LAB # 10

To Study and Understand PV Panel and Battery Sizing

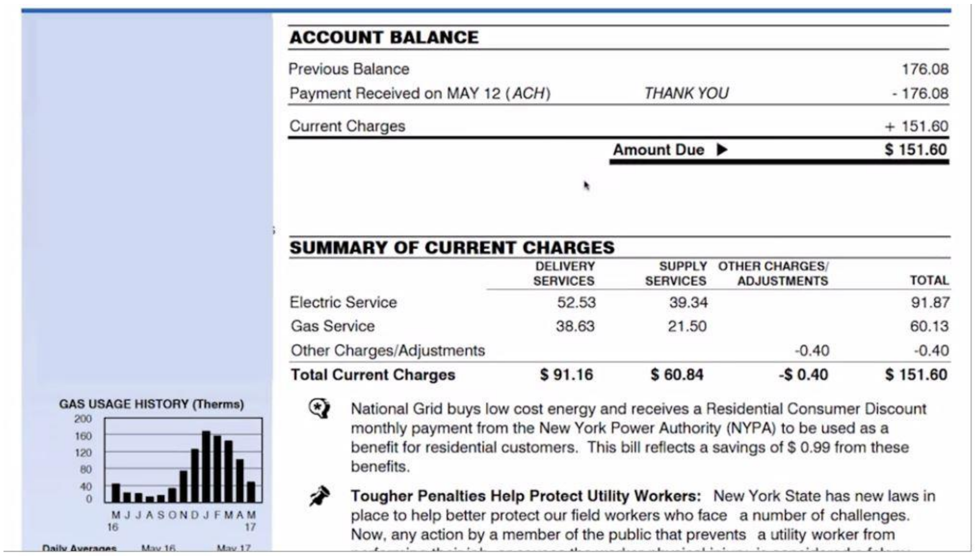
Objectives:

- To Study and understand how to Develop a basic PV system design based on an electrical consumption need
- To understand how to calculate number of PV panels required
- To study and understand about battery sizing
- To understand how to calculate number of batteries required

Related Theory:

We've looked in previous lab, how to assess individual energy loads for devices. Now, we can look at an energy load for a whole building, and the easiest way to do that is to simply look at ***utility bill***. So, let's take a look at one of these ***electrical bills***.

Now, this is one from a local logical supplier in upstate New York although also a national provider, and there are a few things that are listed in here. One is that there is a bill for both electric service and gas service because this utility provider provides both. However, we're just going to be looking at ***electric service*** knowing that this home does not use electric service for heat and uses gas service for heat. So, one of the important piece is not necessarily the dollar values here, but it is the ***electric usage history***. Notice that the units are in ***kilowatt hours***.



ACCOUNT BALANCE

Previous Balance		176.08
Payment Received on MAY 12 (*ACH*)	*THANK YOU*	- 176.08
Current Charges		+ 151.60
	Amount Due ▶	**$ 151.60**

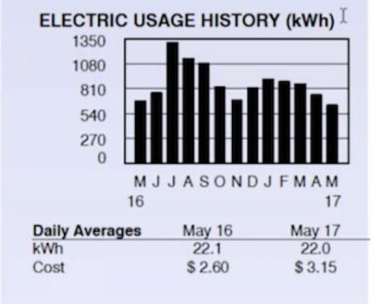
SUMMARY OF CURRENT CHARGES

	DELIVERY SERVICES	SUPPLY SERVICES	OTHER CHARGES/ ADJUSTMENTS	TOTAL
Electric Service	52.53	39.34		91.87
Gas Service	38.63	21.50		60.13
Other Charges/Adjustments			-0.40	-0.40
Total Current Charges	**$ 91.16**	**$ 60.84**	**-$ 0.40**	**$ 151.60**

National Grid buys low cost energy and receives a Residential Consumer Discount monthly payment from the New York Power Authority (NYPA) to be used as a benefit for residential customers. This bill reflects a savings of $ 0.99 from these benefits.

