Estimation of Capital and Levelized Cost for Redox Flow Batteries

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What are we trying to accomplish?

- PNNL grid analytics team has established ESS cost targets for various applications
- PNNL cost/performance model estimates cost for redox flow battery systems of various chemistries
  - drives research internally to focus on most important components/parameters/metrics for cost reduction and performance improvement
  - Open source model will be made available for industry use and validation
- Model drove PNNL 1 kW prototype design
- Design of larger demonstration systems expected to be facilitated using model

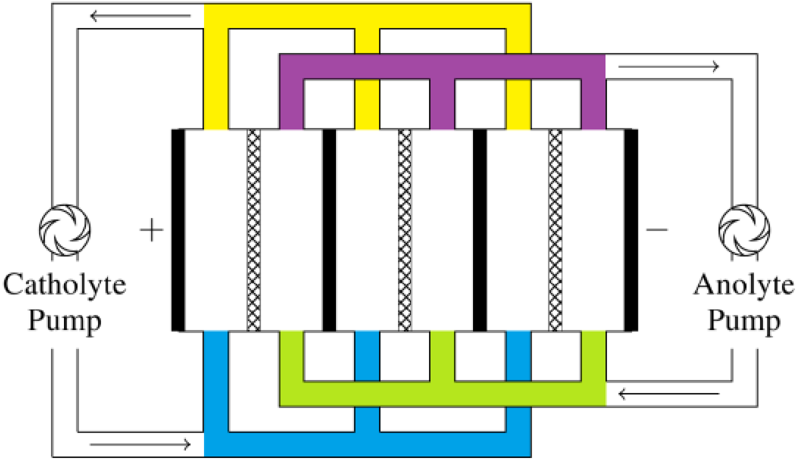
Accomplishments

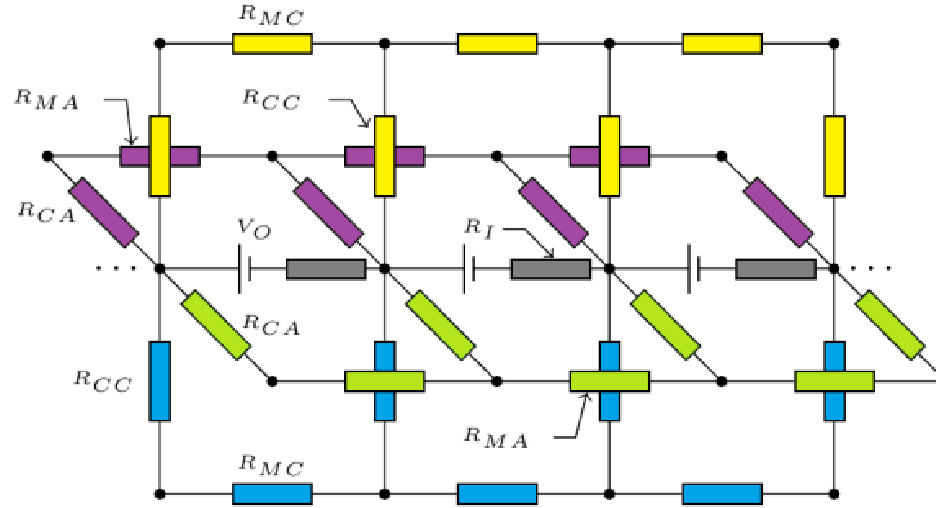
- Developed cost/performance model incorporating electrochemical performance, pumping loss, shunt current loss
- Investigated three chemistries
  - All Vanadium, Gen 1 V-V (1.5M, 3.5M H_2SO_4, 10 to 40 ºC)
  - All Vanadium PNNL Gen 2 V-V (2-2.5M, 5M HCl, -5 to 55 ºC)
  - PNNL Iron-Vanadium (1.5 M, 5M HCl -5 to 55 ºC)
- Estimated capital cost & levelized cost for 1 MW systems with various E/P ratios
- Validated PNNL model using PNNL 1 kW, 1 kWh stack performance data
- Provided a roadmap for cost effective redox flow battery systems of appropriate chemistry for various applications.
- Plans to provide an open source version of PNNL model for rigorous testing and validation by the flow battery community

Approach

- Estimated capital cost (power and energy components) for 1MW system with various energy content
- Contacted vendors for each component to obtain budget estimates
  - Cost estimation done for **Present, Near-term and Optimistic** scenarios
    - Present : 50 MW, 100 MWh annual demand
    - Near-term: 300 MW, 600 MWh annual demand
    - Optimistic: 1 GW, 2 GWh annual demand
- Developed integrated battery model to determine losses
  - shunt current, pumping and electrochemical
- Incorporated losses to size the system for desired power and energy
- Determined stack size, design and operating parameters that yield lowest total system cost
- Established where advances in technology can reduce cost and guide internal research and redox flow community

