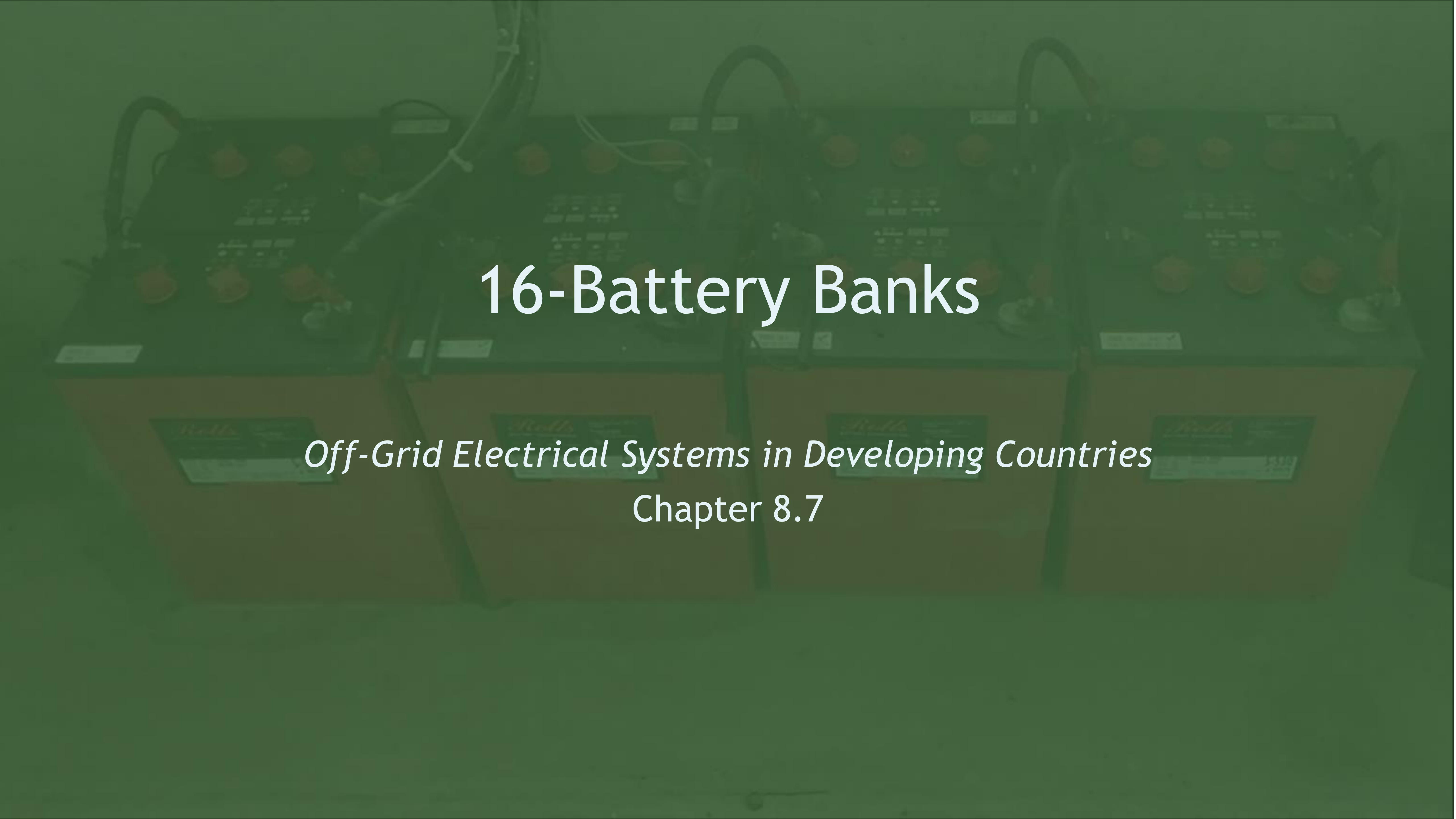


16-Battery Banks

Off-Grid Electrical Systems in Developing Countries

Chapter 8.7

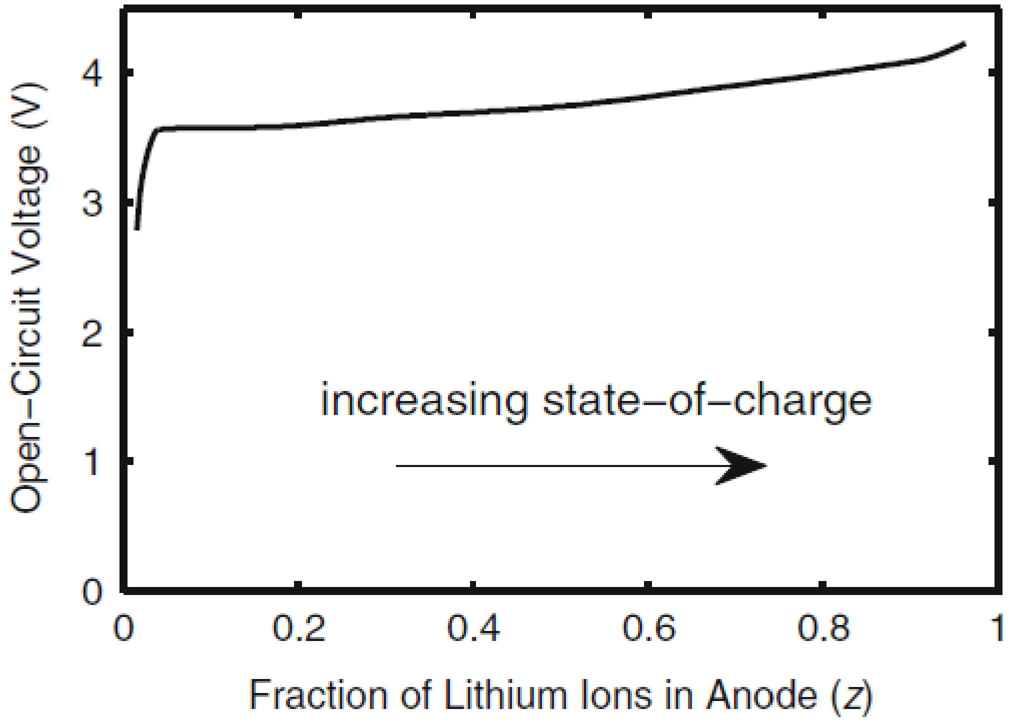
Learning Outcomes

At the end of this lecture, you will be able to:

- ✓describe how batteries can be arranged in series and parallel to form a battery bank
- ✓determine the energy and charge capacity of a battery bank
- ✓design a battery bank to meet certain nominal voltage and capacity requirements

Lithium-Ion Batteries

- Read Chapter 8.6
- Lithium-ion considerations:
  - Greater standard cell potential (3.2 to 3.6 V) which improves energy density
  - Flatter IV curve
  - Longer cycle life (usually)
  - Less toxic
  - More expensive
  - Protection from thermal runaway needed



Battery Banks

- Off-grid batteries usually have capacity of a few kilowatthours or less
- When greater capacity is needed, the batteries are combined into a battery bank
- Higher voltages are possible in battery banks

(Courtesy GVE Projects)

Battery Bank Strings

Connecting batteries in strings (series) increases the DC bus voltage

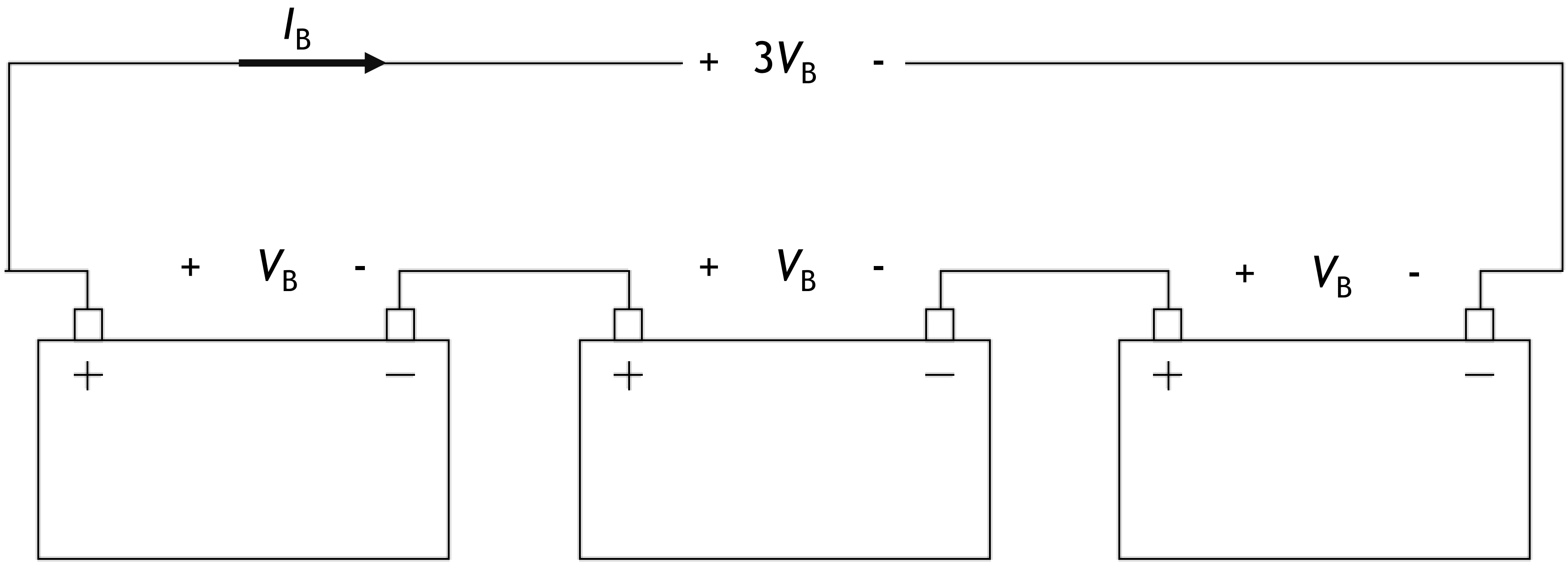
$$V_{\text{bank}} = \sum_{i=1}^{N_{\text{series}}} V_{\text{B},i}$$

N_{series}: number of batteries in series
$V_{\text{B},i}$: terminal voltage of battery i (V)
V_{bank}: terminal voltage of the battery bank (V)