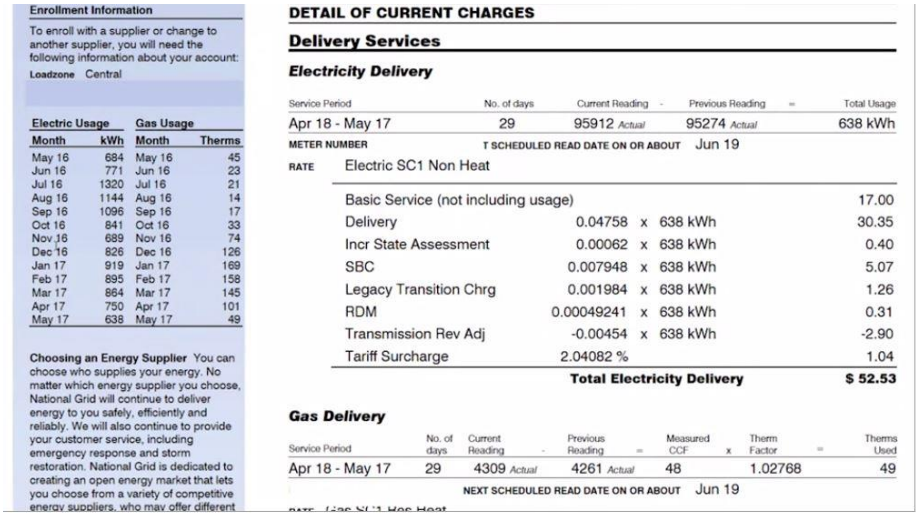
Tougher Penalties Help Protect Utility Workers: New York State has new laws in place to help better protect our field workers who face a number of challenges. Now, any action by a member of the public that prevents a utility worker from

So, we have a usage of energy for ***each month*** shown below and they show historically how much energy is being used each month. So, if we want to get an overall electric energy usage for the ***year***, we could ***sum*** each of those months individually within the bill to get an idea of what the ***annual energy usage*** is going to look like, but we see trends for June and July and August being higher for electricity, slightly lower in November and December as the air-conditioning gets turned off and then goes up again in January and February most likely because of the fans and blower units within actually the heating devices in the home, but you get an idea of what the overall energy usage is.



Daily Averages	May 16	May 17
kWh	22.1	22.0
Cost	$ 2.60	$ 3.15

we can actually see the values of the graph in figure shown below. So, you can look at graphically or by value and it's much easier to simply take these numbers, sum them together and get an annual energy usage.



Enrollment Information

To enroll with a supplier or change to another supplier, you will need the following information about your account:

Loadzone Central

Electric Usage		Gas Usage	
Month	kWh	Month	Therms
May 16	684	May 16	45
Jun 16	771	Jun 16	23
Jul 16	1320	Jul 16	21
Aug 16	1144	Aug 16	14
Sep 16	1096	Sep 16	17
Oct 16	841	Oct 16	33
Nov 16	689	Nov 16	74
Dec 16	826	Dec 16	126
Jan 17	919	Jan 17	169
Feb 17	895	Feb 17	158
Mar 17	864	Mar 17	145
Apr 17	750	Apr 17	101
May 17	638	May 17	49

Choosing an Energy Supplier You can choose who supplies your energy. No matter which energy supplier you choose, National Grid will continue to deliver energy to you safely, efficiently and reliably. We will also continue to provide your customer service, including emergency response and storm restoration. National Grid is dedicated to creating an open energy market that lets you choose from a variety of competitive energy suppliers, who may offer different

DETAIL OF CURRENT CHARGES

Delivery Services

Electricity Delivery

Service Period	No. of days	Current Reading	-	Previous Reading	=	Total Usage
Apr 18 - May 17	29	95912 *Actual*		95274 *Actual*		638 kWh

METER NUMBER **T SCHEDULED READ DATE ON OR ABOUT** Jun 19

RATE Electric SC1 Non Heat

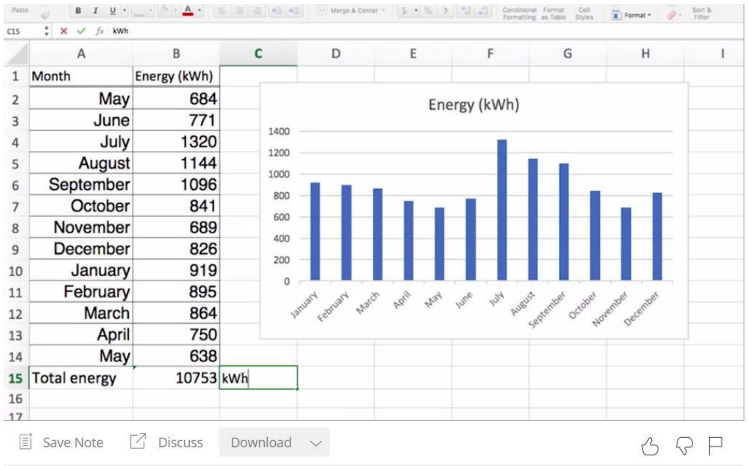
Basic Service (not including usage)				17.00
Delivery	0.04758	x	638 kWh	30.35
Incr State Assessment	0.00062	x	638 kWh	0.40
SBC	0.007948	x	638 kWh	5.07
Legacy Transition Chrg	0.001984	x	638 kWh	1.26
RDM	0.00049241	x	638 kWh	0.31
Transmission Rev Adj	-0.00454	x	638 kWh	-2.90
Tariff Surcharge	2.04082 %			1.04
	Total Electricity Delivery			**$ 52.53**