Pressure Drop, shunt loss optimization





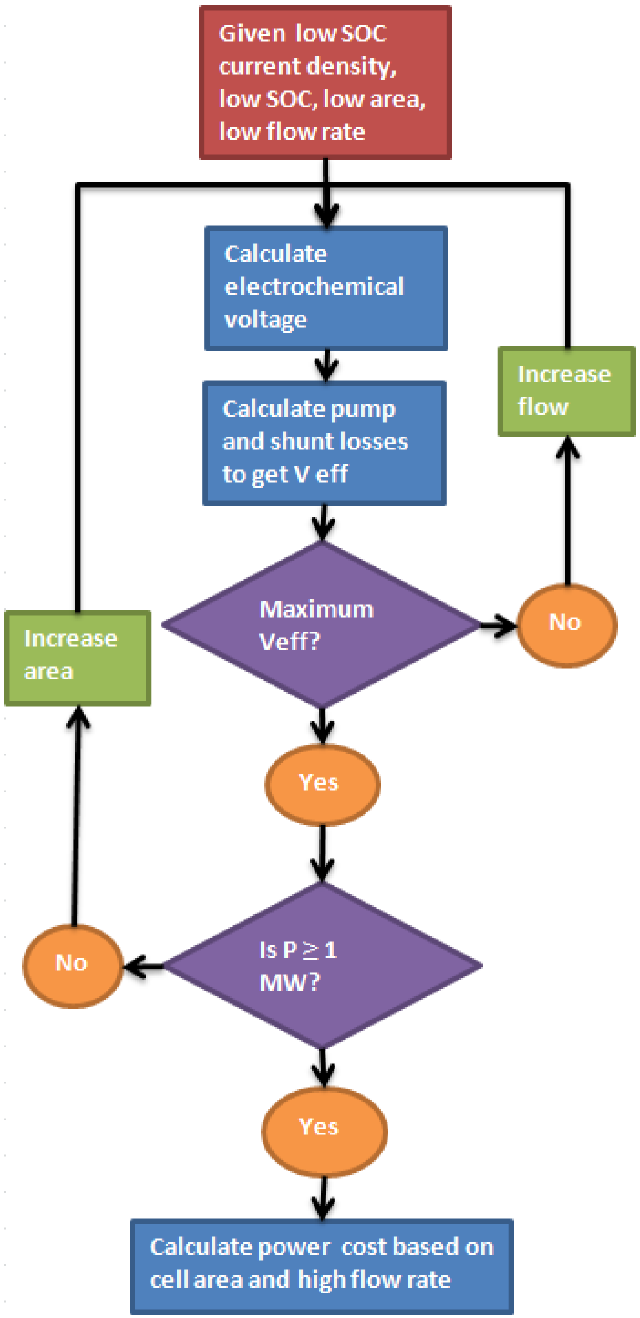
- 75% of the pressure drop is across the felt electrode
- Shunt current loss decreases with increase in electrolyte resistance in manifolds and flow channels.
- Shunt current loss increases with increase in # of cells in a stack

- **Lower # of channels reduce shunt current and pressure drop**
- **Increasing # of channels in flow frame good for flow distribution**

Stack and Flow design

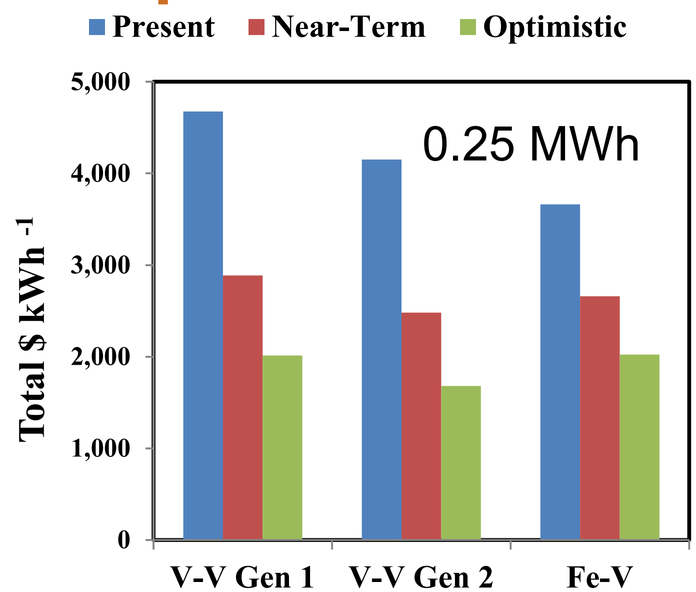
- Electrode area – varying
- Current density – varying
- # cells per stack – 60
- Stack configuration – 6P/6S
- Stack power – 27.8 kW
- Flow rate per polarity – varying
- Bipolar plate thickness – 0.06 cm
- Felt porosity – 0.95
- Felt thickness – 0.45 cm
- Separator – ion exchange membrane or microporous separator

