An Approach to Lithium-Ion Battery System Design

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Deep Space Lighting

What's the appeal?

- Higher power and energy density
  - In terms of both weight and volume
- Near-constant voltage over usable range for LFP
- Very little drop in cell voltage under heavy load
- No significant Peukert effects
- High charge and discharge rates
- No hazardous gases to vent
- Possibly lower life-cycle costs than lead acid

Objectives
(for my own system)

- Relocate batteries, inverter, charger from storage bay near generator to dead space at rear
  - Want to reduce total space occupied by system while increasing capacity
- Want to be able to charge at rate close to generator's capacity to minimize fuel consumption
  - Influences cell type and configuration to some degree, though any Li system will be an improvement over FLA or AGM.
  - Full charge with lead acid batteries requires long period of time at low charge rate (~few hundred watts) while basically idling 12kW generator
- Significantly increase usable capacity
  - Starting with 6 T105s that are several years old. 3*(200Ah)*(12V)*(50% usable for reasonable life)*(they're old)=<3kWh
- No transfer switching
  - Even the short time it takes for a transfer switch to operate can affect some electronics.
  - Want to be able to feed power to batteries and run house at same time—even if shore power is limited.
- Need to be able to charge chassis batteries from house, ~~charge house batteries from alternator, and start generator from either source~~
- Enough power to run air conditioning for ~1 hour (at least).
- Keep it simple to operate and maintain
- No fires, explosions, leaks, or funny smells

Considering Higher (48V) DC Voltage

Pros:

- Smaller copper wire ($$), less lossy
- Greater selection, cheaper inverter options
  - Inverter prices generally scale with DC current ratings, not total power
- Packaging and battery management simplified
- RVIA low voltage standard no longer applies

Cons:

- Need to convert back to 12V for some loads
  - Easy for small loads, not so easy for high-amperage loads like leveling jacks
- More complicated management with 2 DC voltages
- Slightly higher risk of shock

Why 48V?

- Inverter selection. 48V is pretty common for home off-grid systems (along with telephone systems and others)
- High enough to be efficient and cost effective, without introducing HV safety concerns/costs.
- Pre-configured battery modules

Main Components

- Batteries
- Charger
- MPPT controller
- Solar panels
- 48V-to-12V buck converter
- ~~12V-to-48V boost converter~~
  - After striking this from the list, I've added it back
- Inverter

Batteries

- Before we talk about specific batteries, let's take care of some terminology.
- Forget about ratings in Amp-hours.
  - It's only relevant in comparing batteries of the same type and design.
  - Cell voltages are considerably different between FLA and lithium-ion batteries, and even quite different between different lithium chemistries.
  - When combining batteries in series-parallel configurations (e.g. 6V batteries in 12V system), you have to keep track of configuration when adding capacities.
  - Instead, we care about the amount of stored energy (measured in kWh), and the maximum charge and discharge rates (in kW)

How do I figure out what I have now?

- 6V x 225Ah = 1350 Wh = 1.35kWh
- However, as a general rule, for reasonable battery life, it's necessary to limit the depth of discharge to 50% for a lead acid battery.
  - This means that each T105 stores 0.675kWh of usable energy, drawn over 20 hours
  - Thanks to Peukert effect, faster consumption reduces this number further.
- 6 T105s would then be no more than 4.05 kWh of usable energy (when new), weighing 372 lbs. (10.9Wh/lb)

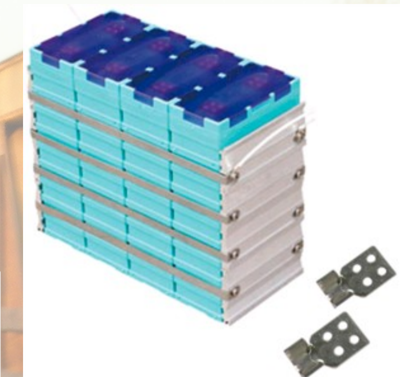
What about for lithium-ion batteries?

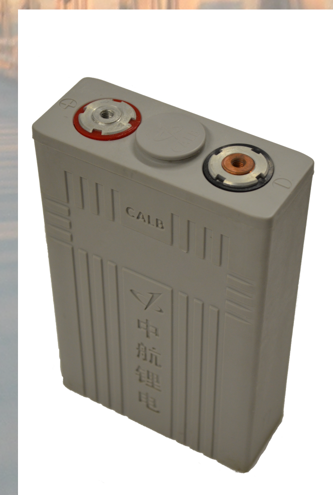
- Different chemistries operate at different cell voltages, but also have ratings in Amp-hours
- Calculate the capacity in kWh for a particular cell, and use 80% depth of discharge:
  - 100Ah CALB 3.2V $LiFePO_4$ cell would store 0.256 kWh, and weigh 7.5lbs (34.1Wh/lb)
  - Roughly 16 cells (120lbs) would be equivalent to 6 T105 batteries

8.62 x 5.59 x 2.63 inches

Common Lithium Battery Form Factors

- Pre-assembled batteries
  - Ready to install, many incorporate battery management systems.
  - Usually made up of LiFePO4 prismatic cells
- Prismatic cells
  - Easiest form factor to work with.
  - Threaded holes for terminal connections, many designed around a system of bus bars to make series and parallel interconnections easy.
- Pouches
  - Usually best capacity/cost ratio, harder to package. Highest specific power.
  - Must understand thermal control when packing tightly together.