Gas Delivery

Service Period	No. of days	Current Reading	-	Previous Reading	=	Measured CCF	x	Therm Factor	=	Therms Used
Apr 18 - May 17	29	4309 *Actual*		4261 *Actual*		48		1.02768		49

NEXT SCHEDULED READ DATE ON OR ABOUT Jun 19

So, as we begin to plan for a photovoltaic system, we take that total energy usage and know that that's our annual load and we will build off of that to be able to look at the annual use. So, let's take a look at that now. We are taking the ***monthly energy usages*** and put them into a ***spreadsheet*** program. The spreadsheet, we have taken the data and also put them into a graphical format, which listed chronologically from January to December.



	A	B	C
1	Month	Energy (kWh)	
2	May	684	
3	June	771	
4	July	1320	
5	August	1144	
6	September	1096	
7	October	841	
8	November	689	
9	December	826	
10	January	919	
11	February	895	
12	March	864	
13	April	750	
14	May	638	
15	Total energy	10753	kWh

So, this is slightly different than the bill where it shows it on a rolling basis from month to month. What we can do is to easily calculate our annual energy usage by just summing all of the values within the year.

So, We have to use the sum function and highlight for May and going backwards to June not including the previous May. So, We have a ***12-month span*** and so by highlighting all those values, We get an energy value usage of ***10,753 kilowatt hours***. So, that tells us that if we have to replace all of our energy usage with photovoltaics, We need a photovoltaic system that would produce 10,753 kilowatt hours.

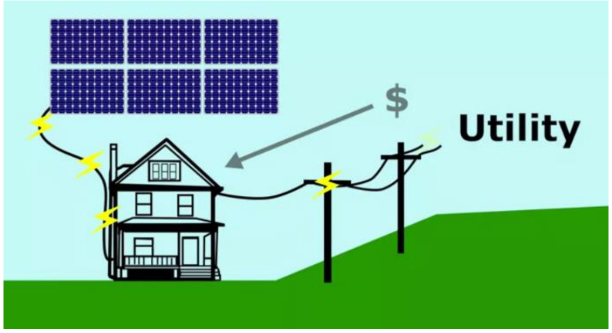
So, in summary, we've looked at how to use the energy bill to calculate the monthly and annual energy usages. Next, we'll look at how to take those energy loads, those usages and convert them to figuring out how many photovoltaic panels we might need to supply that load.

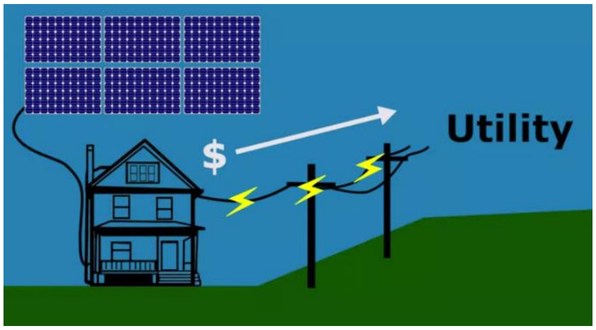
Calculating PV System Size:

A simpler way to ***determine energy demand*** when dealing with a grid-tied building is to use a ***utility bill***. Remember that energy demand to use is an annual event, but it does vary day to day, and possibly month to month or seasonally.

So, while we could calculate daily energy use, we typically plan solar for annual demand. The only time daily variations in energy is critical, is if you're working off grid, or need to make sure that a battery or a photovoltaic system can support the maximum daily energy demand.