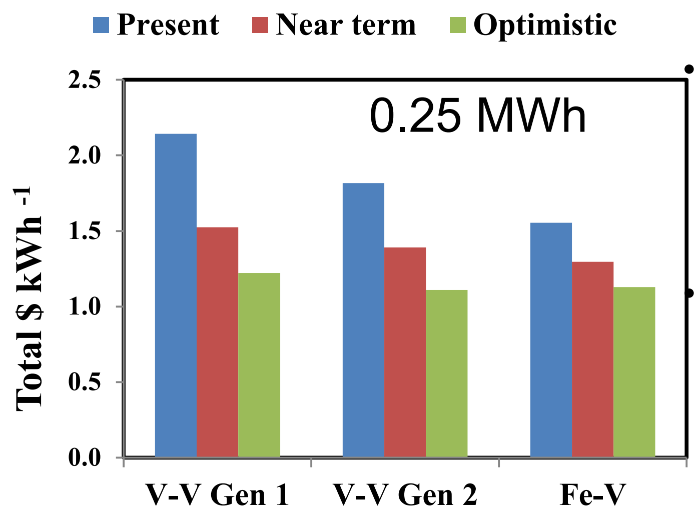
Model flowsheet

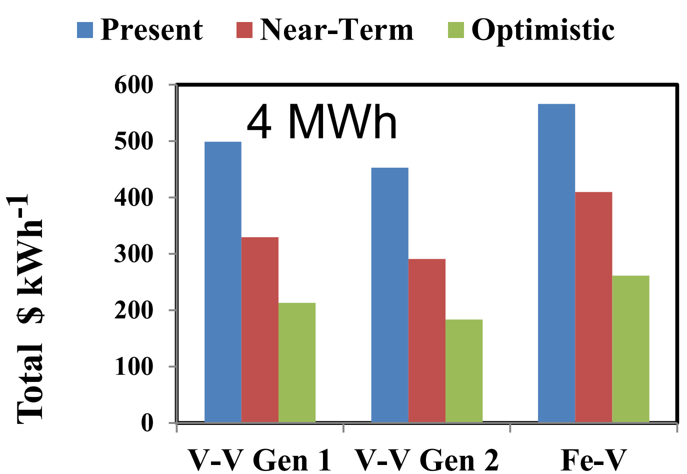


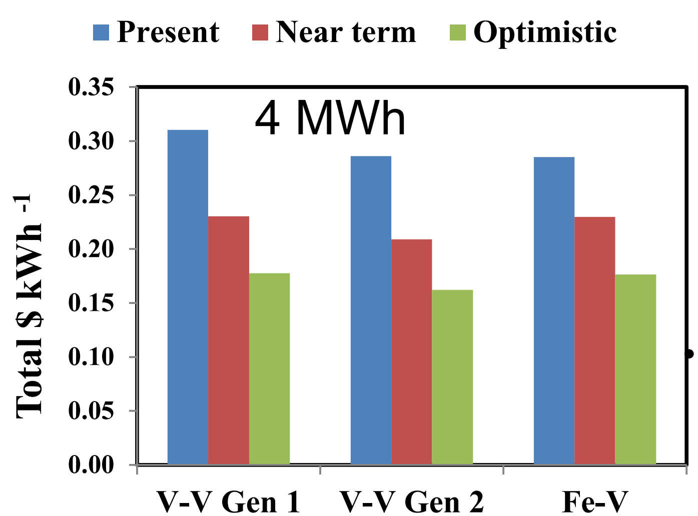
- Size stacks based on area
- Size pumps based on highest flow rate
- Calculate average of Veff for all SOC (Veff_average)
- Determine electrolyte content from Veff_average
- Calculate $/kW, $/kWh, Total $/kWh
- Repeat above calculations for various starting current densities
- Choose set of conditions that lead to minimum $/kWh for the required power and energy
- Vary flow frame channel dimensions and optimize with respect to total system cost