$$V_{\text{bank}} = N_{\text{series}} \times V_{\text{B}}$$

Here we assume that each battery has the same voltage

Battery String



The same current passes through each battery

Parallel Strings

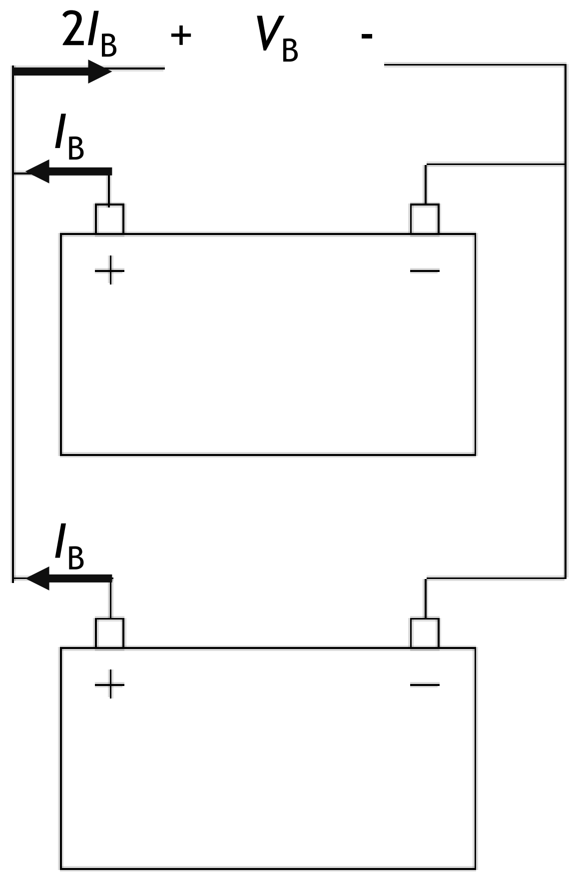
- Batteries of the same voltage can be connected in strings
- Each string contributes equally to the total battery bank current

$$I_{\text{string}} = \frac{I_{\text{Bank}}}{N_{\text{string}}}$$

N_{string}: number of strings
I_{string}: string current (A)
I_{bank}: battery bank current (A)

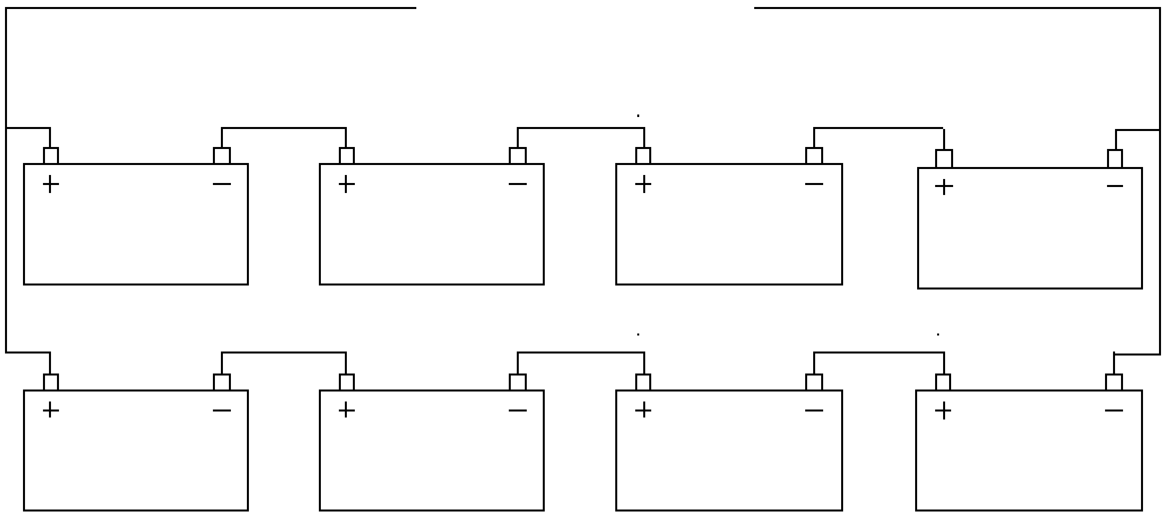
Parallel Strings

Each battery contributes one half of the battery bank current



Battery Bank Configurations

Series/parallel combinations are also possible



Battery Energy Capacity

- Similar to the power capability of PV modules in an array, the energy capacity of a battery bank is independent of configuration of the batteries

$$E_{\mathrm{bank},x} = N_{\mathrm{string}} \times N_{\mathrm{series}} \times e_{\mathrm{B,x}}$$

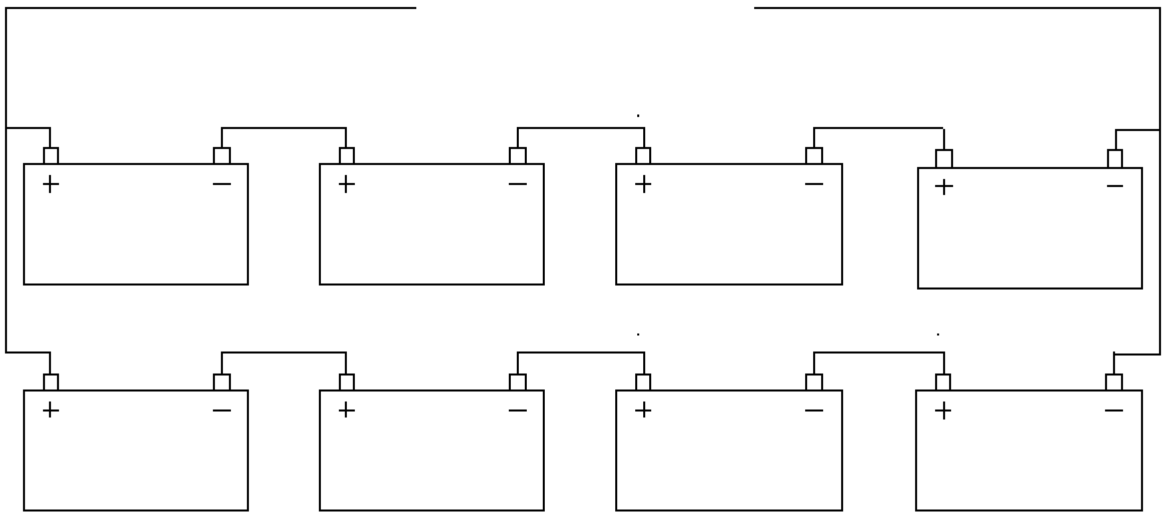
$e_{B,x}$: energy in an individual battery at discharge current of *x* (kWh)
$E_{bank,x}$: energy in a battery bank at discharge current of *x* (kWh)