Let's consider this example of an ***annual usage*** of ***12,000 kilowatt hours***. So, if we use and ***pay*** for 12,000 kilowatt hours per year from our utility, then we would want to ***produce*** 12,000 kilowatt hours of electricity from the PV system during the year, so we come out even. Now that's 100 percent of our annual demand. Because of ***net metering***, it does not mean that we have to produce 100 percent of the demand each day, just annually. Net Metering is essentially a financial system that allows you to sell excess electricity to the utility when production exceeds need but purchase that electricity when the PV system is not meeting the electrical load demand.



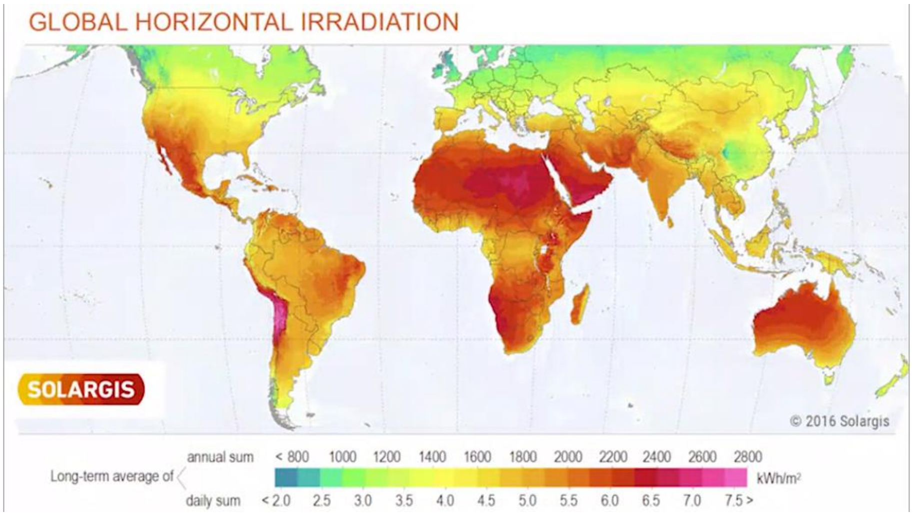


In other cases, we might want to look at ***installing*** a system that's a ***fraction*** of the total electrical need. This is going to be dictated sometimes by ***cost limitations***. Maybe we can't afford a system that's large enough to supplement 100 percent of our energy, or space limitations. Maybe the rooftop or the ground area is too small to accommodate a system that large. There's also oftentimes both financial and electrical limitations for producing more than 100 percent of the electrical need.

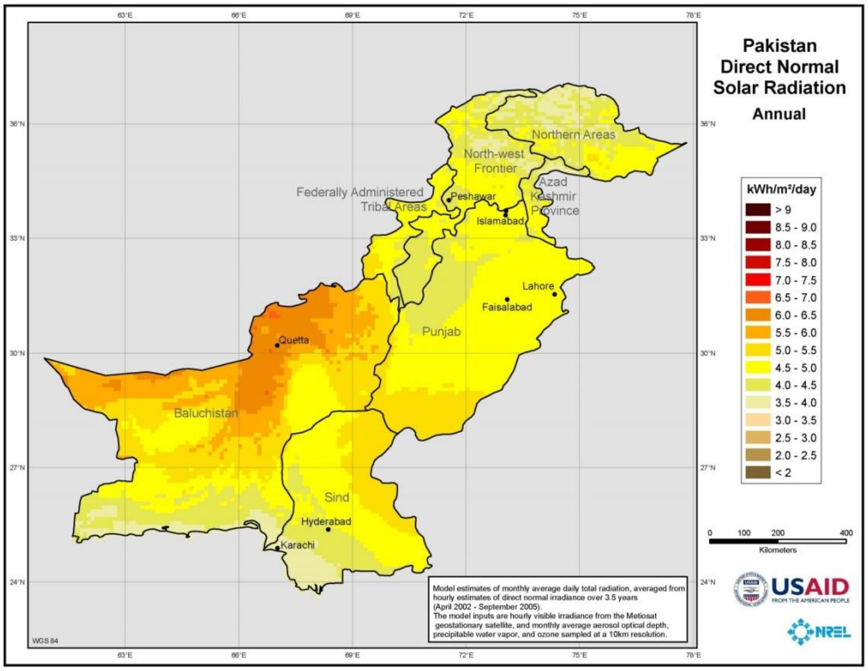
Note: You can't produce more power than your electrical system can accept, and several countries limit that payback on production till no more than maybe 100 or 110 percent of your annual electric load. Otherwise, you end up being what's called an ***independent power producer***.