Capital cost and levelized cost for 1 MW system





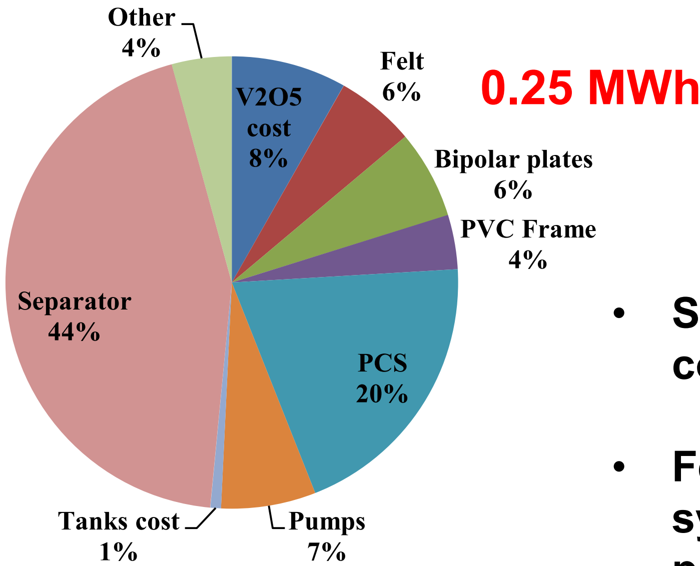


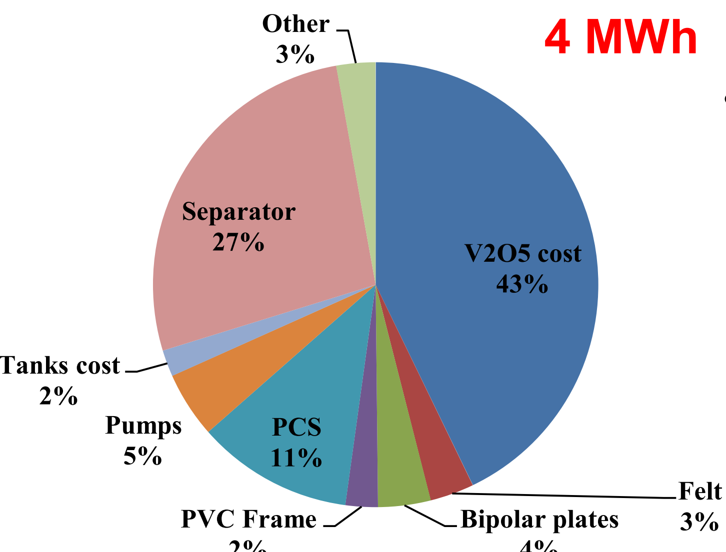


- Capital cost and levelized for V-V Gen 2 lower than Gen 1 for all scenarios and E/P ratios
- Fe-V capital cost for 0.25 MWh system lower than all vanadium Gen 2 for present scenario.
- Levelized cost for Fe-V for 0.25 MWh system lower than V-V Gen 2 for present and near-term scenarios (lower replacement costs for membranes and felt electrodes)
- Levelized cost for Fe-V competitive with V-V Gen 1 for 4h system

Capital cost **Levelized cost**

V-V Gen 2 component cost distribution & sensitivity





- **Separator costs a major component of total system costs (44% for 0.25 MWh and 27% for 4 MWh)**
- **Felt and bipolar plates add up to 10% for 0.25 MWh system; optimization of electrode design to improve performance expected to decreases stack costs**
- **Chemical costs dominate for 4 MWh system (43%)**
- **Room for decrease in 4 MWh system cost by improving efficiency – lower electrolyte and stack costs**

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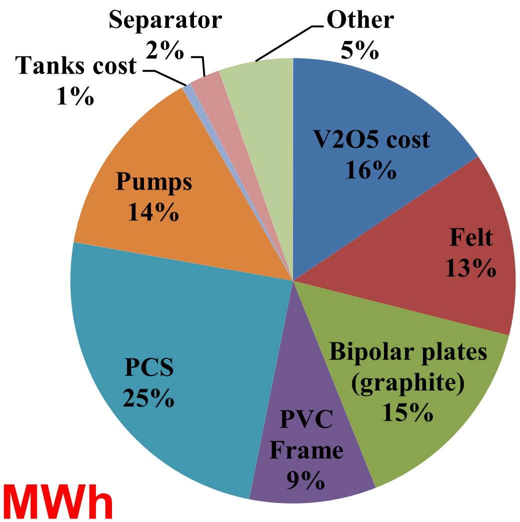
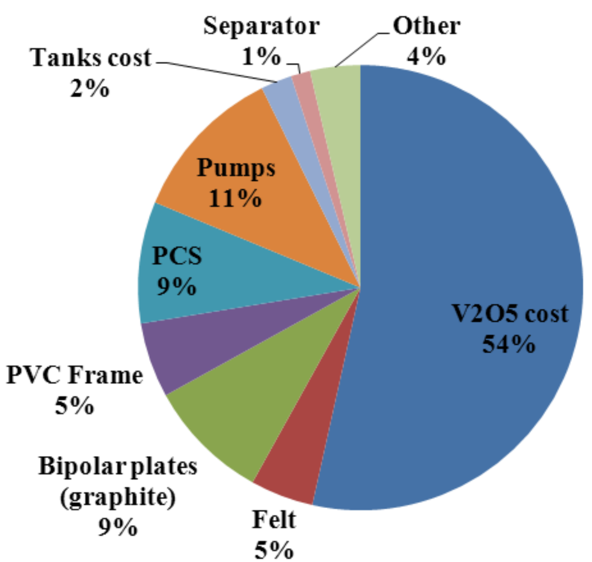
Fe-V component cost distribution & sensitivity



0.25 MWh



4 MWh

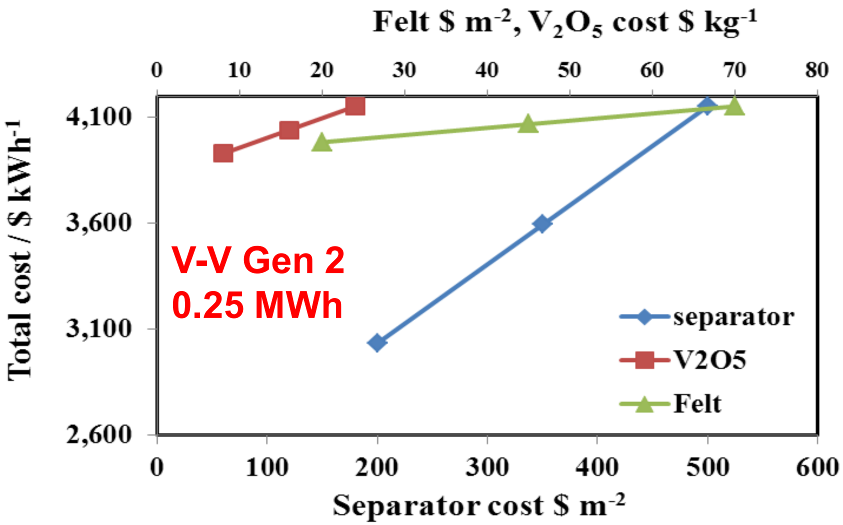
0.25 MWh system

- Felt, bipolar plates, chemical cost and pump cost have about equal importance for 0.25 MWh system
- Optimization of electrode design to improve performance expected to decrease stack costs

4 MWh system

- Chemical costs dominate for 4 MWh system (54%)
- Room for decrease in 4 MWh system cost by improving efficiency to lower electrolyte cost

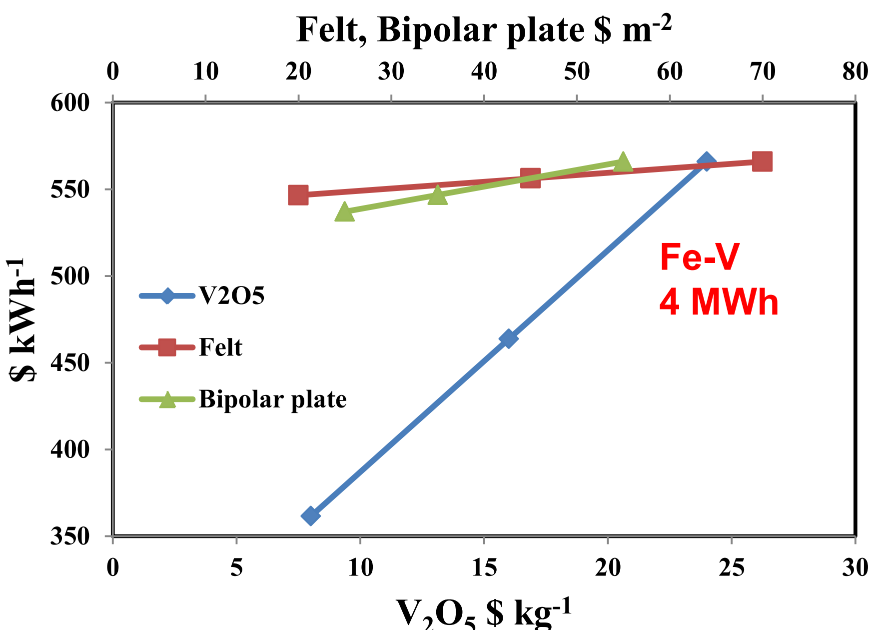
Sensitivity analysis



0.25 MWh V-V Gen 2 system

Highly sensitive to separator costs

Electrode design, flow field design, electrolyte conductivity critical to achieve high power density

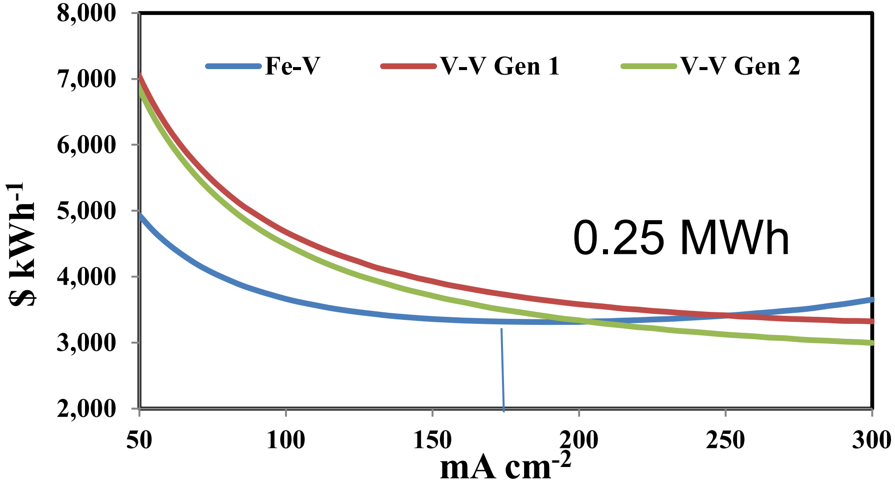


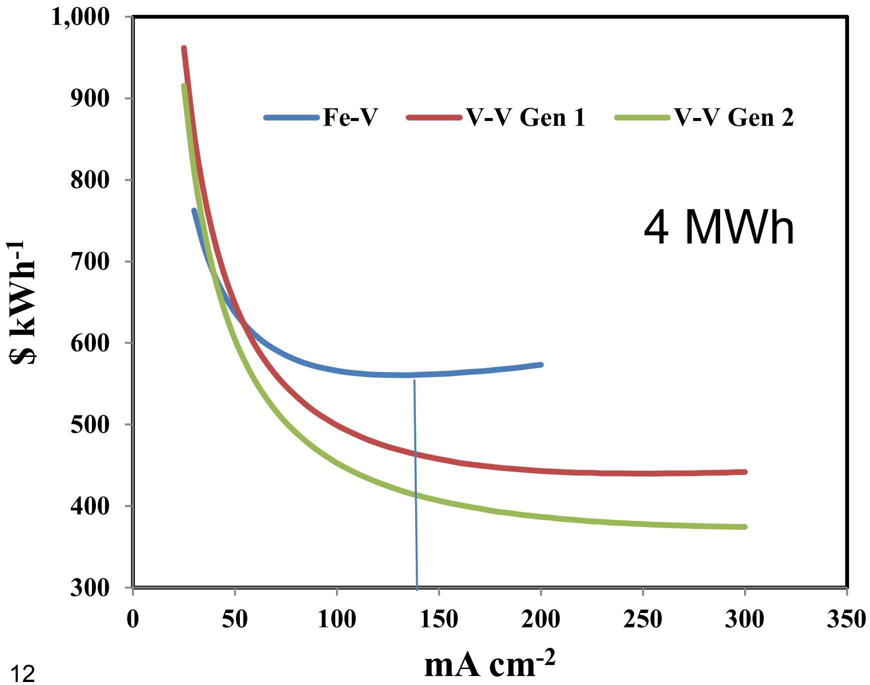
4 MWh Fe-V system

Most sensitive to chemical cost

While not highly sensitive to felt cost, improvement of electrode activity and stack design expected to improve efficiency and reduce chemical costs

