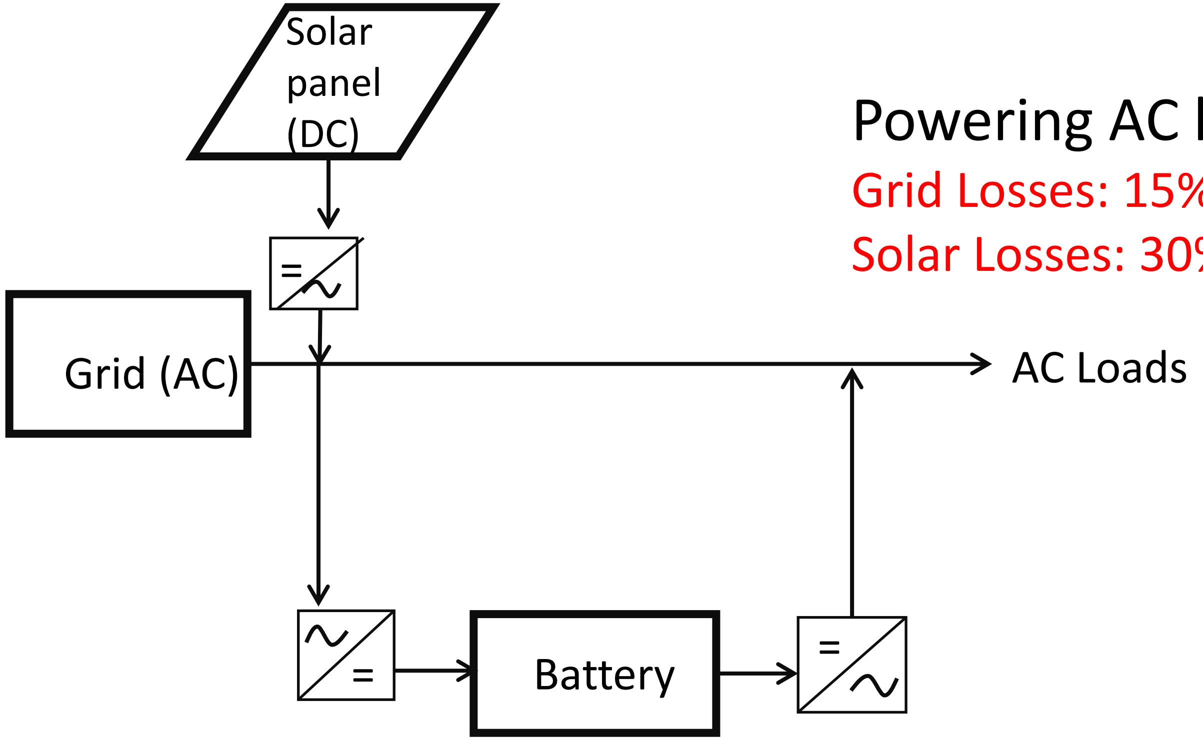


Powering DC loads

Grid Losses: 15% + 10%

Solar Losses: 5% + 10%

Solar and Mains through Battery



Powering AC loads

Grid Losses: 15% + 25%

Solar Losses: 30% +25%

System-losses, Power Costs and Load-shedding

System	DC Losses %			AC Losses %		
	Solar with Mains	Solar without Mains	Only Mains	Solar with Mains	Solar without Mains	Only Mains
Through Battery	5+10	5+10	15+10	30+25	5+25	15+25
without Battery	3	3	6	18	18	0

Source of Power	Per unit cost ₹
Grid	5
Solar-DC	4
Battery adds	12
Solar -AC	6

per day	Total (hrs)	Sunlight (hrs)	Off-sunlight (hrs)
Load shedding (hrs)	4	2	2
Load usage (%)	100	40	60

Assumption

- If Solar is installed: Sun-hours: Sun supplies full load
  - Power Cost = total Power Usage * (1+StoLloss%) * Solar cost per unit
- Else if grid is there: Grid supplies full load
  - Power Cost = total Power Usage * (1+StoLloss%) * Main cost per unit
- When mains and sun is not there, battery supplies full load
  - For off-grid assume solar supplies battery
  - For on-grid assume mains always supplies full battery
  - Power Cost = total power Usage * [(1+BtoLloss%)*12 + (1+BtoLloss%+StoBloss%)*Source cost per unit

Small Homes

- Consider a small household (see slide 92). Build Excel sheets to compute:
  a) How much will be the load consumed per day in Wh assuming that it is an AC Home or a DC home? How much will it cost if it is all grid-power without any power-cuts? Compute for sunlight and non-sun hours separately! How much percentage of power could be saved by using a DC system compared to AC? What will be the cost savings?
  b) If the AC load is to be fed by the grid alone with battery backup, how much load will be consumed from battery considering load shedding? What will it cost? Calculate sun hours and non-sun hours separately. What will be the capacity of the battery?
  c) Repeat the same assuming DC Load alone

Small Homes (Contd)

d) If the system is a solar AC system being fed by a n x 125W solar panel, without grid, calculate the usage from sun and battery and total power-cost per day. How much should be n and battery size?

e) If the system is a solar DC system being fed by a n x 125W solar panel, without grid calculate the usage from sun and battery and total power-cost per day. How much should be n and battery size?

f) If the system is a solar DC system being fed by a 125W solar panel, battery size as computed earlier for grid and with grid, calculate the usage from sun, grid and battery and total power-cost per day.