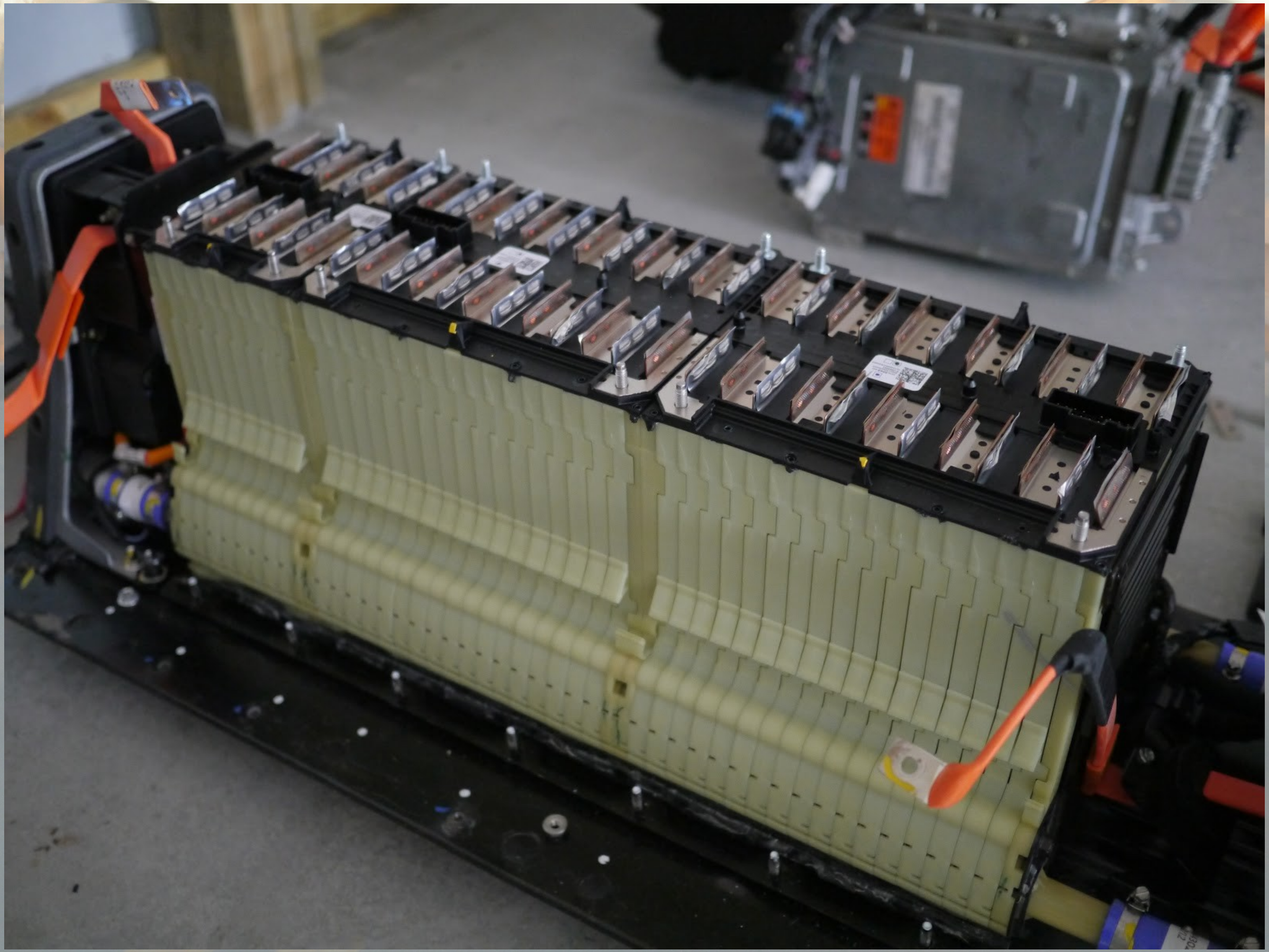


All three form factors shown here are lithium iron phosphate batteries (LiFePO4, or LFP).

Common Chemistries

- Lithium iron phosphate (LiFePO4, LFP)
  - Available in prismatic cells, easy configuration, probably most robust of any commercially available cells.
  - Easily sourced in cell sizes from 40-200Ah
  - Generally 3.2-3.5V/cell
- Other chemistries are not readily adaptable to RV use (cost, safety, availability concerns)
- Lithium manganese spinel
  - Essentially same chemistry as everyday consumer batteries (phones, laptops, etc.)
  - Most extensive application is Chevrolet Volt
    - 16kWh total capacity, 288 cells
    - 4.2V/cell at 100% charge
  - Including used packs, by far cheapest acquisition cost