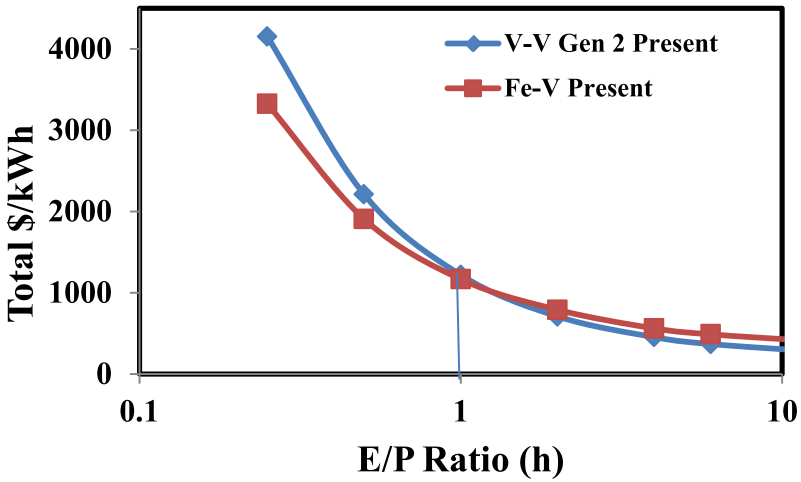
Sensitivity towards max current density

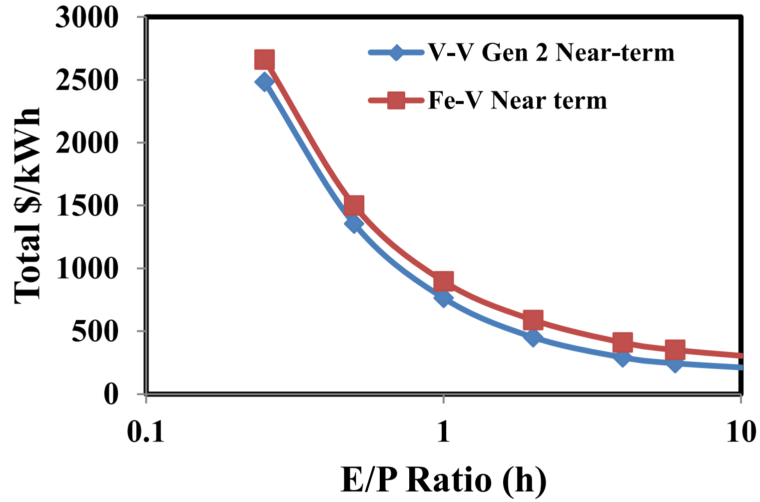


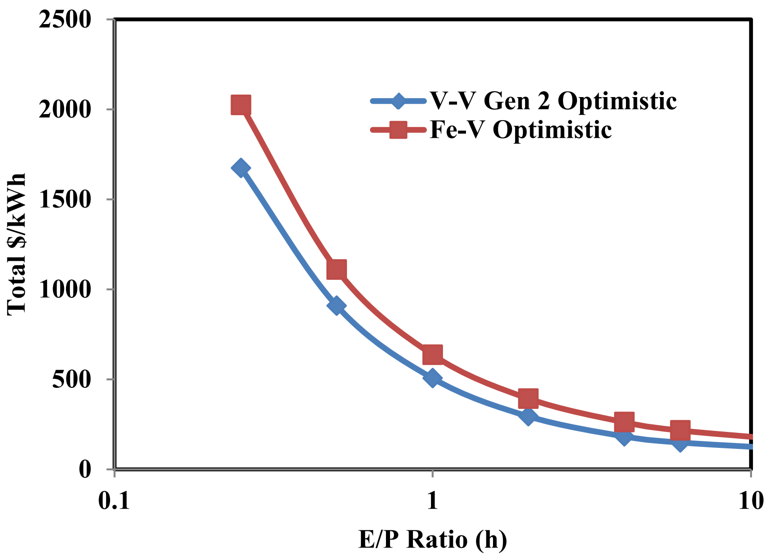


- V-V Gen 2 offers most opportunity for reduction in cost with increasing current density
- Fe-V 0.25 MWh system goes through a minimum in cost at 170 mA/cm2
- Fe-V 4 MWh system lowest cost operating point is at 135 mA/cm2
- Improved electrode, flow field and stack design can benefit this chemistry across the E/P range