Adjusting for Location and System Losses:

Now that we know how to calculate annual energy demand, we're going to move forward, and look at sizing the whole photovoltaic system. ***Solar energy insulation*** or incident solar radiation varies across the globe, and varies due to differences in latitude, as well as, climate.



We're going to need some ***mapping tool*** to help us understand that total insulation value. Several resources are available, but at this point, we're going to look at just one simple online map that are downloaded from the National Renewable Energy Lab or ***NREL***.



Model estimates of monthly average daily total radiation, averaged from hourly estimates of direct normal irradiance over 3.5 years (April 2002 - September 2005).
The model inputs are hourly visible irradiance from the Metiosat geostationary satellite, and monthly average aerosol optical depth, precipitable water vapor, and ozone sampled at a 10km resolution.

This map of the ***Pakistan*** is color-coded to show what areas have high amounts of sunlight, which are red and orange, and low amounts. Photovoltaic power output depends on the sunlight level. That means that the more power that comes out of the panel will occur if it's sunny out, and less power comes out when it's cloudy or night-time. ***Photovoltaic energy which is a time of use measurement combines the hours of sunlight, and the intensity.***

Things are not as simple as just looking at the energy of sunlight though, or the panel power, because we also need to think about ***efficiency*** of the system. Photovoltaics have an efficiency of about ***10 to 20 percent***. That means that only 10 or 20 percent of the light that hits the panel is actually converted into usable electricity. Luckily that's already faction to the power rating on the panel.

Aside from their internal efficiency of the solar panel, there are ***losses*** from things such as ***wiring mismatches*** from junctions and differences and wire sizing, the inverter which converts the direct current to alternating current, as well as, simple things like ***dust*** that falls on the panel surface, which lowers the amount of sunlight available to be converted. Another efficiency limitation is ***temperature mismatch***. What's interesting about photovoltaic panels is that when the ***temperature goes up, the efficiency goes down***.

So, overall, between the wiring mismatch, dust temperature losses, a module loses about 10 to 20 percent from the nameplate or panel rating itself. So, the ***true power*** that's delivered by a ***panel*** is only about ***80 to 85 percent*** of what's listed. So, we need to plan for that as we size our system.

Let's look at an example where a photovoltaic system produces 10,000 watts of electrical power. Because of the external efficiency limitations, only 80 percent of that power can be collected, or 8,000 watts.

$$Power\ Rating\ \ X\ \ Efficiency = Power\ Output$$

$$10{,}000\ \ X\ \ 0.8 = \ 8000w$$

So, we always need to ***oversize*** a system to overcome that external efficiency limit. So, if we truly wanted 10,000 watts to be delivered to our home or our building, we would divide by 80 percent as:

$$\frac{Power\ Output}{Efficiency} = Power\ Rating$$

$$\frac{10{,}000}{0.8} = 12{,}500\ w$$

Now Calculate another value for photovoltaic panel production, where efficiency is 85% and we want photovoltaic panel to produce 12,000w.

Calculating System Size:

Let's jump back to that ***installation map of Pakistan*** shown above and look at the resource that's available to us. We're going to use an example where we have around ***5.5 kilowatt hours*** per square meter of sunlight, which is also known as ***full sun hours***.

A full sun hour is defined as the solar insolation a particular location would receive if the sun were shining at its maximum value for a certain number of hours.

That maximum value is defined by the Standard Test Condition of 1,000 watts per square meter. Let's consider the example of an ***annual usage*** of ***12,000 kilowatt hours***. So accordingly, to the legend on the map, this value of ***5.5 full sun hours*** shows up at about an orange color. That ***orange color*** corresponds to somewhere ***near Quetta***, Pakistan. Since we need annual sunlight energy, we're going to have to multiply that ***daily full sun hour level by 365 days*** to get the total annual energy or ***total annual full sun hours per year*** as following:

$$Daily\ Full\ Sun\ hours\ \ X\ \ 365\ days = Annual\ Full\ Sun\ hours$$

$$5.5\frac{h}{d}\ \ X\ \ 365\frac{d}{y} = 2008\frac{h}{y}$$

Now PV system size will be:

$$PV\ System\ Size = \frac{\left(\frac{Energy\ Demand}{Annual\ Full\ Sun\ hours}\right)}{Efficiency}$$

$$PV\ System\ Size = \frac{\left(\frac{12{,}000Kwh}{2008\frac{h}{y}}\right)}{0.8} = 7.47kw$$

The calculation tells us our photovoltaic system size needs to be about 7.47 kilowatts to supply the annual 12,000-kilowatt hours load in a location that receives 5.5 full sun hours per day.