Another Reason for 48V



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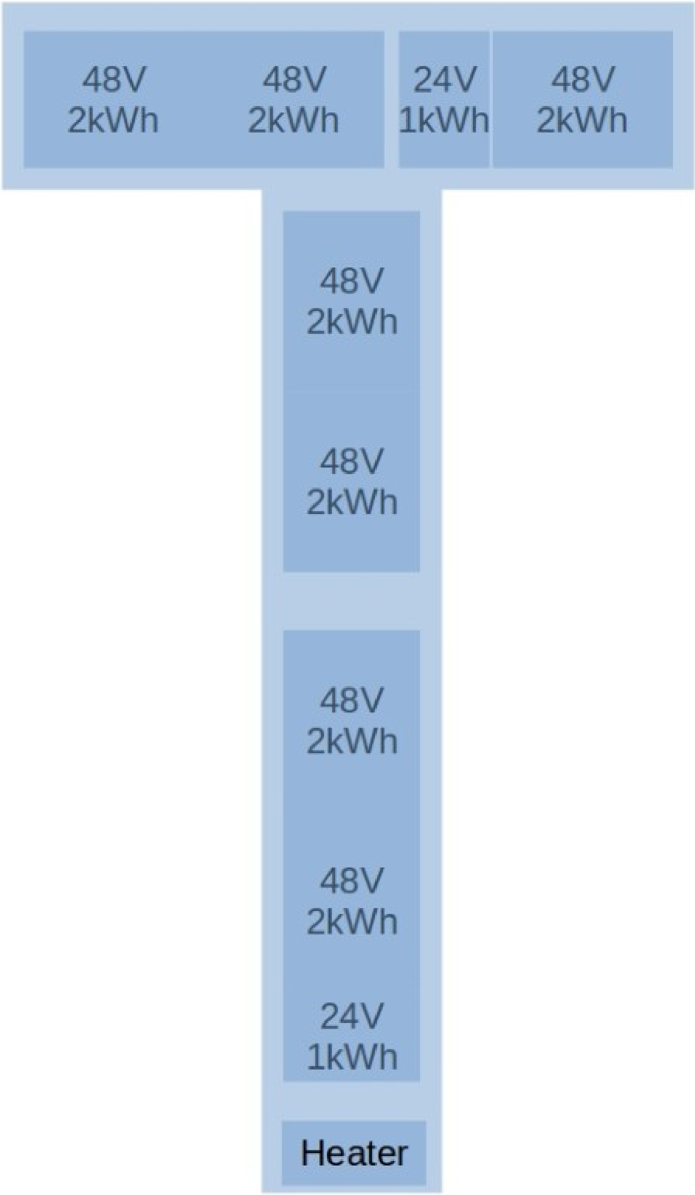

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Charging a Lithium-Ion Battery Bank

- Will an existing charger "work" on a 13.2V lithium-ion battery pack?
  - Maybe. On a 3-stage charger, bulk charging will be current limited by the charger, float stage may not be high enough, or too high, to reach full charge.
  - It's also possible to overcharge a lithium-ion bank. The voltage rise nearing 100% SOC can be very quick, and many 3-stage chargers do not switch to float mode fast enough.
  - More importantly, an existing 3-stage charger can be expected to charge much more slowly than what the battery bank can handle.
    - This means longer time running the generator!

Do I need a battery management system (BMS)?

- A battery management system connects to individual cells to monitor cell voltages. Many also control a shunt, so that individual cells can be taken out of the charging circuit when fully charged.
- If individual cells are properly connected and at the same state of charge when connected, detailed monitoring is not really needed any more than with lead acid systems.
- State of charge cannot be effectively estimated with voltage, so some sort of monitor keeping track of net power in/out of battery is necessary.
- Lithium-ion batteries can be severely damaged, if not rendered unusable, with as little as one discharge too far. A low-voltage disconnect is a must to protect the batteries.
- A battery management system does provide health information about individual cells that allows you to know more about what's going on, and can make re-balancing cells easier (but that shouldn't be needed).

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How complicated is the charging process?

- Simpler than lead acid.
- Provided voltages are properly set, a single “bulk” charging stage is adequate.
  - Remember, generally we want to operate between 10% and 90% state-of-charge, which is mostly the flat-voltage region. The key requirement is the ability to set the charge voltage correctly.
- Depending on the capability of the charger and batteries, thermal management and current limits may be necessary.
  - Since these cells can be damaged by charging at elevated temperatures, a temperature cutoff for the charger is recommended. This also prevents overheating when charging at a high rate.

Are there good chargers already available?

- The best (but pricey) charger option is offered by eMotorWerks.
- Open-source hardware and software, available fully assembled or as a parts kit
- 12kW charge rate, 97% efficiency, power-factor corrected.
  - Even at this rate, a Volt battery pack is being charged at only a small fraction of what it can handle!
- Any input voltage or frequency from 85VAC (120VDC) to 400VAC
  - No more worries about low voltage at the pedestal!
- Software-selectable voltages, and programmable current limits
  - In other words, it can be set to charge at <15A on a 15A outlet, or 50A 220V when that's available.

Are there good chargers already available?

- Morningstar's MPPT controllers can accept power from a DC power supply, and have configurable charging stage voltages.
- Some 48V inverter-chargers already have charge profiles for some lithium-ion chemistries.

48V Inverters

- Lots to choose from
- Many offer split-phase 220V output
- Have to watch for 220V only inverters
  - Though a center-tap isolation transformer could make this workable
- Must be at least able to configure for 60Hz operation (remember, most of the rest of the world operates on 50Hz)
- Many have charge controllers built-in
  - Some even have dedicated wind/solar inputs with MPPT algorithms
- Surge capacities are typically very high—often 5x steady-state rating
- Cost per kW AC power out is generally lower than an equivalent 12V inverter