Cost effectiveness at various E/P ratios



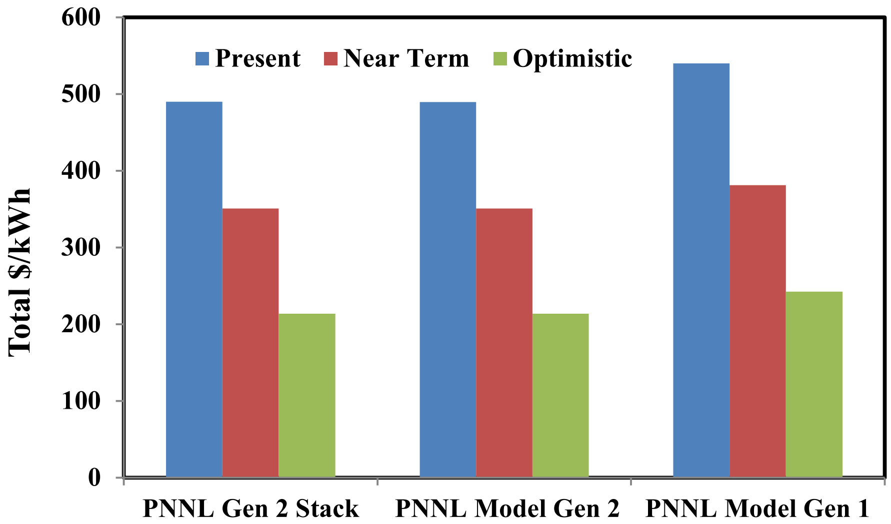




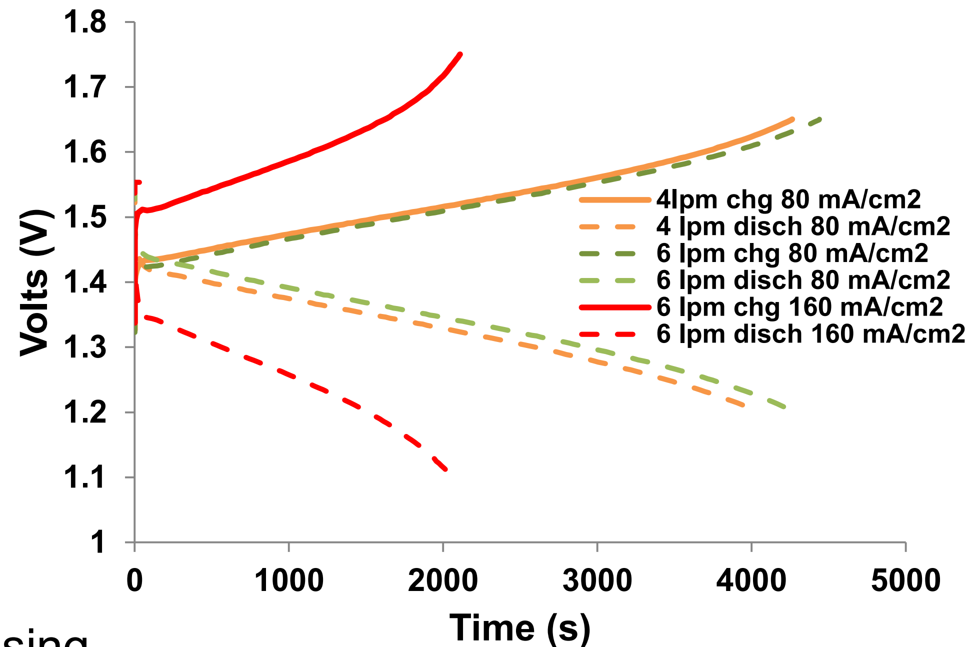
- **Fe-V more cost effective than Gen 2 for present scenario at E/P < 1**
- **On a levelized cost basis, at E/P < 1, Fe-V is more cost effective for near-term scenario also, and equivalent to Gen 2 for optimistic scenario**
- **For E/P > 1, V-V Gen 2 most cost effective**

Model validation with PNNL 1kW/1 kWh Gen 2 stack data

1 MW 4 MWh system cost



1kW 1 kWh stack data operated at 80 mA/cm^2



- 1 MW 4 MWh system cost estimated using
  - ✓ stack data for performance
  - ✓ PNNL model for same operating conditions
    - *model validated*
- All vanadium Gen 1 costs under same operating conditions higher than Gen 2 costs

Summary and future work

- Cost-performance model developed that takes into account electrochemical performance, pumping and shunt current loss
- Cost effectiveness of various chemistries for different applications determined
- Pathway established to further drive costs down by improved electrode & flow frame design and optimization of operating parameters
- Open source version of this model will be made available shortly
  - Interactive
  - Allows running various scenarios
  - Expected to benefit redox flow battery community
- Future work
- Further optimization will be done for battery operation in various applications
  - Use bottoms-up approach for estimation of component cost
  - Perform detailed analysis with respect to payback period for various applications using for V-V Gen2 and Fe-V
- Publication – paper has been prepared – to be submitted

Acknowledgement

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