Battery Charge Capacity

- The charge capacity of a battery bank is equal to the charge capacity of a single battery multiplied by the number of strings
- The number of series connected batteries does not affect the charge capacity of a battery bank (but it does boost the voltage)

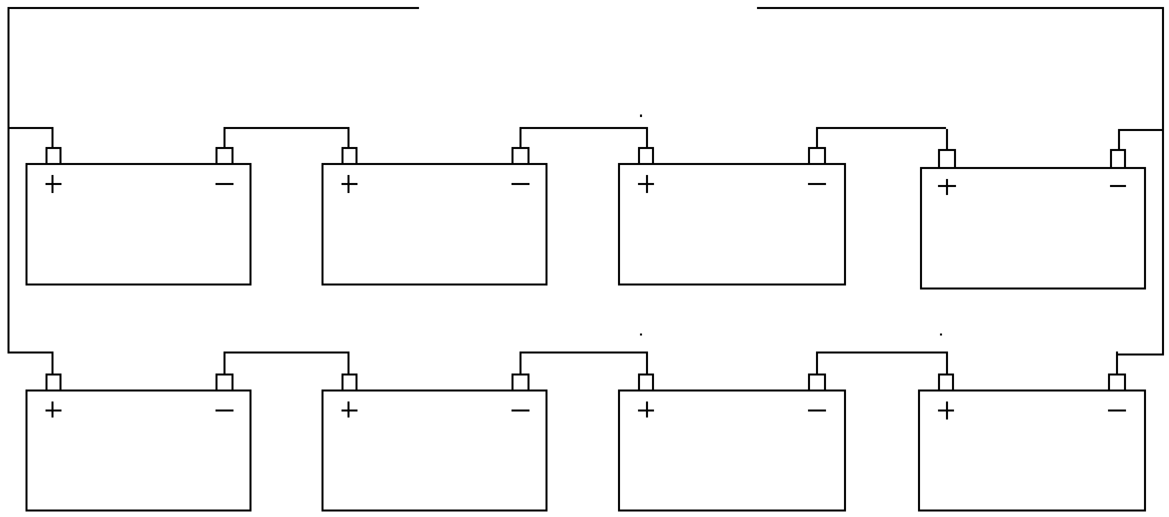
Exercise

- Assume eight Trojan 06 375 batteries are arranged as shown
- Identify:
  - The number of strings
  - The number of batteries per string
  - The nominal voltage of the battery bank
  - The energy capacity of the battery bank (0.05C)
  - The charge capacity of the battery (0.05C)



Exercise

- The number of strings: 2
- The number of batteries per string: 4
- The nominal voltage of the battery bank: 4 x 6V =24V



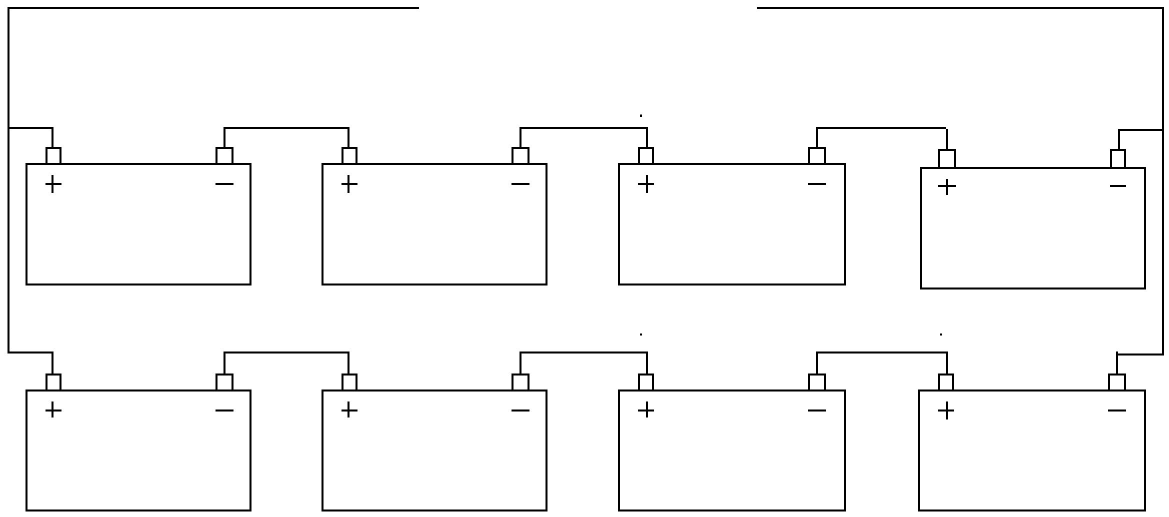
Exercise

- The energy capacity of the battery bank (0.05C):

  8 x 2.25 = 18 kWh

- The charge capacity of the battery (0.05C)

  375 x 2 = 750 Ah



In other words, the battery bank is equivalent to a single 24 V, 750 Ah battery

Design Example

Design a battery bank using the Trojan 06 375 that is capable of supplying 20A at 12V for a 60-hour period

Design Example

Design a battery bank using the Trojan 06 375 that is capable of supplying 20A at 12V for a 60-hour period

First note that we need exactly two batteries per string to meet the 12V requirement. The total number of batteries will therefore be integer multiples of 2 (2, 4, 6, ...)

Design Example

Design a battery bank using the Trojan 06 375 that is capable of supplying 20A at 12V for a 60-hour period

Now do a quick calculation of the charge capacity needed:

20A x 60hrs = 1200Ah

Design Example

Design a battery bank using the Trojan 06 375 that is capable of supplying 20A at 12V for a 60-hour period

Next, determine the approximate number of strings needed

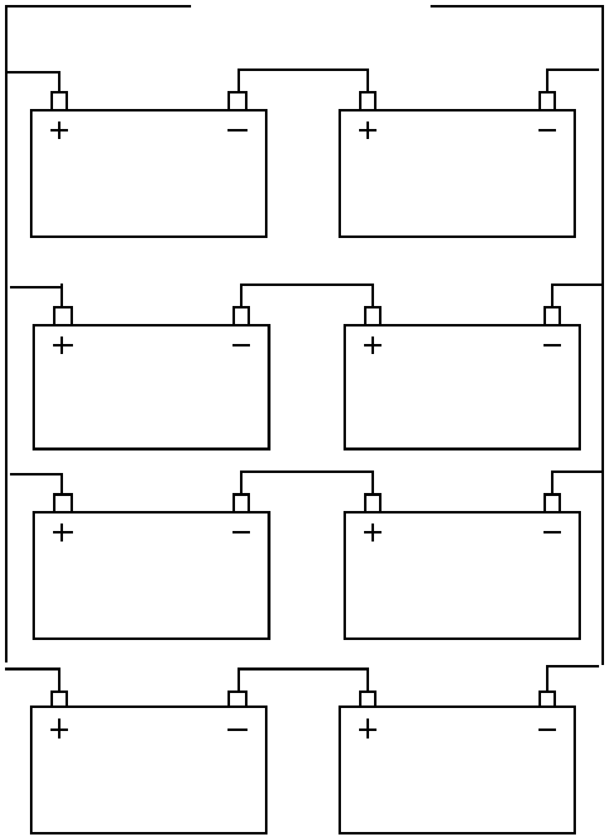
The battery will be discharged over a 60-hour period, which is somewhere between the 48-hour and 72-hour rate listed in the spec sheet

Design Example

Design a battery bank using the Trojan 06 375 that is capable of supplying 20A at 12V for a 60-hour period

Let’s consider the 48 hour rate since it is more conservative (it assumes that the whole 1200 Ah is discharged in 48 hours, not 60). The capacity is 389 Ah. Using this rate a total of 1200Ah/389Ah = 3.08 strings are needed, which we would round up to four strings.

The battery bank is connected as



Design Example

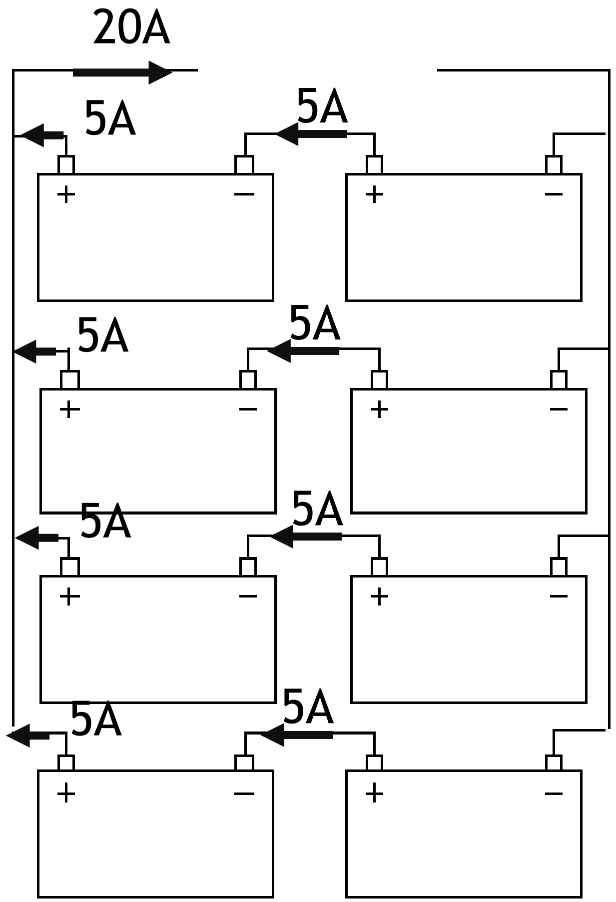
How long will this battery bank last given the load is 20A?

Each string supplies: 20/4 =5A

Current at 72 hour rate: 394/72 = 5.47A

Current at 100 hour rate: 400/100= 4.0A

The battery will last somewhat longer than 72 hours, but not as long as 100 hrs. We could use Peurket's Equation to improve our estimate



Design Example

Work in your team to design a battery bank that is capable of supplying 52 A at 48 V for 40 hours using the Rolls S-1450

Design Example

- One possible solution: 2 strings of 24 batteries in series (48 batteries total)
- Each string has 2V x 24 = 48 Volts
- Each string provides 52/2 = 26 A (which is just below the current at the 50 hour rate)
- Total capacity is 2 strings x 1338 = 2676Ah; required 52 A x 40 hours = 2080 Ah

Other Considerations

- All batteries in a battery bank should be of the same model, age, and condition
- Limit the number of strings (for safety)
- Few larger batteries are preferred to many smaller batteries
- Provide ventilation and spill protection

Additional Examples

Consider the Renology AGM 200 battery with capacity table shown below. Compute the discharge current corresponding to the 5-hour rate.

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah

Additional Examples

Consider the Renology AGM 200 battery with capacity table shown below. Compute the discharge current corresponding to the 5-hour rate.

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah

$$\text{Discharge Current (A)} = \frac{\text{Charge Capacity (Ah)}}{\text{Hour Rate (h)}} = \frac{172.3}{5} = 34.46\text{A}$$

Additional Examples

Consider the Renology AGM 200 battery. How long will the battery be able to supply a constant current load of 25A before reaching its cut-off voltage? Assume the Peukert Exponent is 1.17.

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah

Additional Examples

Consider the Renology AGM 200 battery. How long will the battery be able to supply a constant current load of 25A before reaching its cut-off voltage? Assume the Peukert Exponent is 1.17.

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah
Current	50.97A	34.46 A	19.05 A	10 A

Computing the current for each capacity in the table, we see that 25A lies between the 5 hour and 10 hour rates, but is closer to the 10 hr rate. Apply Peukert’s equation based on the 10 hour rate

Additional Examples

Consider the Renology AGM 200 battery. How long will the battery be able to supply a constant current load of 25A before reaching its cut-off voltage? Assume the Peukert Exponent is 1.17.

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah
Current	50.97A	34.46 A	19.05 A	10 A

$$c_{25} = c_{x_r}\left(\frac{x_r}{x}\right)^{k-1} = 190.5\left(\frac{19.05}{25}\right)^{1.17-1} = 181.9 \text{ Ah}$$

This looks believable because it should be between 172.3Ah and 190.5 Ah

Additional Examples

- Consider the battery bank shown consisting of six 12V, Renology AGM 200 batteries. Compute the battery bank voltage, charge capacity, and energy capacity at the 20 hour rate.

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah
Current	50.97A	34.46 A	19.05 A	10 A

$$\text{Hour Rate (h)} = \frac{\text{Charge Capacity (Ah)}}{\text{Discharge Current (A)}} = \frac{181.9}{25} = 7.28\textbf{hr}$$

Additional Examples

- Consider the battery bank shown consisting of six 12V, Renology AGM 200 batteries. Compute the battery bank voltage, charge capacity, and energy capacity at the 20 hour rate.

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah
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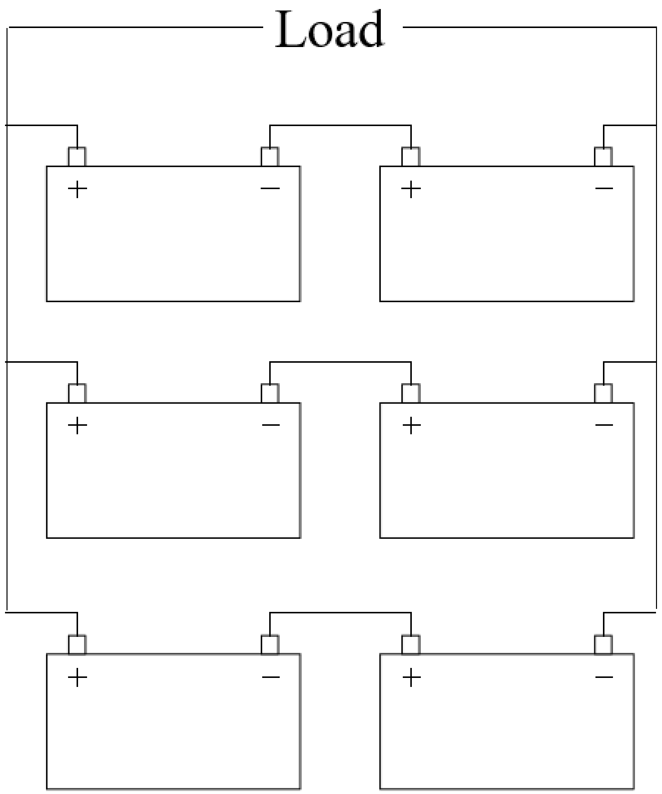

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Hour Rate	3 hr	5 hr	10 hr	20 hr
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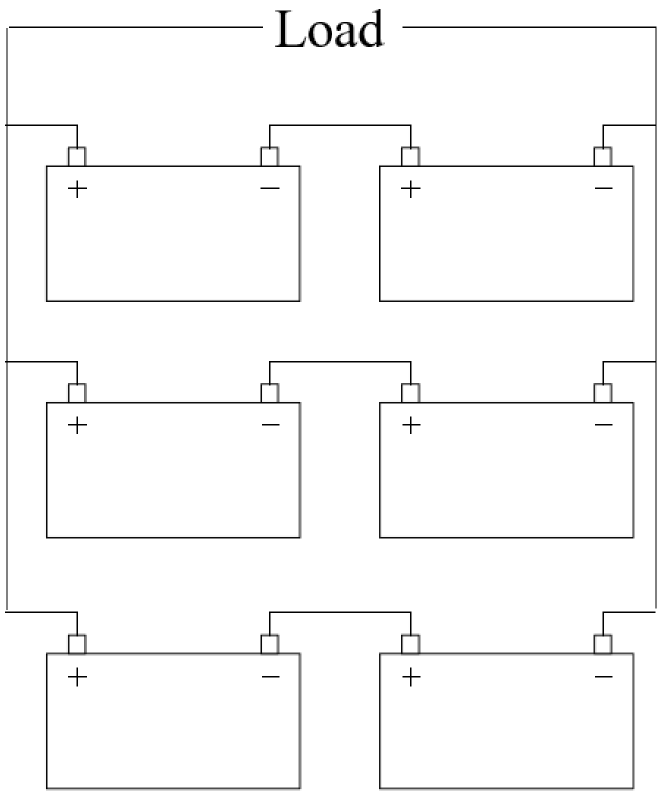
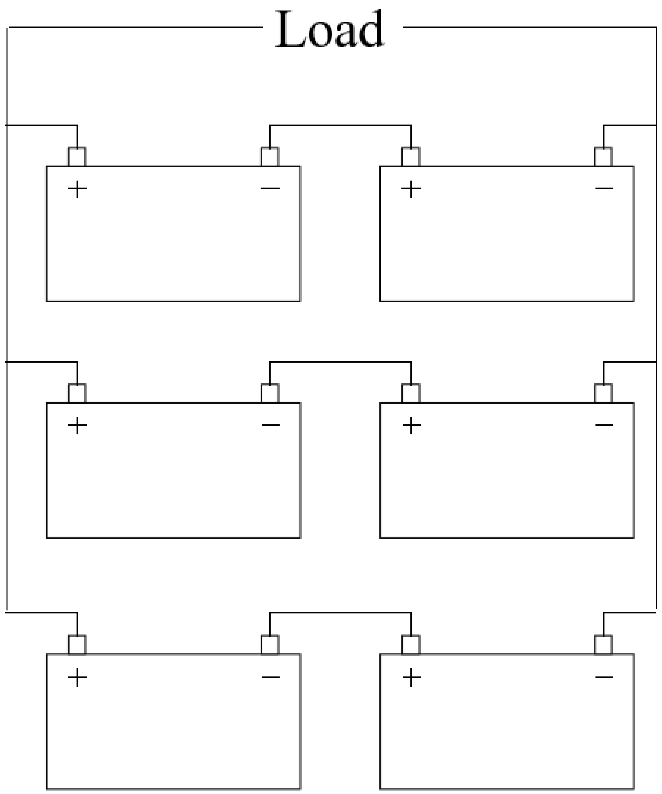


Battery bank voltage: 2 x 12 V =24 V (two in series)
Charge Capacity: 200 Ah x 3 = 600 Ah (three strings)
Energy Capacity: 6 x 12V x 200 Ah = 14.4 kWh (six batteries total)

Additional Examples

- Estimate how long the battery bank can supply a 60 A load until the cut-off voltage is reached?

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah
Current	50.97A	34.46 A	19.05 A	10 A



Additional Examples

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Hour Rate	3 hr	5 hr	10 hr	20 hr
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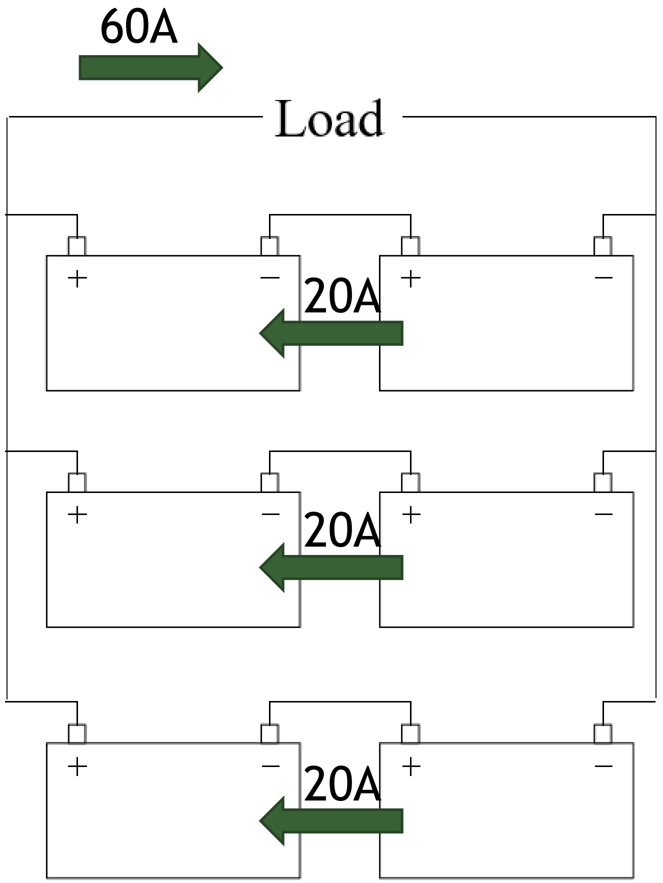


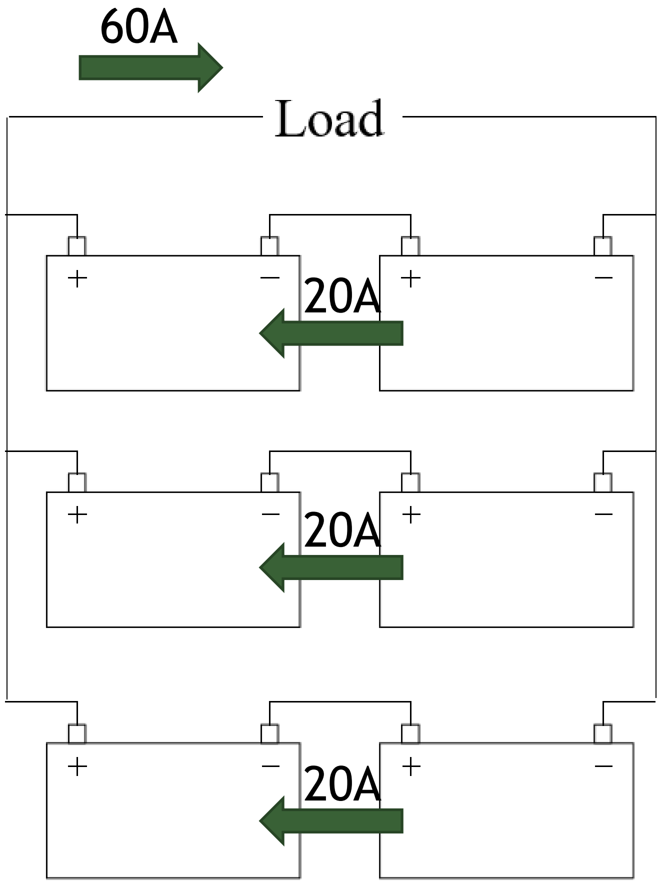
The current is divided evenly between the three strings. Each string (and battery) supplies 20 A.

Additional Examples

- Estimate how long the battery bank can supply a 60 A load until the cut-off voltage is reached?

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah
Current	50.97A	34.46 A	19.05 A	10 A

The capacity at a discharge current of 20A is not in the table, so estimate the capacity using Peukert's equation. The result should be close to the 10-hour rate since this rate corresponds to 19.05A.



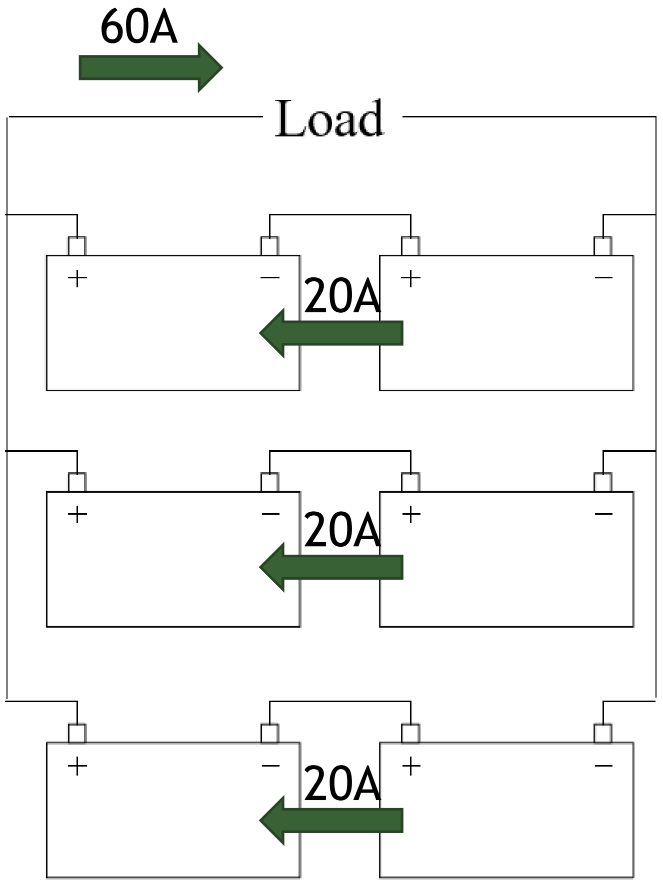
Additional Examples

- Estimate how long the battery bank can supply a 60 A load until the cut-off voltage is reached?

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah
Current	50.97A	34.46 A	19.05 A	10 A

$$c_{20} = c_{x_r}\left(\frac{x_r}{x}\right)^{k-1} = 190.5\left(\frac{19.05}{20}\right)^{1.17-1} = 188.9\ \text{Ah}$$

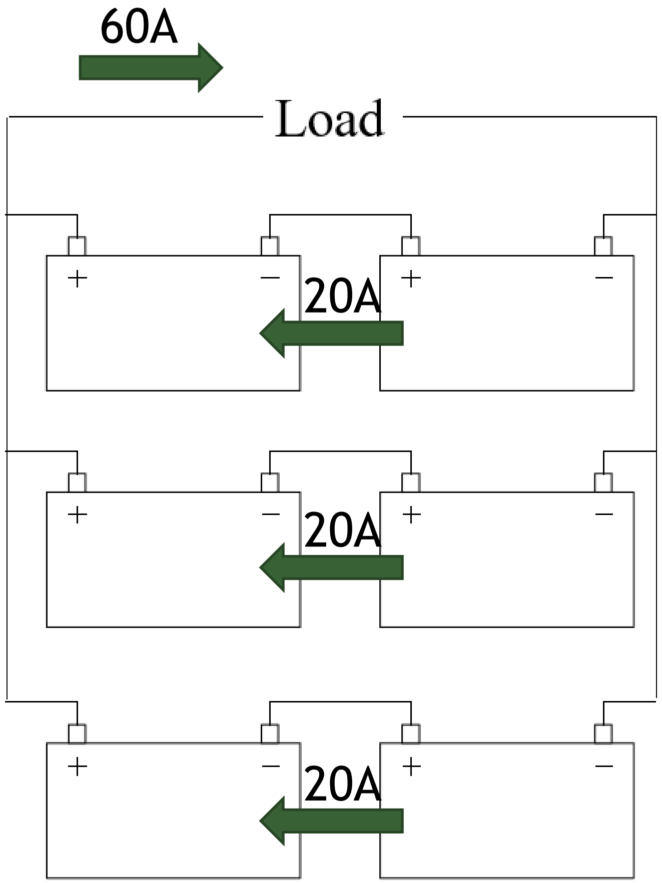
$$\text{Hour Rate (h)} = \frac{\text{Charge Capacity (Ah)}}{\text{Discharge Current (A)}} = \frac{188.9}{20} = 9.44\text{hr}$$



Additional Examples

- What is the energy capacity when the battery bank is discharged at 60A?

Hour Rate	3 hr	5 hr	10 hr	20 hr
Capacity	152.9 Ah	172.3 Ah	190.5 Ah	200 Ah
Current	50.97A	34.46 A	19.05 A	10 A



Energy Capacity: 6 x 12V x 188.9 Ah = 13.6 kWh (six batteries total)

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