Charging from Truck Alternator

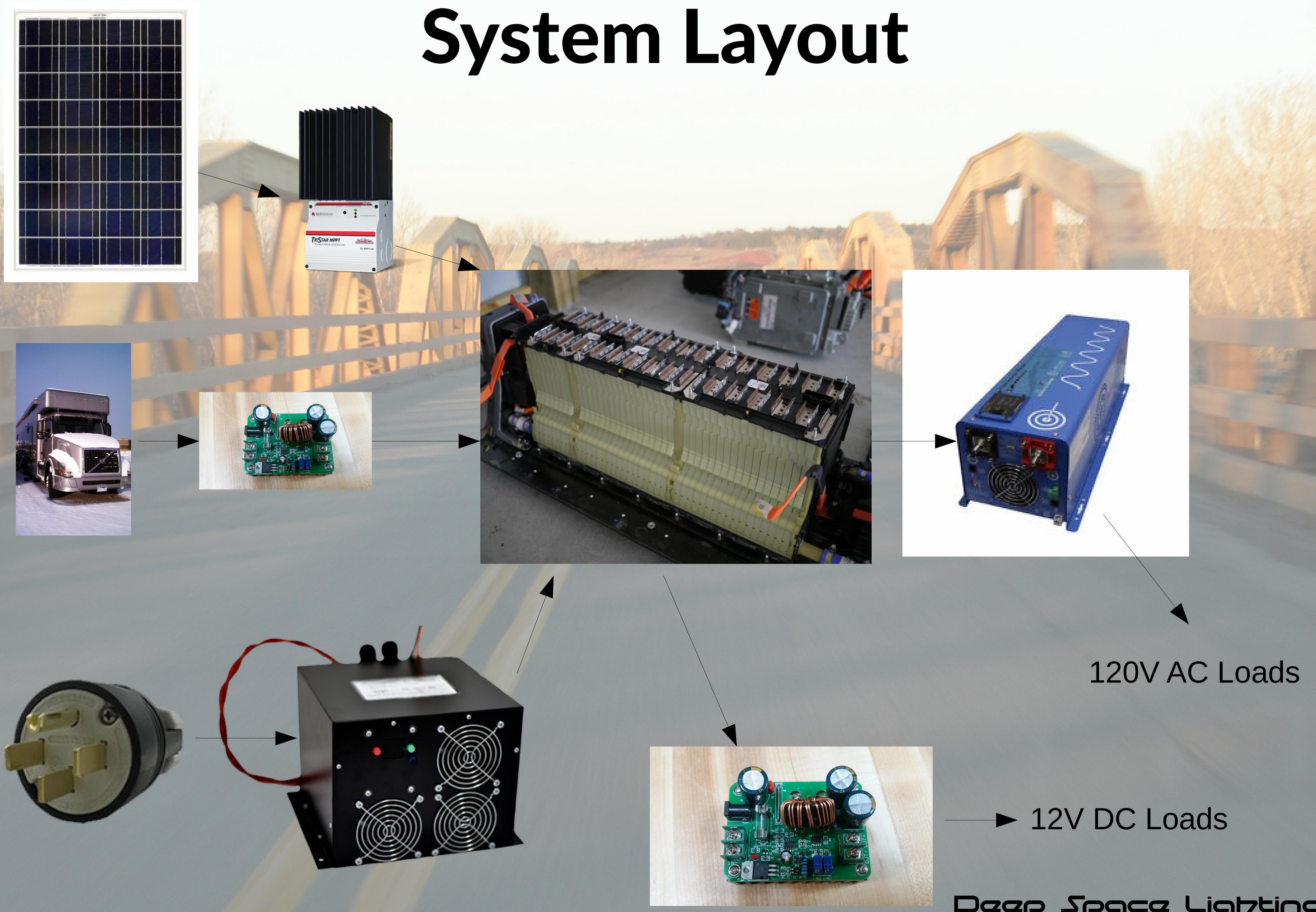
- Not all that much power can be expected
  - Typical 160A (peak) alternator outputs <2kW, and still has to run truck systems
- Need to step up to 48V battery voltage
- Need to limit current drawn from 12V system

50A at 12V input, $30

Supplying 12V Loads

- What's left after AC loads?
  - Leveling jacks
  - Water pump
  - Lighting
  - 12V outlets
  - Radios
  - Antenna amplifiers
  - Refrigerator, water heater, and furnace controls
  - Air conditioning thermostats
- All except leveling jacks easily serviced by buck converter located at DC load center.
- Unlike when operating a normal battery system, buck converter will provide a much more stable DC voltage
  - Lights won't dim when the water pump is on!

System Layout



Now the fun stuff!

- That was all theory, and what I thought I knew at last year’s rally.
- Actually buying a battery pack and building the system is (of course) different
- To make sure I didn't end up with a bunch of expensive paperweights, the system is being built in stages.

Buying the Battery

- There are several databases of junk yards where you can find parts inventory.
- Cheapest battery pack in the country when I started looking was less than 15 miles away, so I went to take a look.
  - It was being stored on a pallet outside, and the yard wouldn't budge on a $400 core charge. Pass.
- Next one I would cross paths with was just outside Dallas. A little more expensive asking price, but $15 core charge (?!?!) was waived.

~~Texas~~ Drivers Wreck a Lot of Cars!

Sometimes the battery comes with a car…

Challenge

- Getting a 430 lb battery pack transported in a 4-door car
- Needs to be loaded quickly with a forklift—not exactly the only customer pulling up to the dock that day.
- Basically, we want to put an ET Junior in the trunk, but with a weird “T” shape

It fit, but even lithium-ion batteries aren't light

Now what?