So, what does this mean? Well, if we look at the popular press, or in news clippings, it might say a 10-kilowatt system was installed, or a 1-megawatt system was installed. These kinds of numbers are talking about the installed power of the system. *Remember, that power doesn't actually tell us anything about the energy that's produced*. If we take that same sized system and put it in other near northern areas, it will produce less energy, because there's less sunlight. Sunny areas will produce more energy. So, this power rating gives you an idea of how much energy is produced, based on sunlight levels.

Now that we know the total power, the next step is to take that power and determine how many ***photovoltaic modules*** are needed to equate to that power. To do this, we take the total system power and divide by the power rating of the photovoltaic modules you might use.

$$No.of\ Modules\ Required = \frac{System\ Power}{Module\ Power}$$

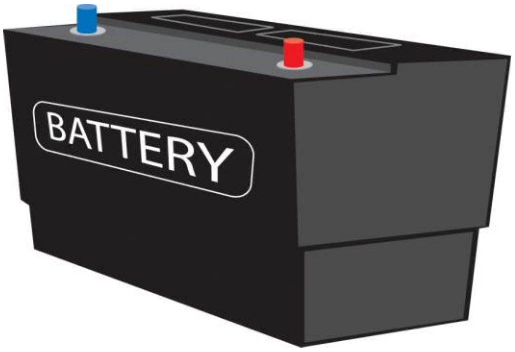
$$No. of\ Modules\ Required = \frac{7.47kw}{200w} = 37.4\ panels$$

We can't have a fractional panel, so we could round up or down, depending on the situation. If we round down to 37 panels, we'll be very close to achieving our need of 12,000 kWh/year.

Let’s Calculate for an alternative option, if maybe we can't afford those 37 panels or can't replace 100% of the load, but maybe we can replace 60% of the load. Calculate no. of modules required for annual 12,000-kilowatt hours load in a location that receives 5.5 full sun hours per day and external efficiency limitations is about 80 percent.

Batteries:

A fundamental characteristic of a photovoltaic system is that power is produced only while ***sunlight is available***. For systems in which the photovoltaic is the sole generation source, an exact match between available sunlight and the load is limited to a few types of systems, for example powering a cooling fan and therefore storage is typically required. Even in hybrid or grid-connected systems, where batteries are not inherently required, they may be beneficially included for load matching or power conditioning. By far the most common type of ***storage*** is ***chemical storage*** in the form of a battery. However, in some cases other forms of storage can be used. An *electric battery is a device consisting of one or more electrochemical cells that convert stored chemical energy into electrical energy*. Each cell contains a positive terminal, or anode, and a negative terminal, or cathode. Electrolytes allow ions to move between the electrodes and terminals, which allows current to flow out of the battery to perform work.



A battery convert's energy stored in the chemical bonds of a material into electrical energy via a set or oxidation/reduction (redox) reactions. Redox reactions are chemical reactions in which an electron is either required or produced. A battery is a source of ***constant DC voltage***. Ideally, the battery should provide constant voltage no matter how much current is drawn through the battery depending upon the Ah capacity of the battery i.e., it will have an I –V curve that is simply a straight up-and-down line.

In any photovoltaic system that includes batteries, the batteries have a major effect on the system, impacting performance, cost, maintenance requirements, reliability, and design of the photovoltaic system. *The cost of the batteries in a stand-alone system is similar to the cost of the photovoltaic modules.*

The important battery parameters are:

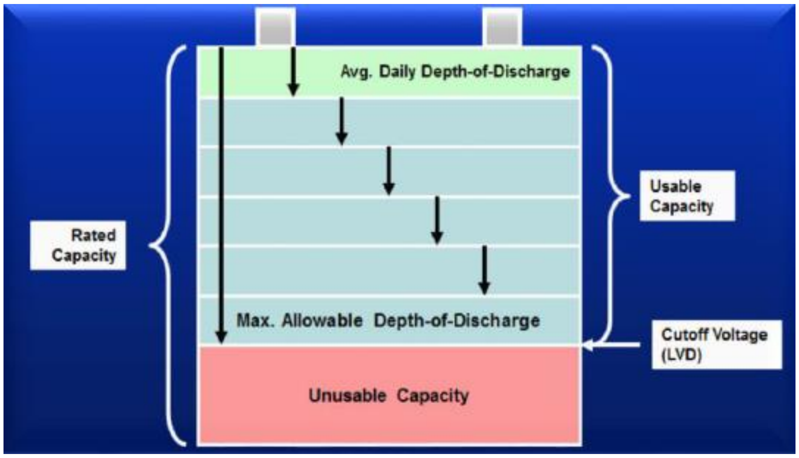
- Battery capacity (measured in units such as amp-hour (Ah))
- Voltage (and how these change and interact with other system parameters)
- Depth of discharge (DOD)
- Lifetime of the battery (no. of cycles)