Power Consumption in AC and DC Homes

Power through Grid:
No load-shedding

Device	Numbers	Number of operational hours a day	AC System		DC System	
			Wattage (W)	Power cons per day (Wh)	Wattage (W)	Power cons per day (Wh)
Tubelights	2	6	36	432	18	216
Fans	2	12	72	1728	30	720
Bulbs	2	10	40	800	5	100
Phones	1	4	6.5	26	5	20
TV	1	10	40	400	30	300
Losses				0%		6%
	Per day load consumption (Wh)			**3386**		**1437.36**
Per day cost of power (all grid) (Rs)				**16.93**		**7.19**
		Percentage power saved by DC system (%)			**57.55**	
		Cost savings per day of DC over AC (₹)			**9.7**	

AC Home with Inverter
DC Home with Inverterless

Home on Grid with 4 hour load-shedding
Uniform Load Assumption

AC	Pwr Cons (Wh)	Loadshed durn (h)	Load required (Wh)		Per Day power cost (Rs)	
			from battery	from grid	from battery	from grid
During sun hours	1354.40	2	282.17	1072.23	6.21	5.36
During non - sun hours	2031.60	2	282.17	1749.43	6.21	8.75
Overall	3386.00	4	564.33	2821.67	12.42	14.11
per hour load	141.08					
				cost/day ₹	26.52	

DC	Pwr Cons (Wh)	Loadshed durn (h)	Load required (Wh)		Per Day power cost (Rs)	
			from battery	from grid	from battery	from grid
During sun hours	574.94	2	119.78	455.16	2.33	2.41
During non - sun hours	862.42	2	119.78	742.64	2.33	3.94
Overall	1437.36	4	239.56	1197.80	4.66	6.35
per hour load	59.89					
				cost/day ₹	11.01	

Solar-AC off-grid Home

	Pwr Cons (Wh)	Solar power (Wh)	Load consumed (Wh)				Per Day power cost (Rs)	
			from solar	from battery	to battery	Batt surp	from solar	thru batt
sun hours	1354.40	4500	1598.19		2756.72		9.59	0.00
non - sun hours	2031.60			2539.5				46.32
Overall	3386.00	4500				217.22	9.59	46.32
per hour load	141.08							
				Per day cost of power (Rs) =				55.91

Solar Panel required = 8 x 125 W(p)
Battery Size (VRLA) = 5 kWh

Solar-DC off-grid Home

	Pr Cons (Wh)	Solar power (Wh)	Load consumed (Wh)				Per Day power cost (Rs)	
			from solar	from battery	to battery	Battery surp	from solar	thru battery
Sun hours	574.94	1687.5	592.19	0	1040.54		2.37	0.00
non - sun hours	862.42	0	0.00	948.65			0.00	15.35
Overall	1437.36	1687.5				91.88	2.37	15.35
per hour load	59.89							
				Per day cost of power (Rs) =				17.72

Solar Panel required = 3 x 125 W(p)
Battery Size (VRLA) = 2 kWh

AC home: Grid + solar(125W) + Battery

			sun hours	Off sun hrs	Overall
During power cut	Load Requirement (Wh)		282.17	282.17	564.33
	Available Solar power (Wh)		562.50	0.00	562.50
	Load consumed (Wh)	From Solar	332.96	0.00	332.96
		From Grid	0.00	0.00	0.00
		From Battery	0.00	282.17	282.17
	Per day power cost (Rs)	From Solar	2.00		2.00
		From Grid			0.00
		From Battery		6.21	6.21
Power available from grid period	Load Requirement (Wh)		1072.23	1749.43	2821.67
	Available Solar power (Wh)		229.54		229.54
	Load Consumed (Wh)	From Solar	194.53		194.53
		From Grid	877.71	1749.43	2627.14
		From Battery			
	Per day power cost (Rs)	From Solar	1.38	0.00	1.38
		From Grid	4.39	8.75	13.14
		From Battery	0.00	0.00	0.00
			Power cost / day ₹		**22.72**

Battery charged from Grid
4 hours power cut

DC home: Grid + solar(125W) + Battery

			sun hours	Off sun hrs	Overall
During power cut	Load Requirement (Wh)		119.78	119.78	239.56
	Available Solar power (Wh)		562.50	0.00	562.50
	Load consumed (Wh)	From Solar	123.37	0.00	123.37
		From Grid	0.00	0.00	0.00
		From Battery	0.00	119.78	119.78
	Per day power cost (Rs)	From Solar	0.49	0.00	0.49
		From Grid	0.00	0.00	0.00
		From Battery	0.00	2.13	2.13
Power available from grid period	Load Requirement (Wh)		455.16	742.64	1197.80
	Available Solar power (Wh)		301.38	0.00	301.38
	Load Consumed (Wh)	From Solar	292.60	0.00	292.60
		From Grid	162.56	742.64	905.20
		From Battery	0.00	0.00	0.00
	Per day power cost (Rs)	From Solar	1.17	0.00	1.17
		From Grid	0.86	3.94	4.80
		From Battery	0.00	0.00	0.00
				Power cost / day ₹	**8.59**

Battery charged from Solar
4 hours power cut

To Summarise: Small Home Results

Device	Numbers deployed	Operation hrs/ day
Tubelights	2	6
Fans	2	12
Bulbs	2	10
Air coolers	-	8
Phones	1	4
Laptops	-	5
TV	1	10

	AC Home				DC Home			
	Energy/ day kWh	Cost per day ₹	Battery Size kWh	solar panel Wp	Energy / day kWh	Cost per day ₹	Battery Size kWh	solar panel Wp
AC Grid + 0 LS	3.39	16.93			1.44	7.19		
AC Grid + Battery + 4h LS		26.52	1.1			11.01	0.5	
off-grid + Battery + Solar		55.91	5.1	1000		17.72	1.9	375
AC + Battery + Solar + 4h LS		22.72	0.6	125		8.59	0.25	125

Cost / day includes cost of solar panel and battery

Challenges

- 48V DC to 230V AC 150W inverter with 95% efficiency at ₹1000 BOM

- 48V DC to 12V DC 250W Converter with 93% efficiency

Large Homes

- For large household (see slide 92), build Excel sheets to compute:
  a) Load consumed per day for an AC Home or a DC home. Compute costs, when fed by grid-power without power-cuts?

  b) Repeat the above with 4 hour power-cuts (two in the day and two hours in evening). What will be the capacity of the battery?

  c) Now assume 1kW solar panel; Repeat (b).

  d) Now assume off-grid homes and n x 1 kW solar panel. Repeat (b). How much should be n and battery size?

Large Home Results Summary

Device	Numbers deployed	Operation hrs/ day
Tubelights	6	6
Fans	6	12
Bulbs	6	10
Air coolers	1	8
Phones	4	4
Laptops	2	5
TV	2	10

System	AC Home				DC Home			
	Energy / day kWh	Cost per day ₹	Battery Size kWh	solar panel Wp	Energy / day kWh	Cost per day ₹	Battery Size kWh	solar panel Wp
AC Grid + 0 LS	12.38	61.92			5.34	26.70		
AC Grid + Battery + 4h LS		97.01	4.13			40.90	1.78	
off-grid + Battery + Solar		204.48	18.58	4000.00		65.83	7.05	2000.00
AC + Battery + Solar + 4h LS		87.40	2.06	1000.00		31.35	0.89	1000.00

Cost / day includes cost of solar panel and battery

Residential Complex

- For a 12 flats residential complex with 12 flats (see slide 93), build Excel sheets to compute:

  a) Energy consumed per day assuming an AC Home and a DC flats? How much will it cost if powered by grid without load-shedding?

  b) Now assume 4 hour load shedding (2 in day and 2 hours in evening) and assume appropriate battery size (for complex). Repeat (a) and find battery size.

Residential Complex Results

Device	Numbers deployed per flat	Operation hrs/ day
Tubelights	2	6
Fans	2	12
Bulbs	2	10
Air coolers	-	8
Phones	2	4
Laptops	1	5
TV	1	10

Number of flats within the residential complex = 12: common battery

System	AC Home				DC Home			
	Energy / day kWh		Cost per day per flat ₹	Battery Size for complex kWh	Energy / day kWh		Cost per day per flat ₹	Battery Size for complex kWh
	per flat	For complex			per flat	For complex		
AC Grid + 0 LS	3.71	44.544	18.56		1.75	20.94	8.73	
AC Grid + Battery + 4h LS			29.08	14.85			13.36	6.98

Cost / day includes cost of solar panel and battery

To Sum Up

- In all contexts
  - DC homes become far more economical as compared to AC homes
  - Solar DC adds huge benefit: make homes less dependent on grid
  - Cost of power for Solar DC off-grid homes (even with current battery costs) become comparable to that on grid