- Battery needs to be out of car to transport bike to race in 36 hours
- No extra hands
- No big tools
- Has antifreeze in cooling loop
- Can't make noise late in RV park

Disassembling in Place

- Composite cover held on by a bunch of bolts, lifts off easily in one piece. Lightweight part—10lbs max.
- First order of business is reducing the chances of shock. ~300V DC wouldn't be fun.
  - Main cables between each of the 3 main sections disconnected
  - Measurements showed all cells to be within 0.01V of each other
- Coolant hoses between section at top of “T” and the rest looked to be the high point in the system. Lines disconnected, module unbolted from base plate.
- Biggest section has to come out first. Weight approximately 175 lbs.
  - Don't tip, or car will smell like antifreeze forever.

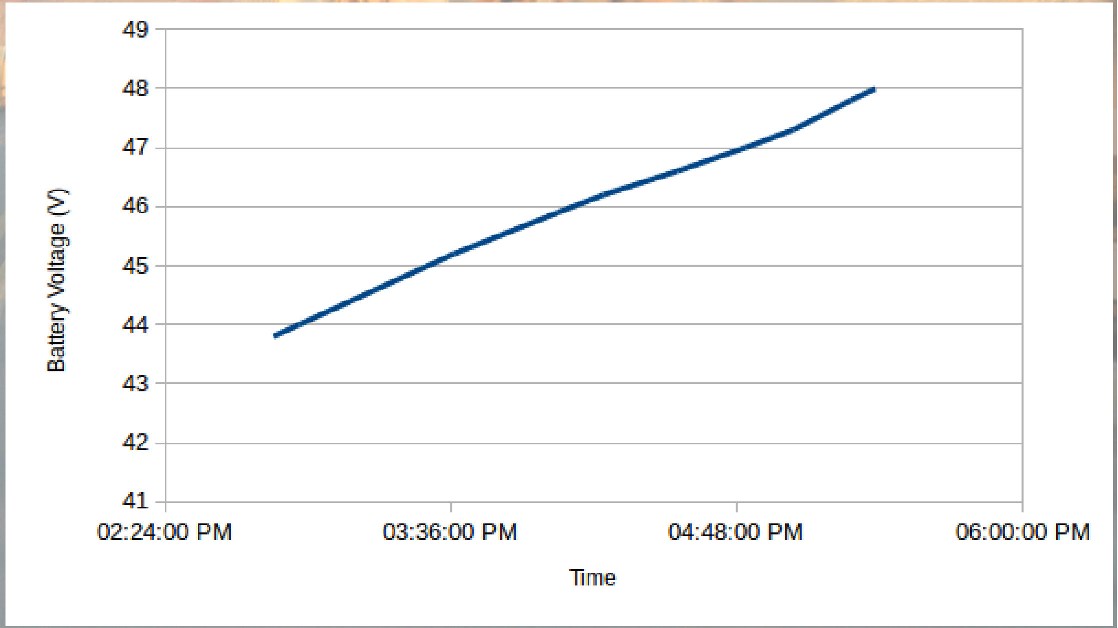
Getting the big section into RV was not easy...

First attempt charging

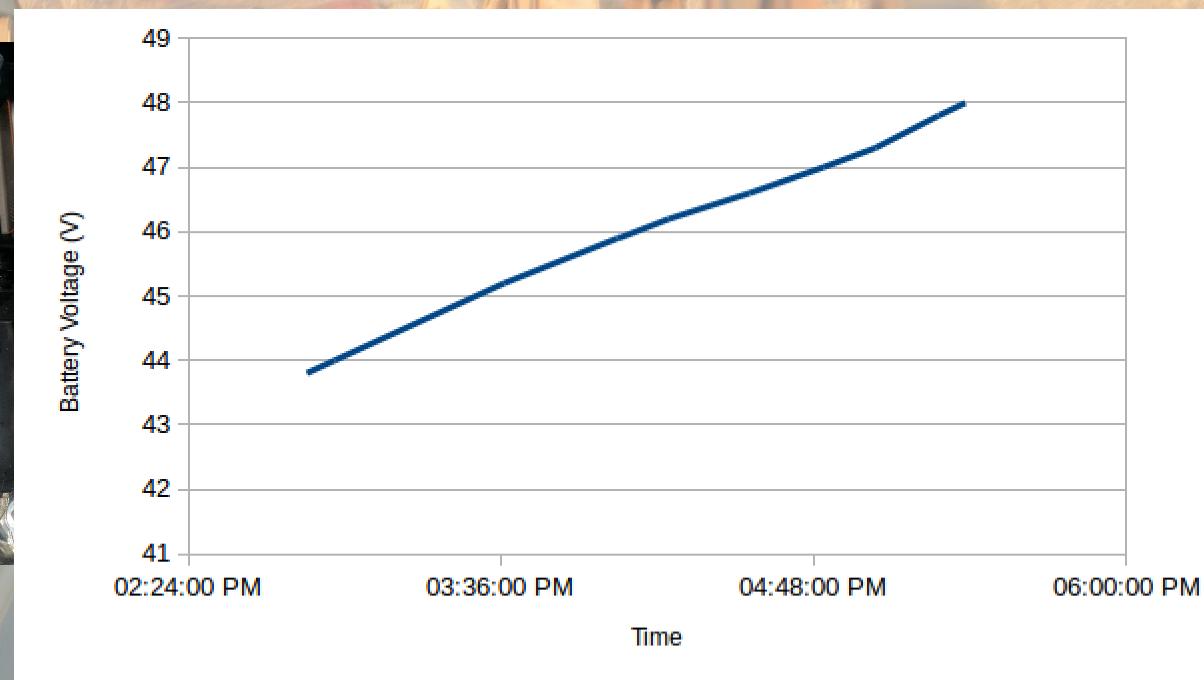
- Used 24V inverter/charger on one 24V section
- Found that lowest configurable voltage cutoff for bulk charging would be too high for battery bank
- Li-ion batteries can charge capacitors inside inverter very quickly!
- Still useful—got an idea of heating, learned a few things about making connections under plastic cover easily

Second charging exercise

- Constant-current mode charging with 48V charger on inverter
- Manually stopped charging
- Recorded voltage vs. time (proportional to power in)
- Drop after stopping charging <0.5V

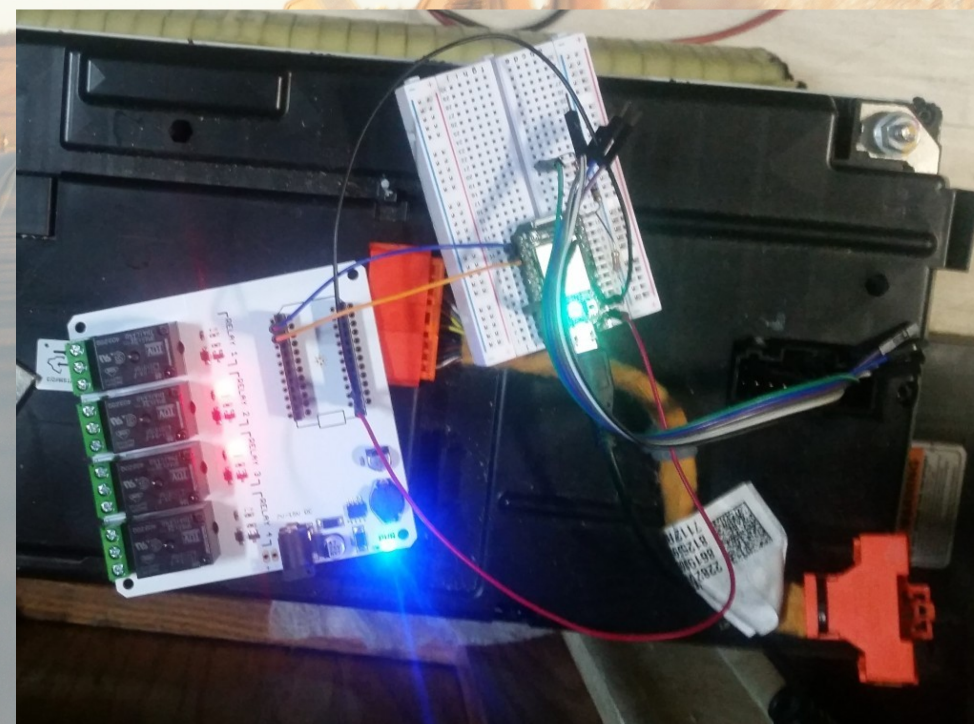


Second charging exercise



Charger Controller

- Couldn't find what I needed, so built my own
- Voltage tells us state of charge—no need for fancy monitoring to really know (as with LA or LFP).
- If cell voltages are the same, state of charge is the same
  - Cell balancing, if needed, is simple and boring
- Voltage divider circuit gets battery voltage down to voltage compatible with analog input on microcontroller
- Controller is same as Wednesday's workshop
- Measures module voltage, and battery pack's internal thermistors
- Separate relays for enabling charging and discharging



Skipping a bunch of bench testing...

- Built platform above floor, in dead space below bottom of cabinet
- All 3 battery sections would fit, with the top of the T disconnected at the coolant manifold.
- Forward section has left the RV for another project...

Safety

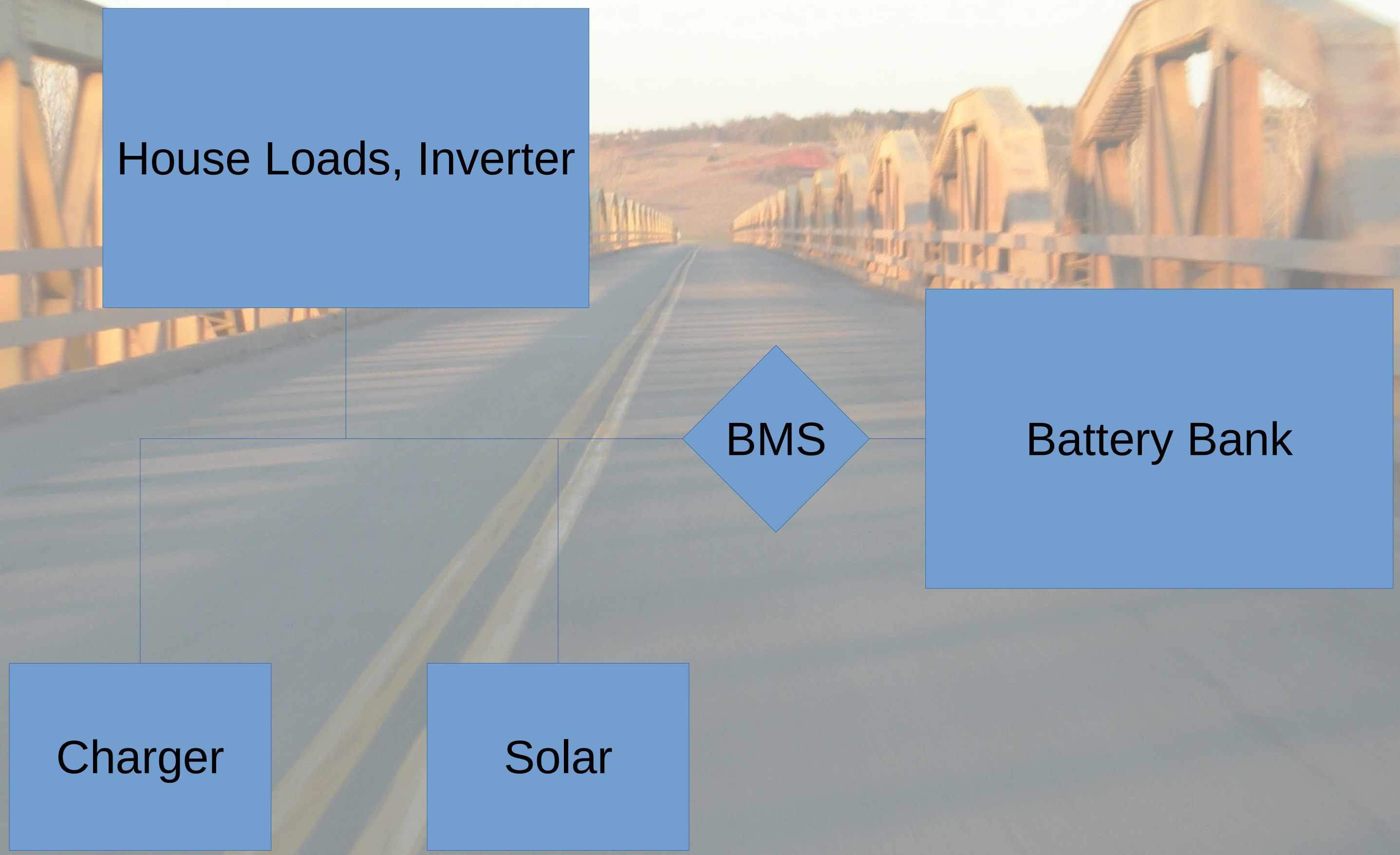
- Lots of energy stored in these batteries, and it's very readily available
- Need to minimize potential for short circuits where there isn't any circuit protection
- Keep things covered as much as possible
- One tool in hand at a time, set tool down before doing anything else.

Preventing Over-Charging and Over-Discharging

- As a good nuclear engineer (maybe), I want to see independent and redundant means of protecting the battery.
- Inverter's low voltage shutoff is higher by ~4V than where we need to protect battery
- Separate low voltage disconnect interrupts battery feed.

- Need to be able to charge battery when low voltage shutoff is activated

Typical Battery Monitoring System Configuration



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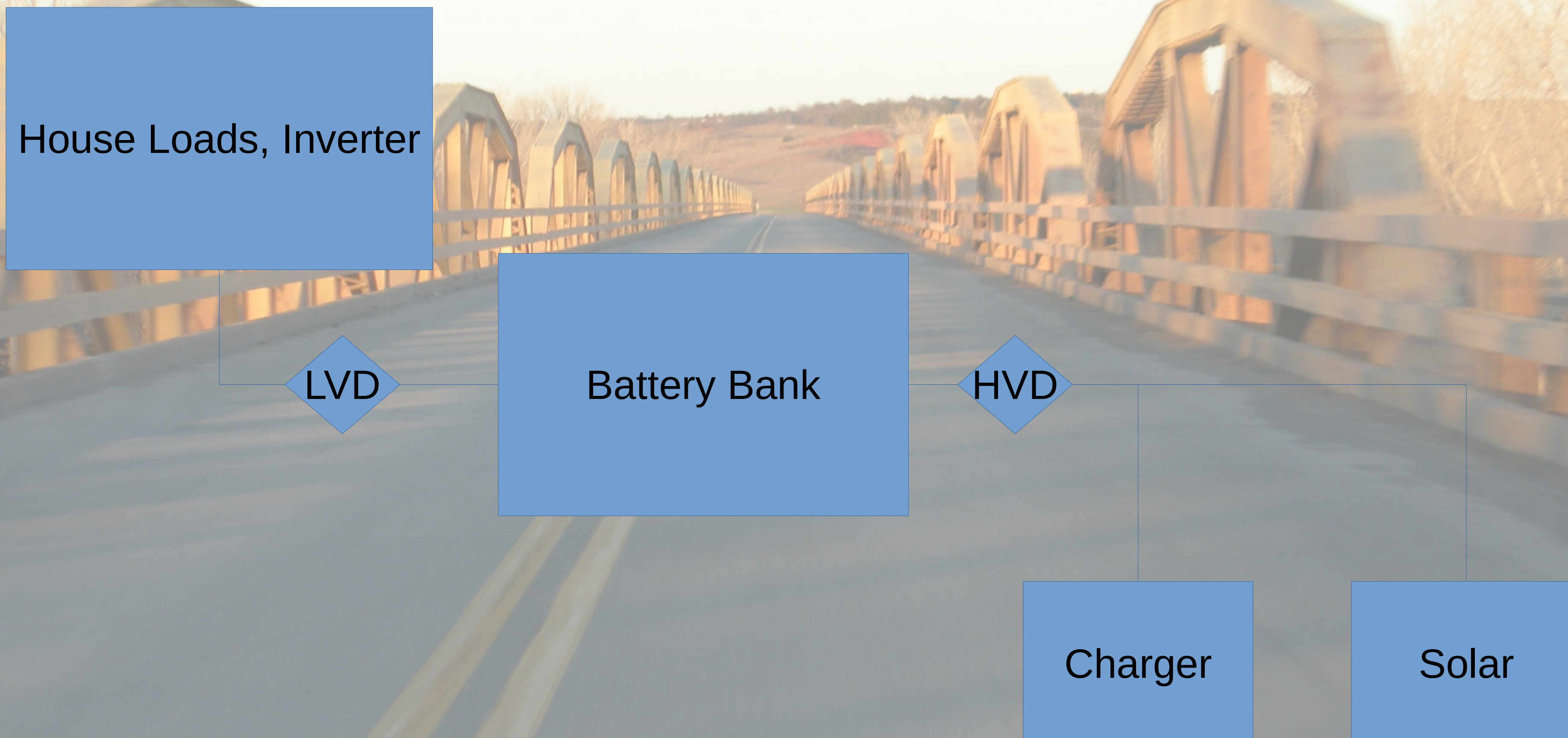
What you’d much rather have



Good place for inverter?

- Dead space next to furnace, louvered front panel
- Conditioned space, not too far from batteries
  - Basically in between batteries and power distribution panels
- Inverter fits with reasonable amount of clearance after relocating heater duct

Which Inverter/Charger?

- AIMS 48V 2000W for round one
- 6000W for 20 sec surge rating
- Built-in 20A charger
- Autotransformer
- Transfer switch
- Ground/neutral bonding relay
- Auto generator start
- ~$650, with US-based engineering and support
- Reasonably quiet with automatic fan control
- Handled laser printer, microwave, laptop, ice maker, TVs and dishwasher at the same time
- Simple, but seemingly robust design and construction

Preventing Over-Charging and Over-Discharging

- As a good nuclear engineer (maybe), I want to see independent and redundant means of protecting the battery.
- Inverter's low voltage shutoff is higher by ~4V than where we need to protect battery
- Separate low voltage disconnect interrupts battery feed.
- If charge controller loses power, charging is disabled, but discharging is still permitted.

- Need to be able to charge battery when low voltage shutoff is activated

Observations after Use

- Really pleased with battery performance
  - Under heavy load (>3kW), <0.5V drop
  - Temperature rise during charging ~1 degree
- Cable sizes needed at 48V are much easier to work with than those needed for much smaller systems at 12V
- Even breadboard circuit is still working after 1,000 miles on road
- Ran furnace for 30 mins with duct directly on inverter air intake without overheating
- Nice being able to check on battery status remotely

What's next? (From April 2016)

- Bigger inverter
- Stand-alone 12kW charger
- Air conditioner modifications
- Improvements to charger controller
  - User interface
  - Isolation/protection of microcontroller
- Removing 12V batteries and charger
- Connecting generator to chassis (starting) batteries

Removing 12V Batteries

- Need source of 12V power
- Most of the time, 12V loads will be small
  - Water pump <4A
  - Furnace <6A
  - LED lights <<10A total
- But need intermittent power for some big stuff
  - Slide out motor ~30A for <1 min
  - 12V sound system
  - Leveling jacks
  - Starting generator

I cheated.

- Leveling jacks were already configured to operate off of chassis batteries
- Generator should have been configured to start off of chassis batteries
  - Typically, we're starting it because the house batteries need charged…
  - Moved 1 wire, disconnected another to change this.
- Jump starter was able to run slide out motor.
- Currently using 80A converter to run 12V stuff

I really cheated.

- In tracing wires, I found that I could deliver power to just the slide out from the chassis batteries.
- No extra equipment—if the truck will start, I can open/close slide out.

Reconfiguring Batteries to Start Generator

- Battery separator was located in battery compartment under cab.
- House side cable was moved to chassis batteries, and disconnected beyond generator.
- Now generator is using a battery bank meant for starting, not a deep cycle battery.

“Borrowing” a Battery Section

“Borrowing” a Battery Section

What did I learn from the golf cart project?

- Hard acceleration from the 9kW motor (repeatedly!) doesn’t really get the batteries warm.
  - Why? Even at 10kW, you’re only about 6% of a normal Volt’s peak power.
  - Just 2 2kWh modules (i.e. ¼ of a Volt battery) have no trouble supplying 1000A above safe pack voltages
- Older carts without “soft starting” would be a disaster for a turf maintenance guy
- Randy Agee (RandyA) has modified his golf cart similarly, will be here this week.

Energy Efficiency has to be Considered

- Most RVs (regardless of brand or price range) are VERY poorly insulated.
- Typical RV air conditioners are very inefficient by modern standards.
- With a lot of boondocking, solar panels can pay off even if never connected (though natural shade would be cheaper)
- The goal isn't an over-the-top battery system—it's extended boondocking without compromises in comfort or a giant hole in the wallet.

Air Conditioners

Air Conditioners

- A typical RV air conditioner is either on or off—a single-speed, capacitor-start capacitor run induction motor
- LARGE draw on startup
  - Starting the compressor often dictates generator/inverter sizing
- Not very efficient, particularly in typical ducted configurations
- Running load ~15-17A
- No SEER ratings
- Loud

- Mini-split configured for RV use converts incoming AC to ~380V DC, then runs a brushless DC compressor.
- VERY low draw at startup (~1A)
- Equivalent cooling capacity at ~10A
- >20 SEER
- Quiet
- Variable speed allows reduced capacity operation when enough power isn't available.

Other Features

- Remote controlled
- Some have follow-me remotes, where temperature sensor is in remote
- Heat pump rated to -5°F

Questions?

Next seminar be David Henegar’s presentation *How to be Safe while RVing* at 11:00