Batteries are specified in ***Voltage and Amp-hour capacity***. Total amount of rated battery capacity requirements is based on:

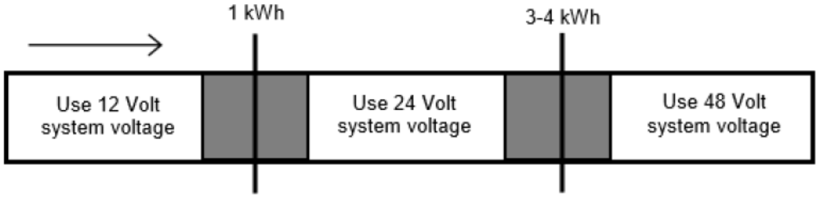
- Desired days of storage (also known as days of autonomy)
- Maximum allowable depth-of-discharge (DOD)
- System losses and efficiencies

Days of Autonomy is the number of days that a fully charged battery bank can meet the system loads without any recharge from the PV array. Greater autonomy periods increase the size of the battery bank and the amount of energy storage. ***5 days*** of Autonomy is ***recommended*** as this provides decent protection from periods of extended cloudy weather. The specified autonomy and maximum allowable depth-of-discharge define the total amount of battery capacity required for a given system load. Greater autonomy periods are used for more critical applications and increase system availability but at higher cost due to the larger battery required. Designing too many days of autonomy into a battery bank, makes it difficult to recharge the battery completely.

Greater autonomy periods increase the size of the battery and increase availability but decrease average daily depth-of-discharge. The ***Depth of Discharge*** is the maximum level that the system is able to discharge the batteries. It is controlled by the Cut Off Voltage (LVD), which is set by the charge controller. Maximum depth-discharge defines the usable battery capacity and is defined by the load cutoff voltage. Greater allowable DOD provides greater system availability, but at the expense of battery health. DOD must be limited in cold climates to protect lead-acid batteries from freezing. Depth of discharge should not be lower than 75%. It is commonly between 50% and 75%.



The final consideration when sizing batteries is selecting the ***system voltage***. System voltage determines the number of batteries that are connected together in series to form the battery bank. Smaller stand-alone systems used for residential and small off-grid applications typically use 12 V or 24 V. The higher the system voltage, the lower the current & the power loss. So higher DC voltages are used for systems with higher power loads to reduce the system currents.



Battery Sizing:

$$Battery\ Capacity\ Required(wh) = \frac{Load\ \ X\ \ Backup\ hours}{DOD\ \ X\ \ \eta}$$

And

$$DOD \propto \frac{1}{Battery\ Life}$$

Where battery Life means no. of battery cycles and

$$1\ Cycle = 1\ Time\ Charge\ and\ Discharge$$

$$\eta = Battery\ Efficiency$$

$$Load\ = Energy\ Consumption$$

For example, we have a load of 2050w with back up time is 1 hours and efficiency of battery is around 80% with DOD about 60%. So, Battery capacity is:

$$Battery\ Capacity\ Required = \frac{2050w\ X\ 1h}{0.6\ X\ 0.8} = 4{,}270wh$$

Let have a single battery capacity around 100Ah and 12V, So:

$$P = V\ \ X\ \ I$$

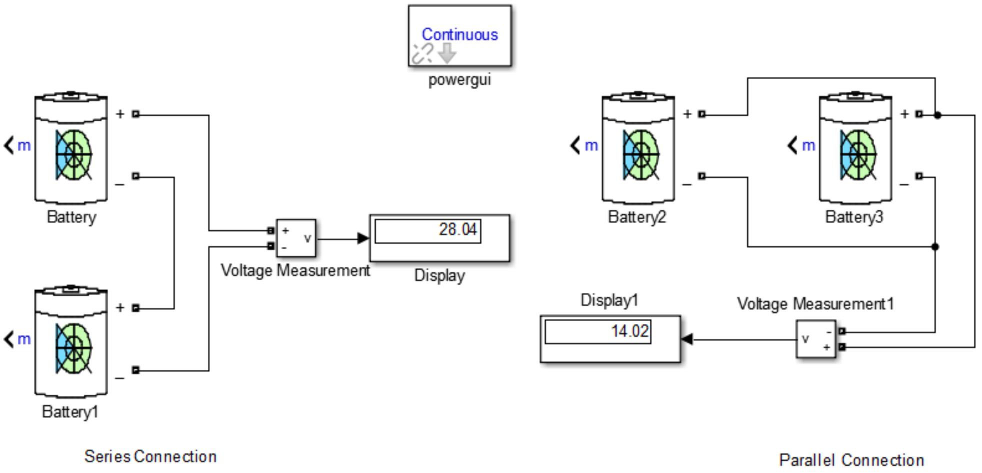
$$P = 12V\ \ X\ \ 100Ah = 1200wh$$

$$No. of\ Batteries\ Required = \frac{Battery\ Capacity\ Required}{Single\ Battery\ Capacity}$$

$$No. of\ Batteries\ Required = \frac{4270wh}{1200wh} = 3.5 \approx 4$$

Battery Connection in Series and Parallel:

We know that voltage added in series while current in parallel, so same analogy is used in batteries as following:



If we use battery capacity of 100Ah and 12V, then in ***two battery series connection***, voltage added and goes to 24v operating voltage while current capacity remains the same as 100Ah. In ***parallel connection of two batteries***, voltage remains the same as 12v but current capacity increases 200Ah.

N_S = No. of batteries in Series

N_P = No. of batteries in Parallel

Let’s draw a connection where our required battery capacity is 24V and 200Ah. Single battery capacity rating is 100Ah and 12V.

Now let’s draw the connection for the above (battery sizing), if the system voltage is 48V and available single battery capacity is 12V and 100Ah then:

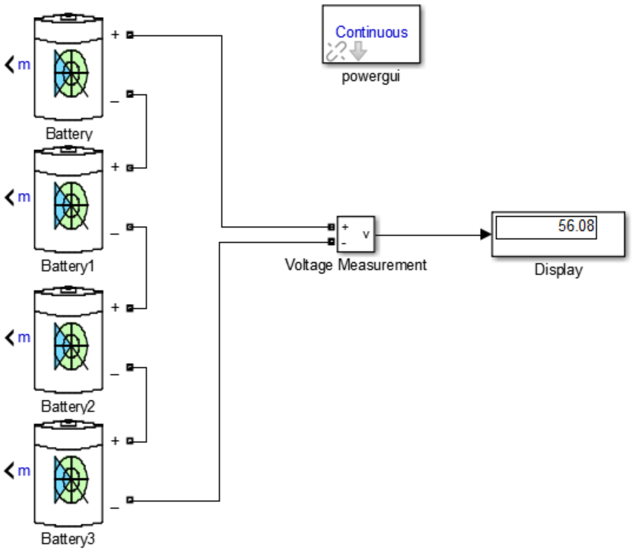
$$N_S = \frac{System\ Voltage}{Single\ Battery\ Voltage}$$

$$N_S = \frac{48V}{12V} = 4$$

Now for parallel connection,

$$Single\ Battery\ Bank\ Capacity\ Required(Ah) = \frac{Battery\ Bank\ Capacity(wh)}{System\ Battery\ Voltage(v)}$$

$$Single\ Battery\ Bank\ Capacity\ Required = \frac{4270wh}{48v} = 89Ah$$



$$N_P = \frac{Single\ Battery\ Bank\ Cap.Req.}{Single\ Battery\ Capacity}$$

$$N_P = \frac{89}{100} = 0.89 \approx 1$$

So, we have

$$N_S = 4\ , N_P = 1$$

So Total no. of batteries is:

$$N = N_S\ X\ N_P = 4\ X\ 1 = 4$$

So, battery bank rating is 48V, 100Ah and 4800wh.

Calculate the no. of battery required & their series and parallel combination for 7.47kw PV system, where backup time for batteries is about 0.5hour and DOD is 75% & Battery efficiency is about 85%. Single battery capacity is 12V and 100Ah and System Voltage is around 48V.

Conclusion and Comments: