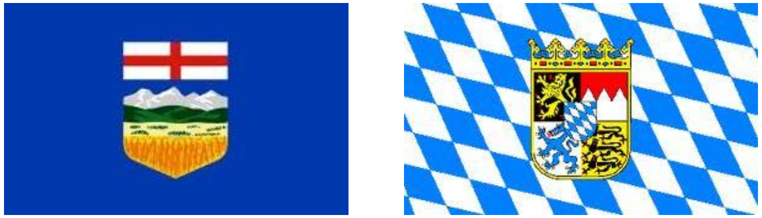
ABBY-net

a cooperation of researchers from Albertan and Bavarian universities

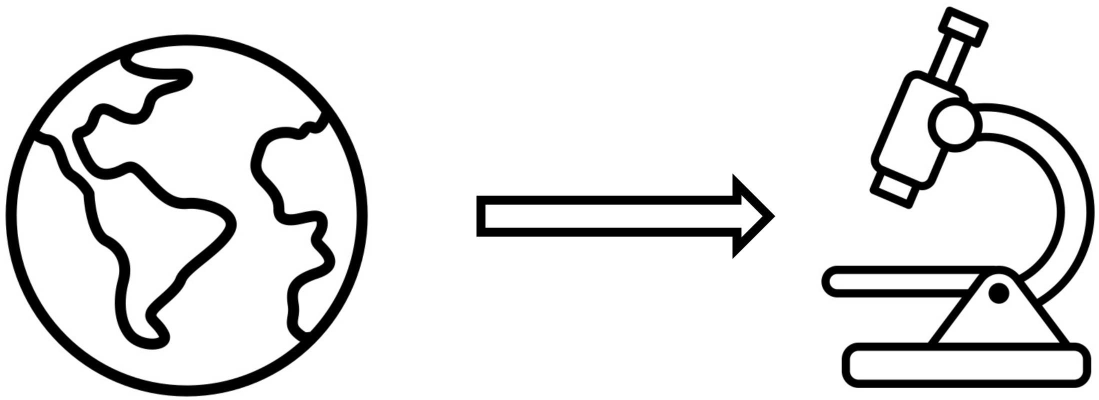


POWER ON SHORT NOTICE: ROLES AND APPLICATIONS OF MECHANICAL ENERGY STORAGE SYSTEMS

Pierre Mertiny

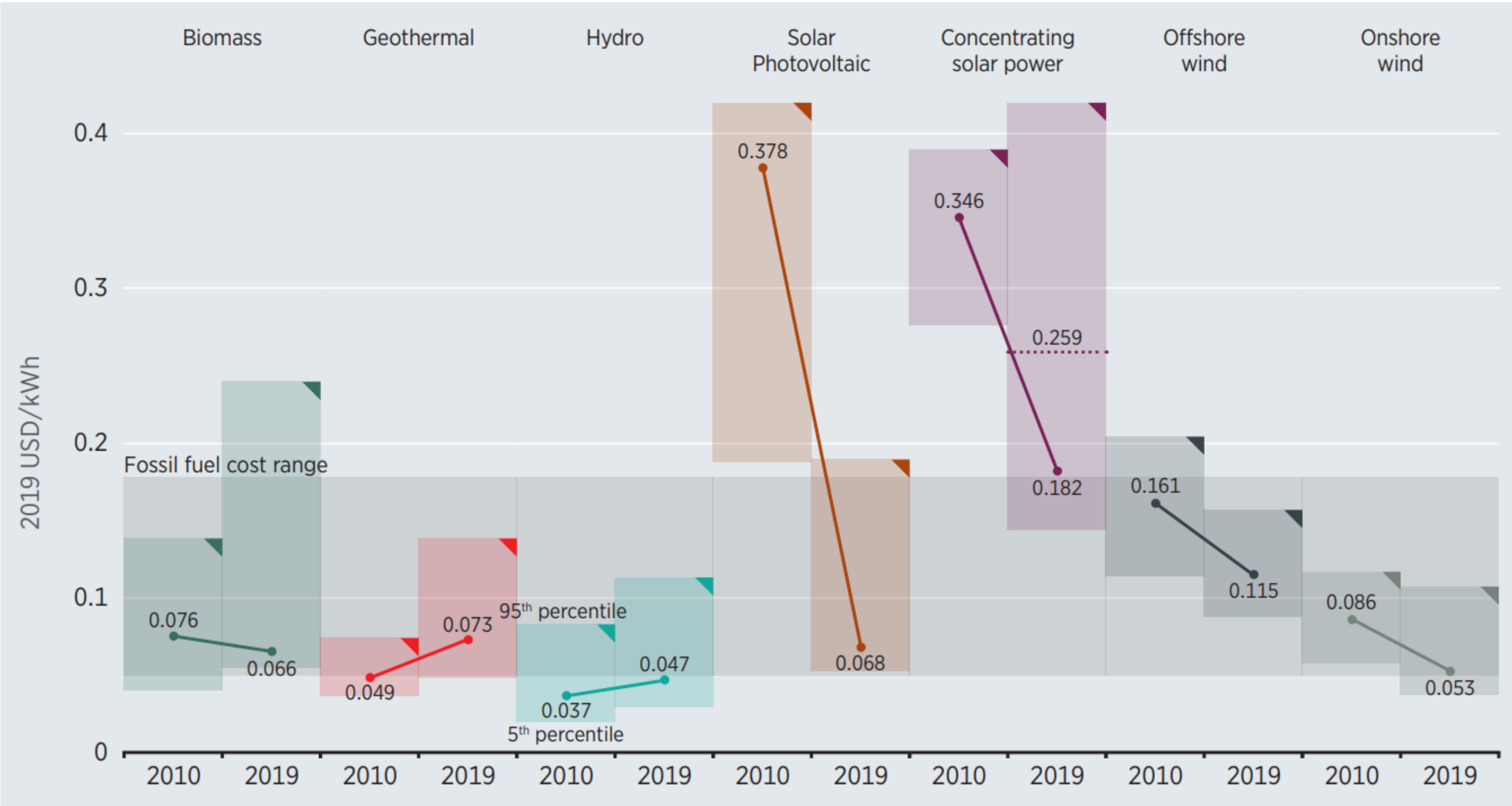
University of Alberta

AGENDA



Big picture → Detail

Global Levelized Cost of Electricity From Utility-scale Renewable Power

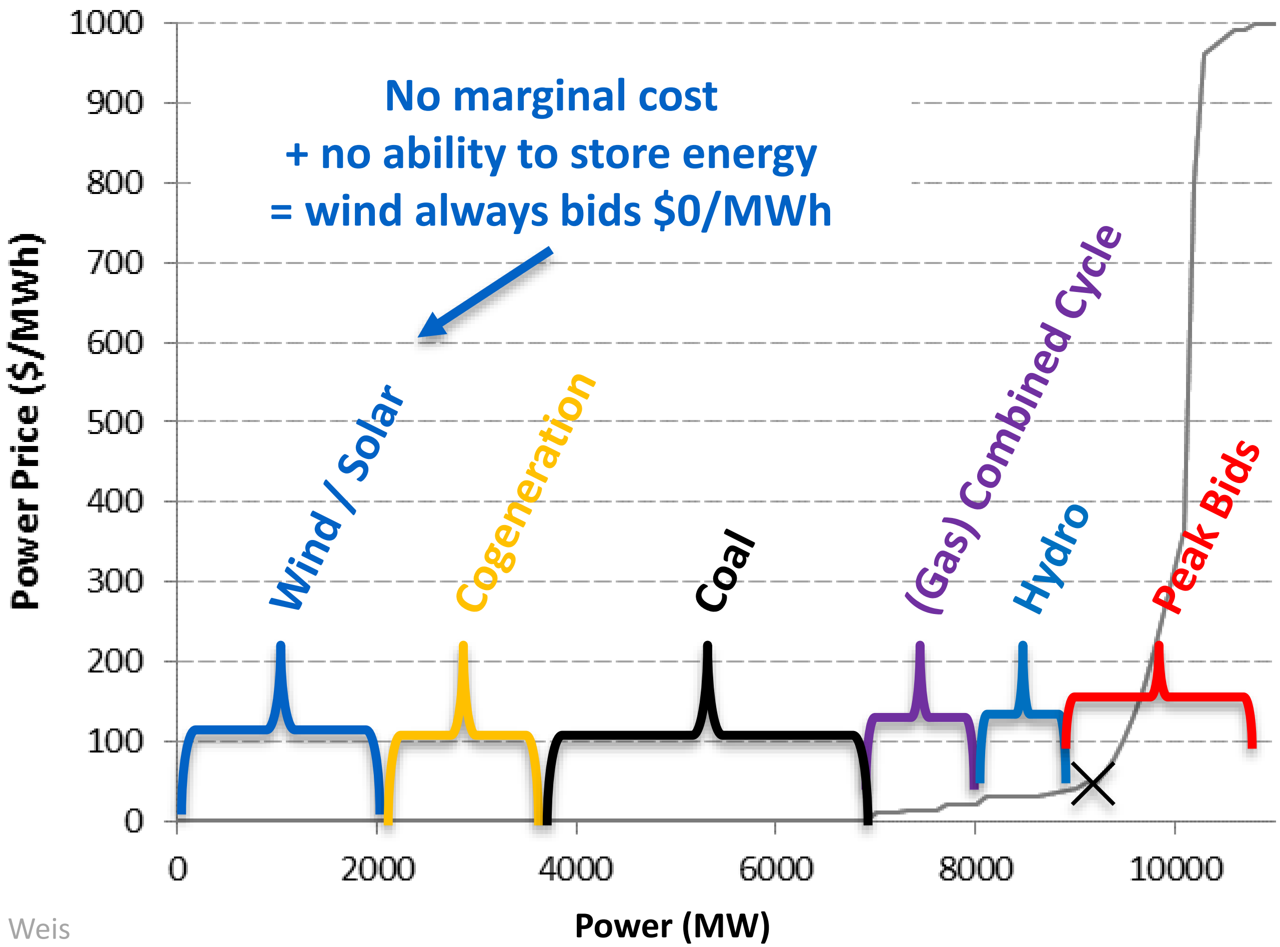


Levelized cost: Capital cost + Fixed operating costs + Variable operating costs

Source: International Renewable Energy Agency (IRENA)

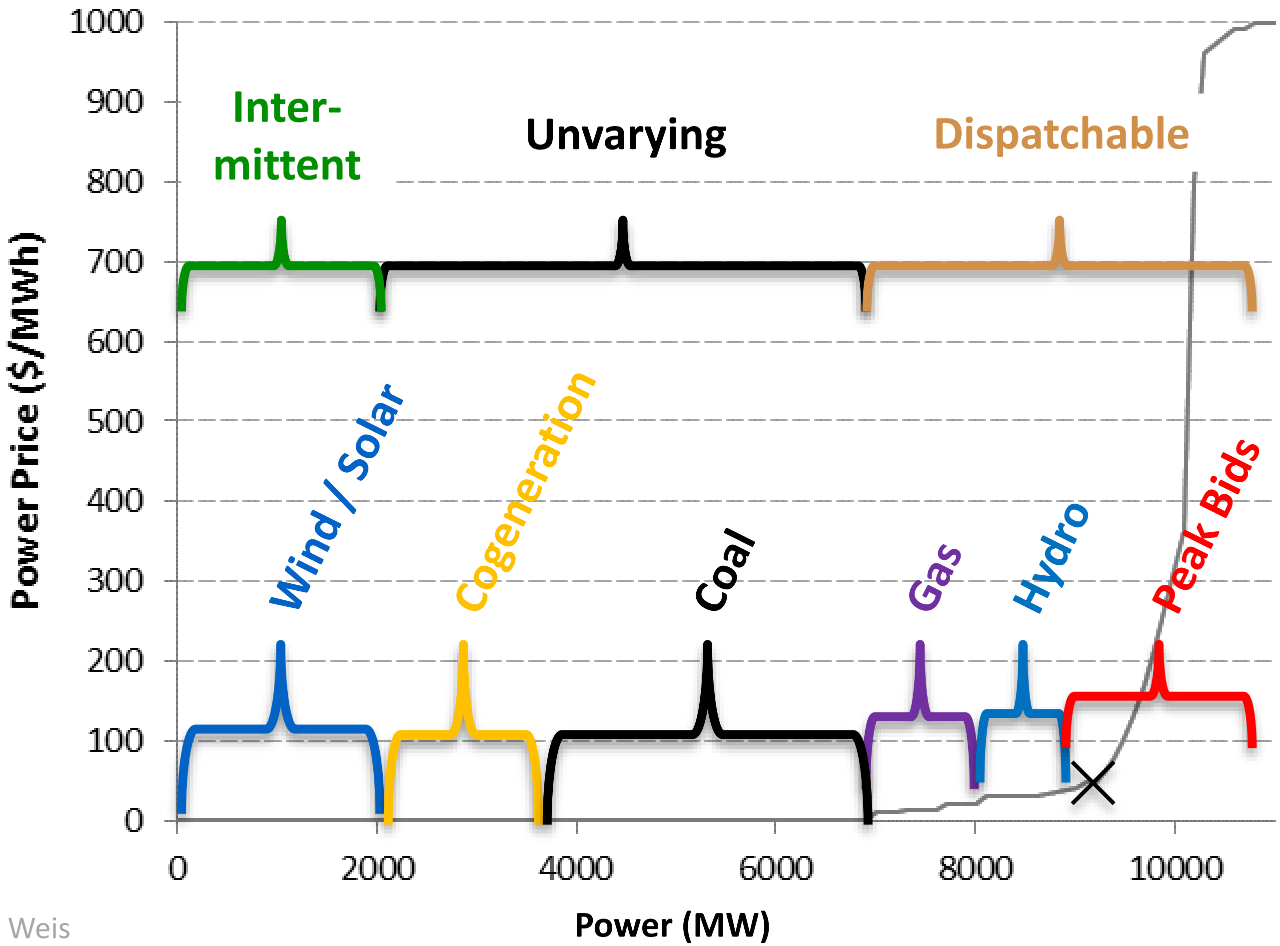
Kalte Dunkelflaute

Renewable Energy Challenges: “Merit Order Effect”



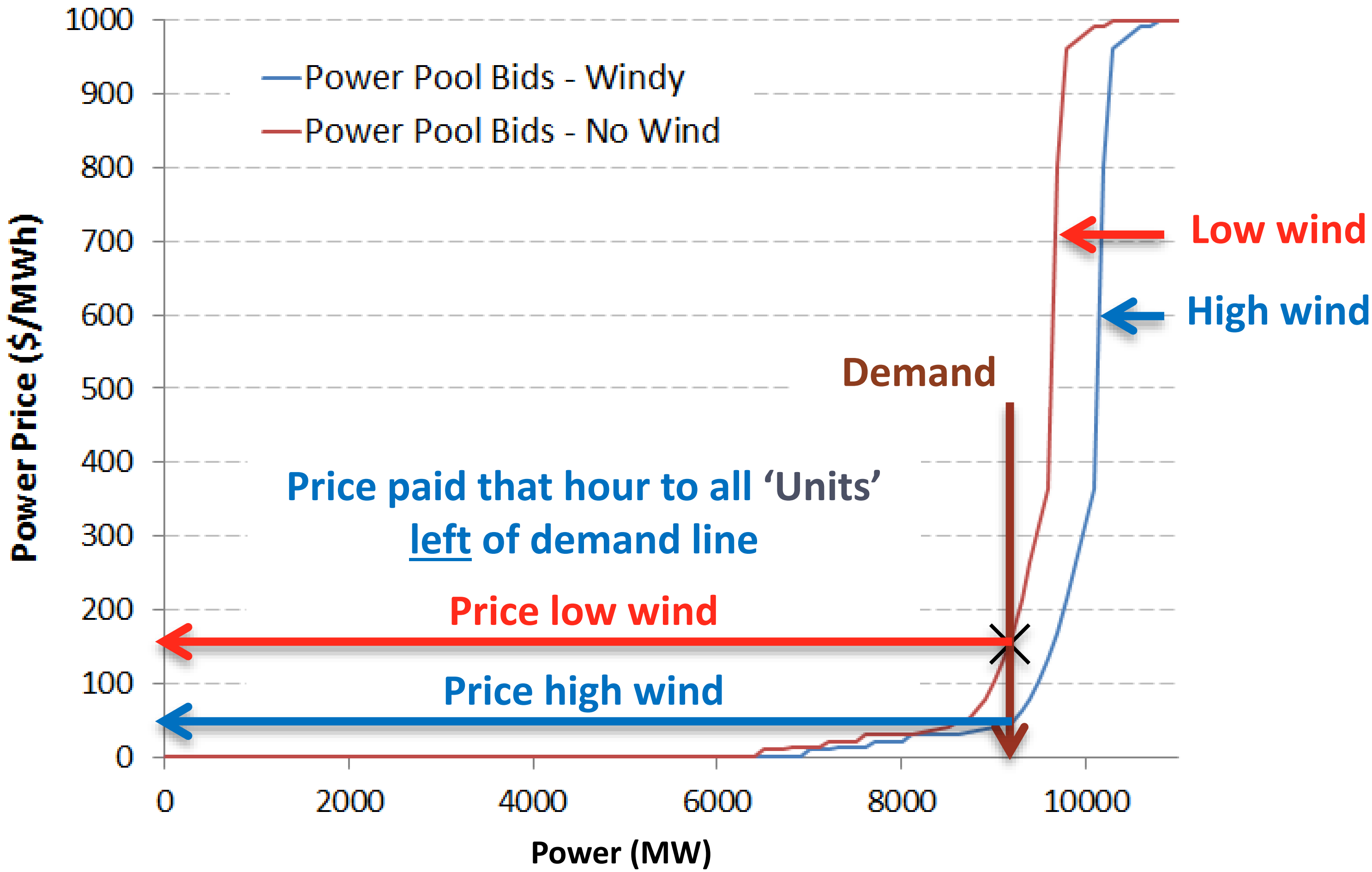
Source: Time Weis

Renewable Energy Challenges: "Merit Order Effect"



Source: Time Weis

Renewable Energy Challenges: "Merit Order Effect"



Electro Mobility Challenges

EV range (=capacity), price and charging time (=power) directly affects EV adoption

- Range and price are inversely related to adoption and have met or are expected to meet average consumer requirements by 2030 in North America
- Charging rate lags behind due to EV battery constraints, <u>grid limitations and current lack of suitable infrastructure</u>

Image Source: Castrol, BP, Oxford Analytica. Accelerating the EVolution: The tipping points to mainstream electric vehicle adoption

Electro Mobility Challenges

Consumers and industries (e.g. trucking) require a spatially inclusive and comprehensive fast charging network

- But, currently charging stations are scarce outside major urban centers. Long distance gaps exist throughout NA.
- Consumers and industries (e.g. trucking) require spatially inclusive and comprehensive fast charging network
- Charging of even partial EV fleet has the potential to significantly impact energy demand from utilities

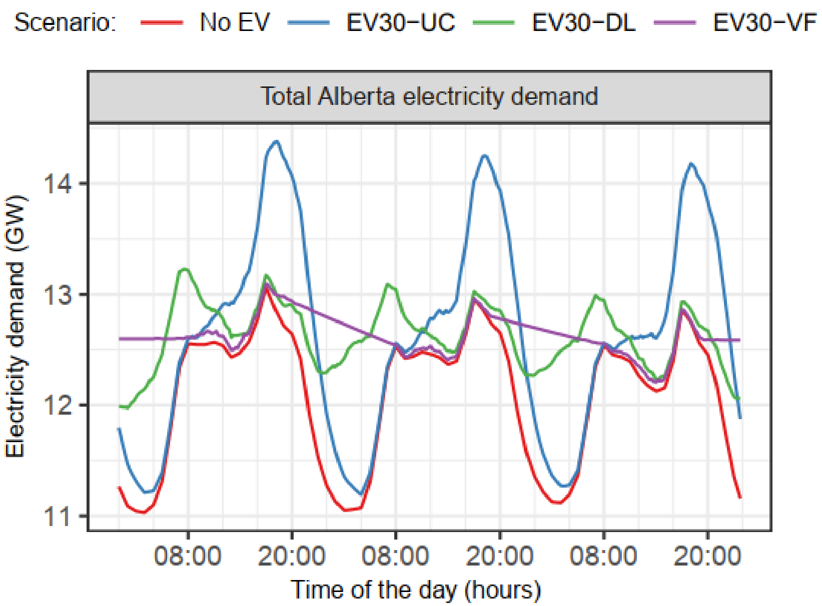


Image Source: G. Doluweera, F. Hahn, J. Bergerson, M. Pruckner. A scenario-based study on the impacts of electric vehicles on energy consumption and sustainability in Alberta." Appl. Energy 268, 2020, 114961.

Summary

Electrical energy storage (EES) is needed to:

- Improve power reliability and resilience
- Enable high ratio of renewable (wind and solar) power generation
- Reduce cost of providing power to consumers
- Enable electro mobility
- Diminish GHG emissions

Classification of EES Technology

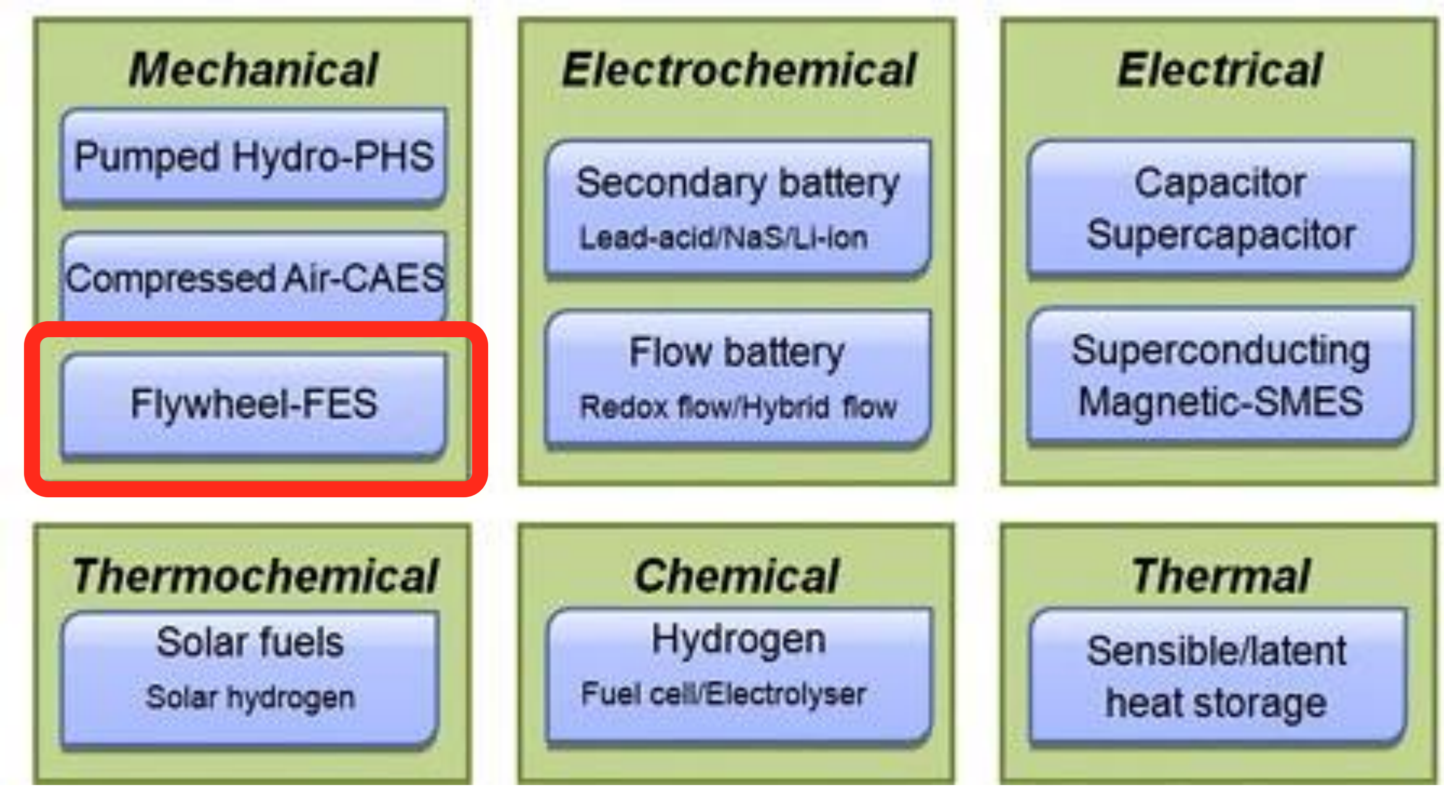


Image source: Luo, X.;Wang, J.; Dooner, M.; Clark, J. Overview of current development in electrical energy storage technologies and application potential in power system operation. Appl. Energy **2015**, 137, 511–536.

Cycle Efficiency

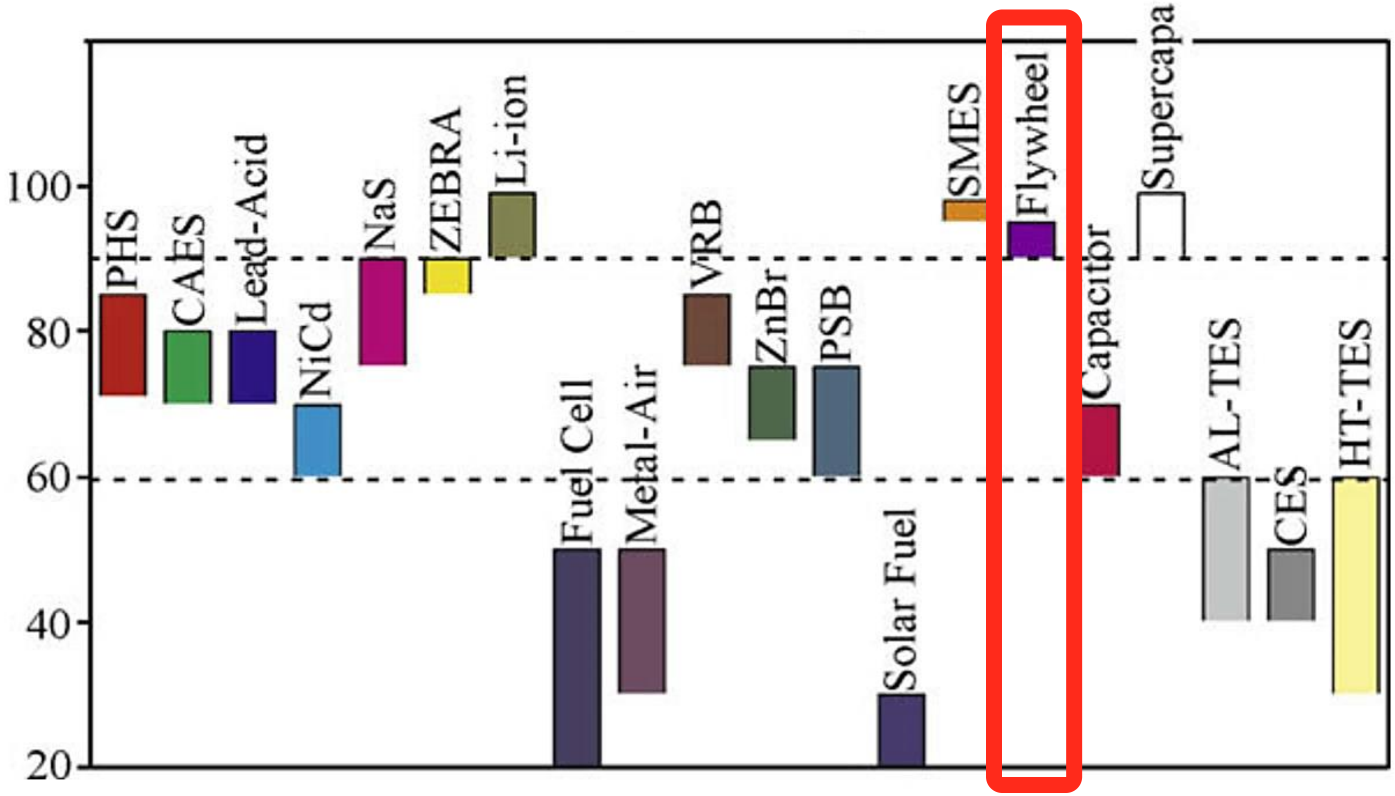


Image source: H. Chen, T.N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding. Progress in electrical energy storage system: a critical review. Prog Nat Sci, 19 (2009), pp. 291-312

Technology Maturity

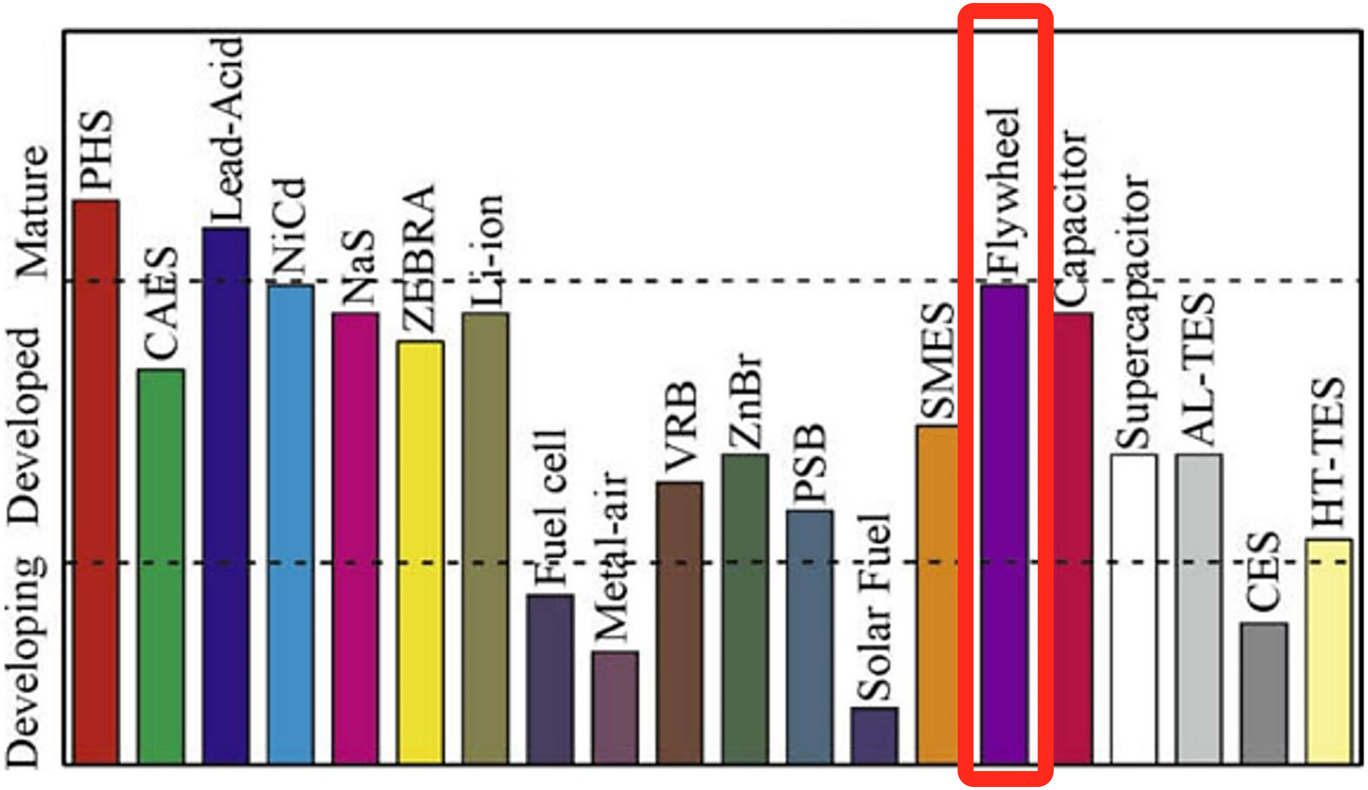


Image source: H. Chen, T.N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding. Progress in electrical energy storage system: a critical review. Prog Nat Sci, 19 (2009), pp. 291-312

EES Operating Range and Challenges to UK Energy Systems

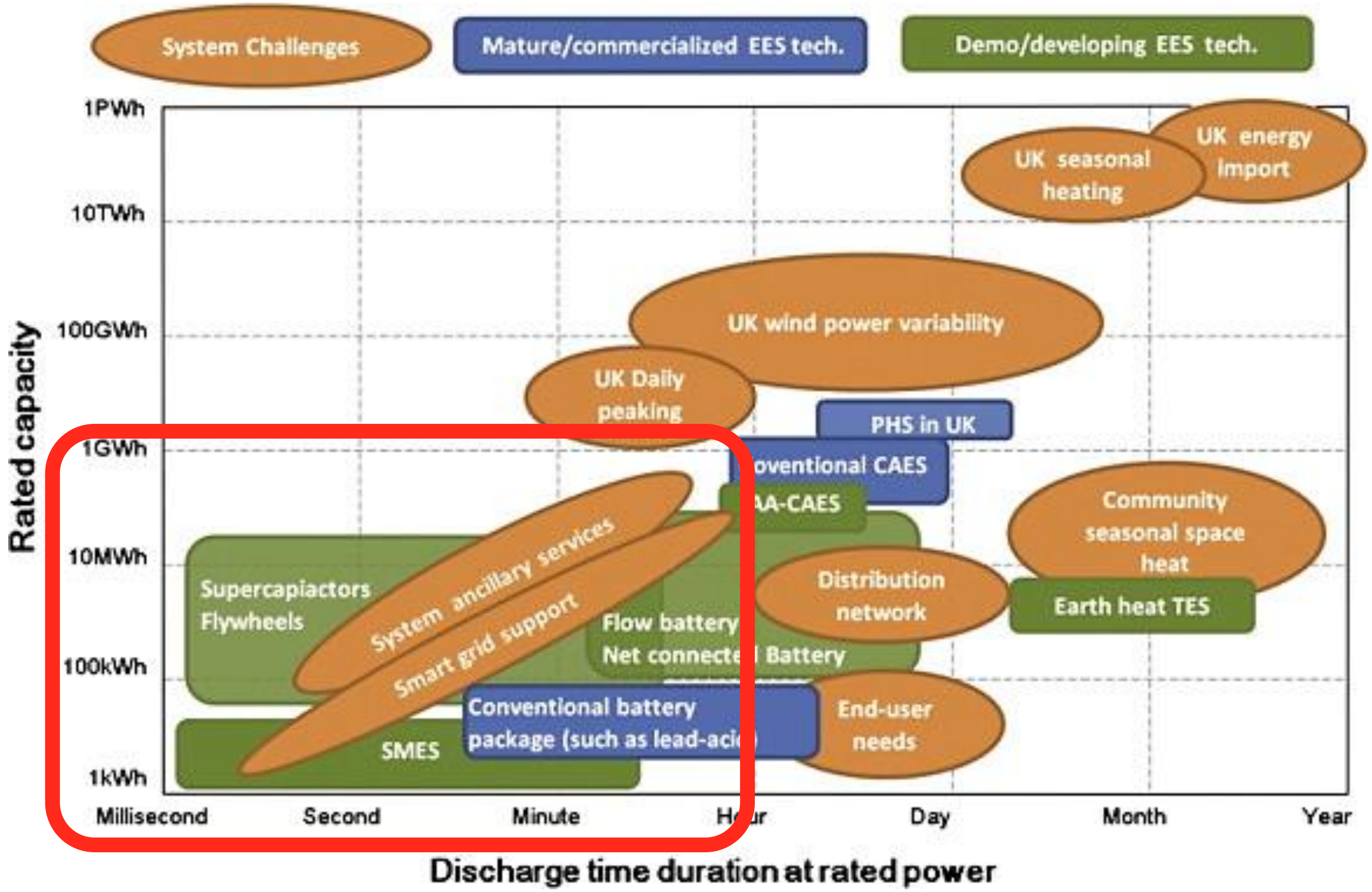
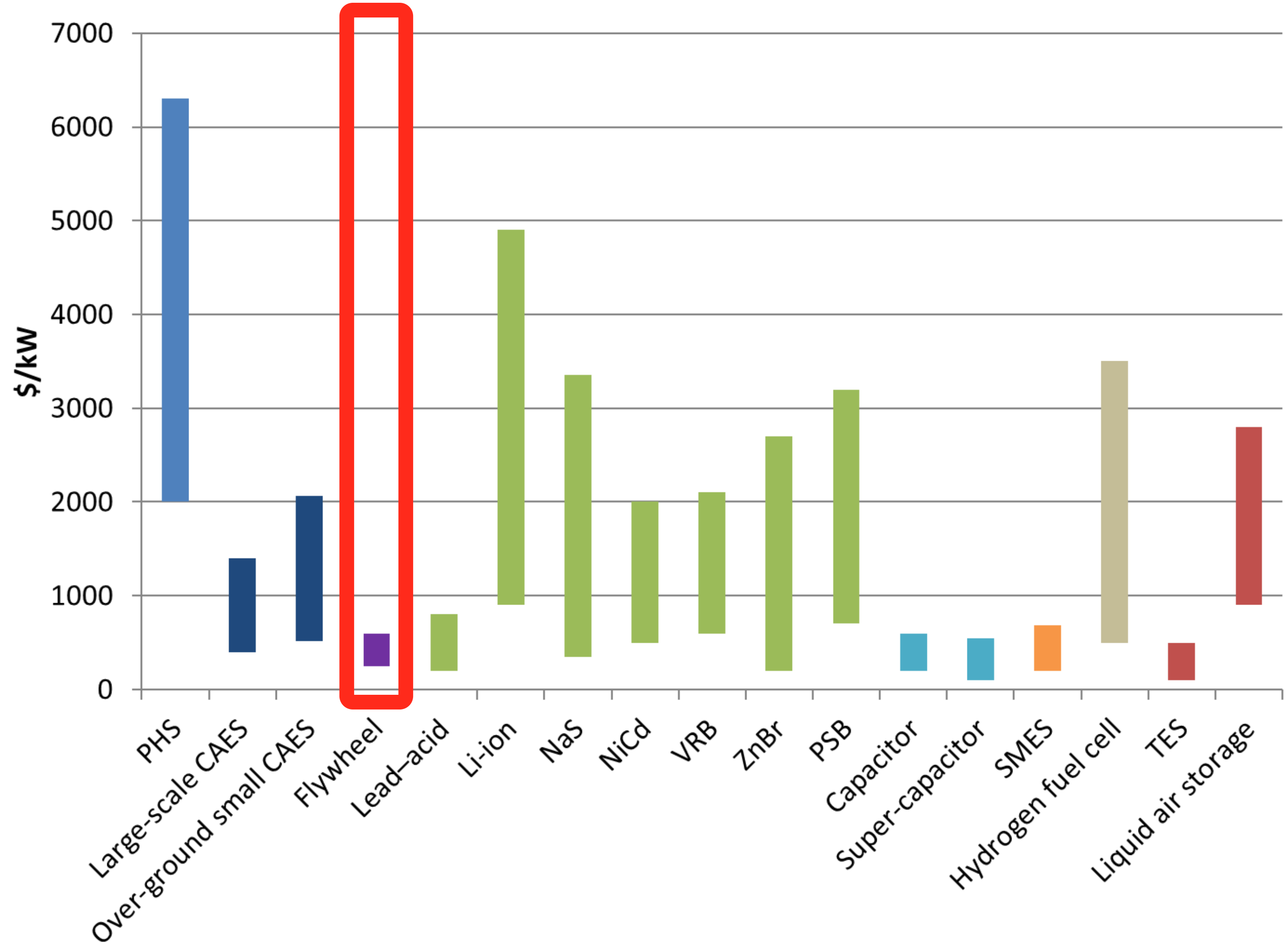


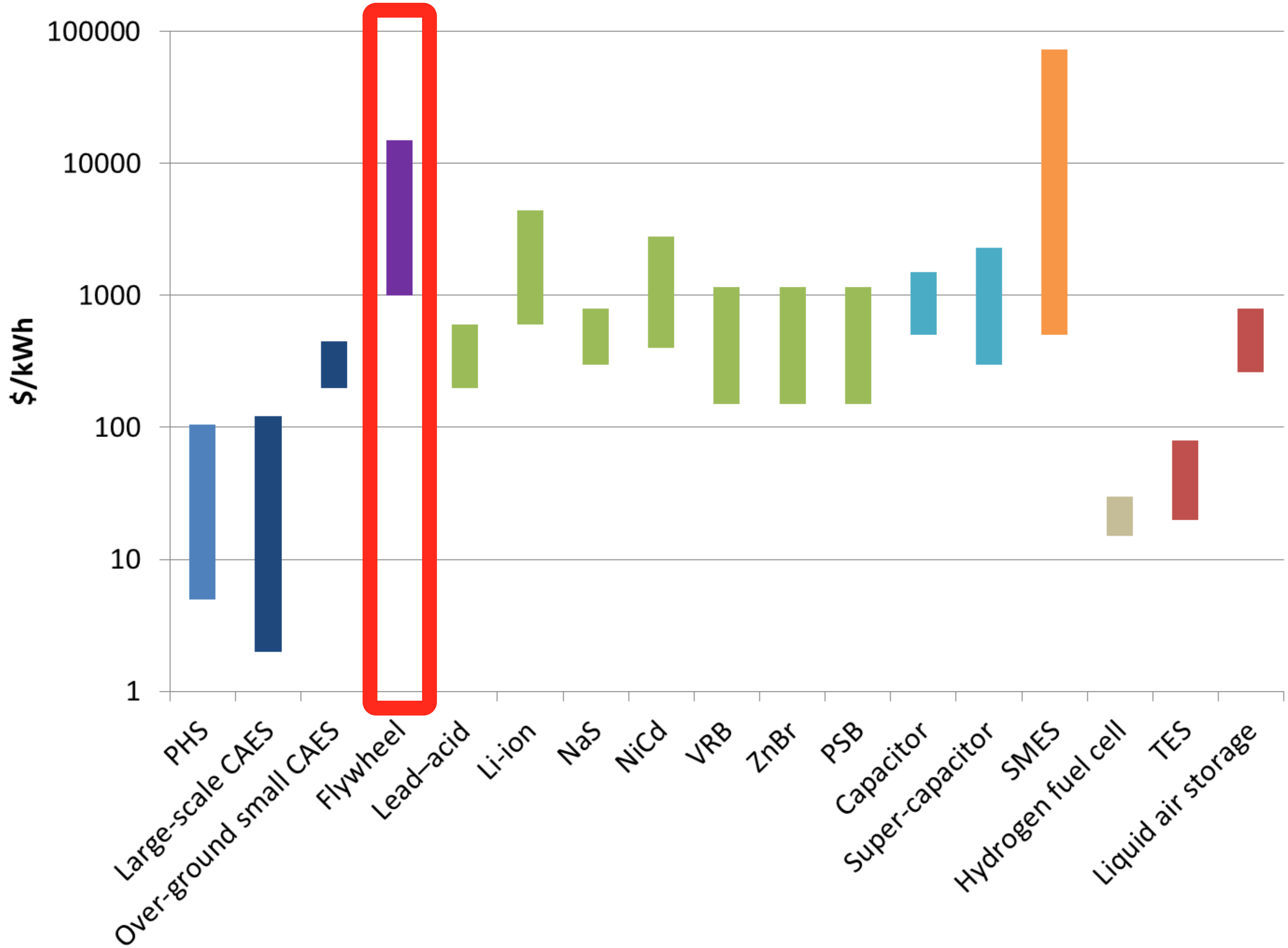
Image source: Luo, X.;Wang, J.; Dooner, M.; Clark, J. Overview of current development in electrical energy storage technologies and application potential in power system operation. Appl. Energy **2015**, 137, 511–536.

EES Capital Cost - Power



Data source: Luo, X.;Wang, J.; Dooner, M.; Clark, J. Overview of current development in electrical energy storage technologies and application potential in power system operation. Appl. Energy **2015**, 137, 511–536.

EES Capital Cost - Capacity



Data source: Luo, X.;Wang, J.; Dooner, M.; Clark, J. Overview of current development in electrical energy storage technologies and application potential in power system operation. Appl. Energy **2015**, 137, 511–536.

Summary

FES application areas

- System ancillary services
- Smart grid support

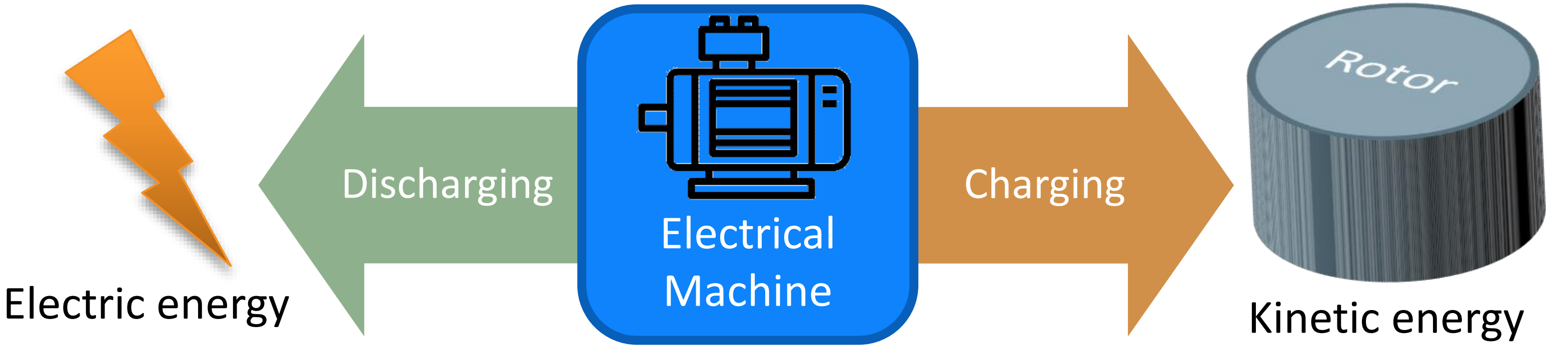
FES attractive attributes

- Excellent cycle efficiency
- Mature technology
- Excellent capital cost in terms of power

FES challenges

- High capital cost in terms of capacity
- High self-discharge (t > minutes, hours)

Basic FES Characteristics



Primary components:

- Rotor (storage device: Determines storage capacity (energy), rotates at high speeds (1,000’s to 10,000’s RPM)
- Electrical machine (motor/generator): Determines rate of charge/discharge (power)

➔ Power and capacity independent design variables

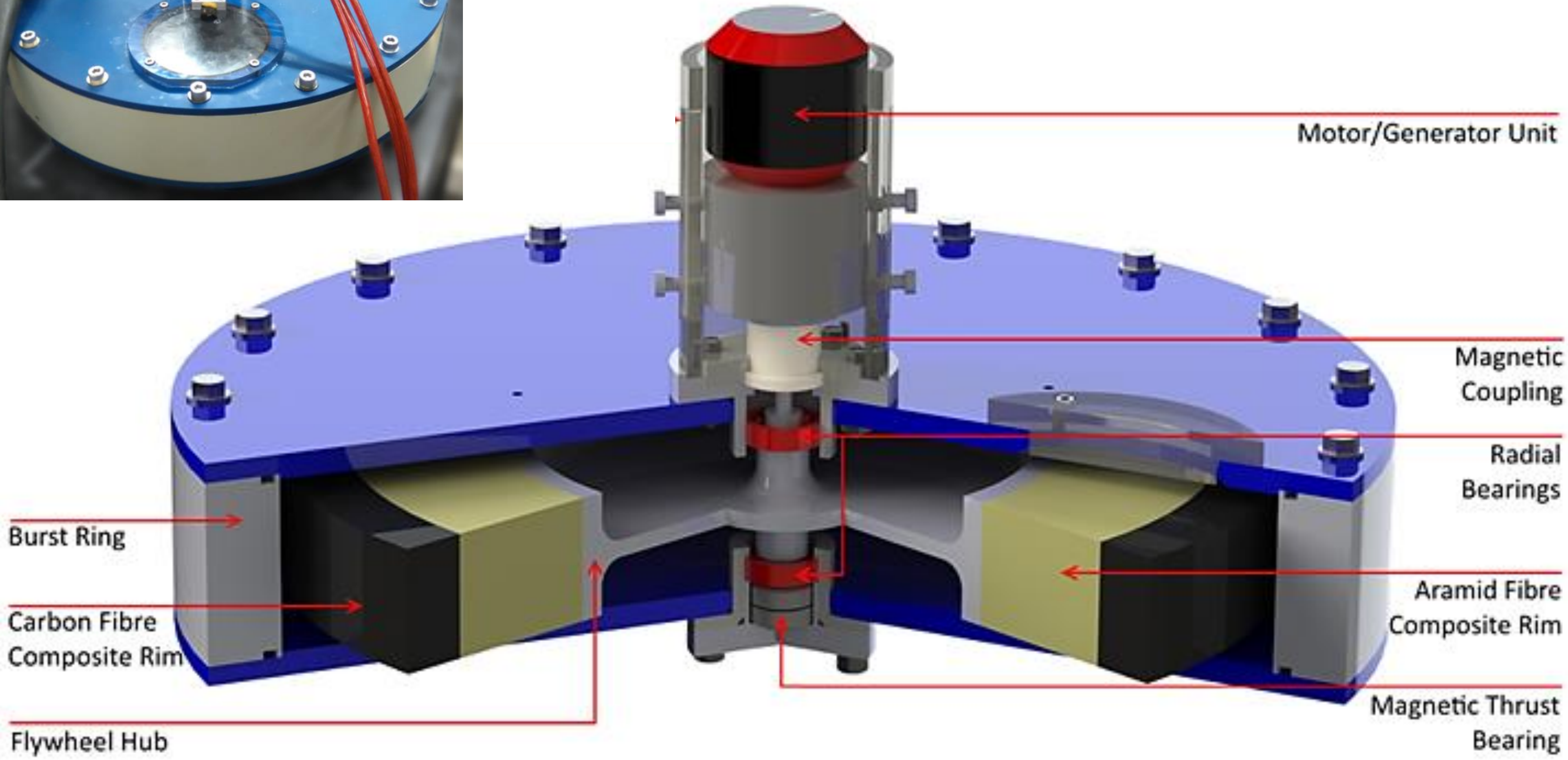
Ancillary components:

- Housing: Safety and vacuum enclosure to reduce air friction
- Bearing system
- Power electronics

Basic FES Components

Rotor materials:

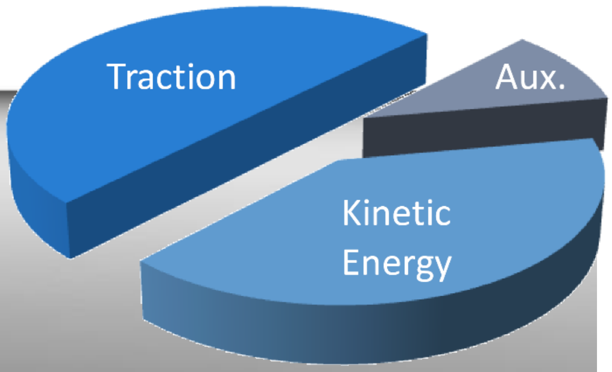
- Monolithic high-strength steel
- Circumferentially wound high-strength fiber-polymer composites (e.g. carbon/epoxy)



FES cross-section view

Optimizing Energy Consumption and Operating Cost with FES in LRT

Collaborators: H. Baier (TUM), M. Secanell (UA)



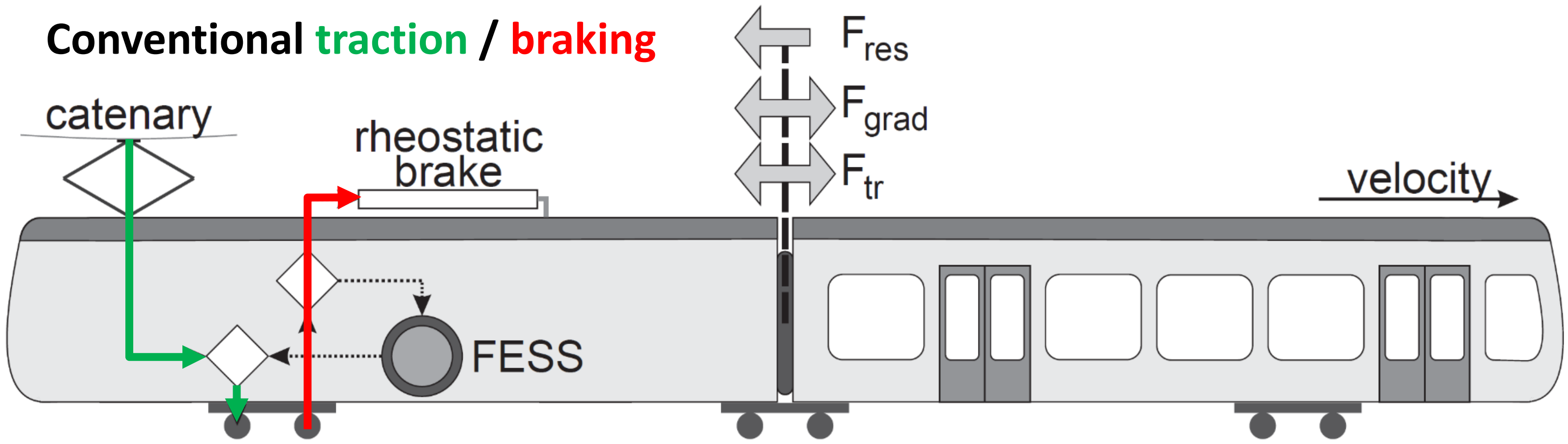
LRT energy usage

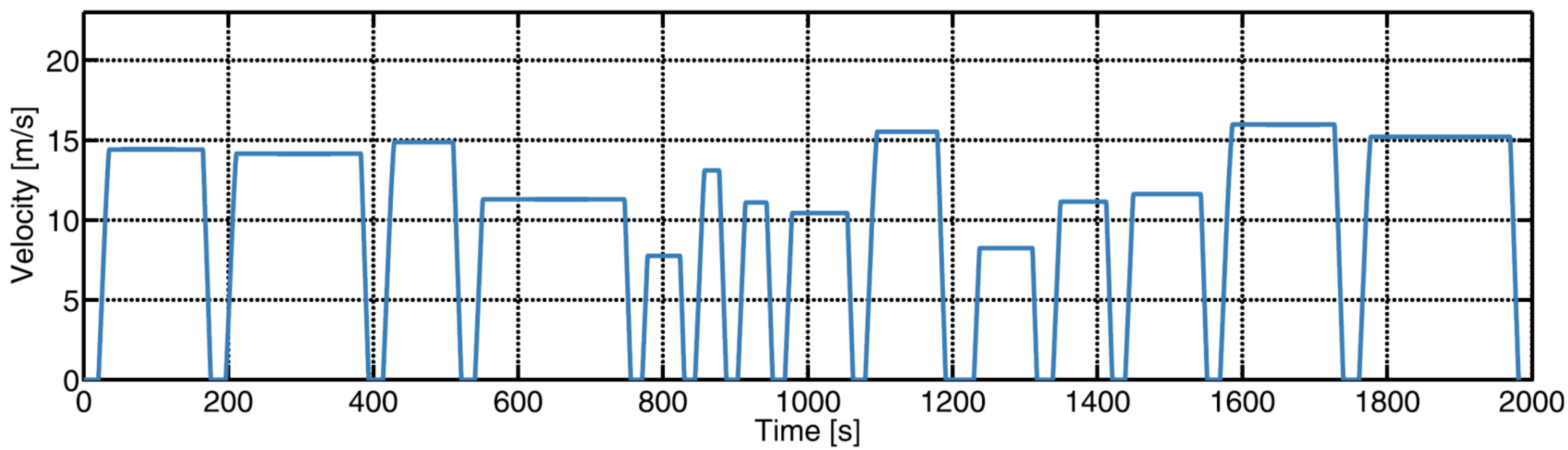
Project objectives

Optimize FESS configurations for regenerative braking in LRT:

- Maximize percent energy savings (PES)
- Maximize percent cost savings (PCS)

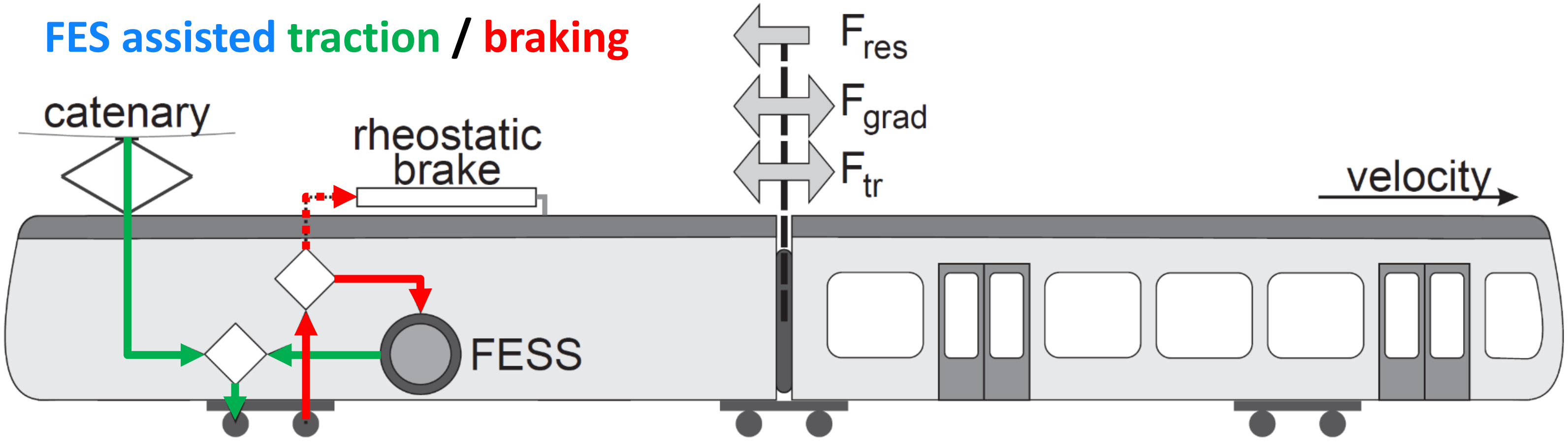
Optimizing Energy Consumption and Operating Cost with FES in LRT

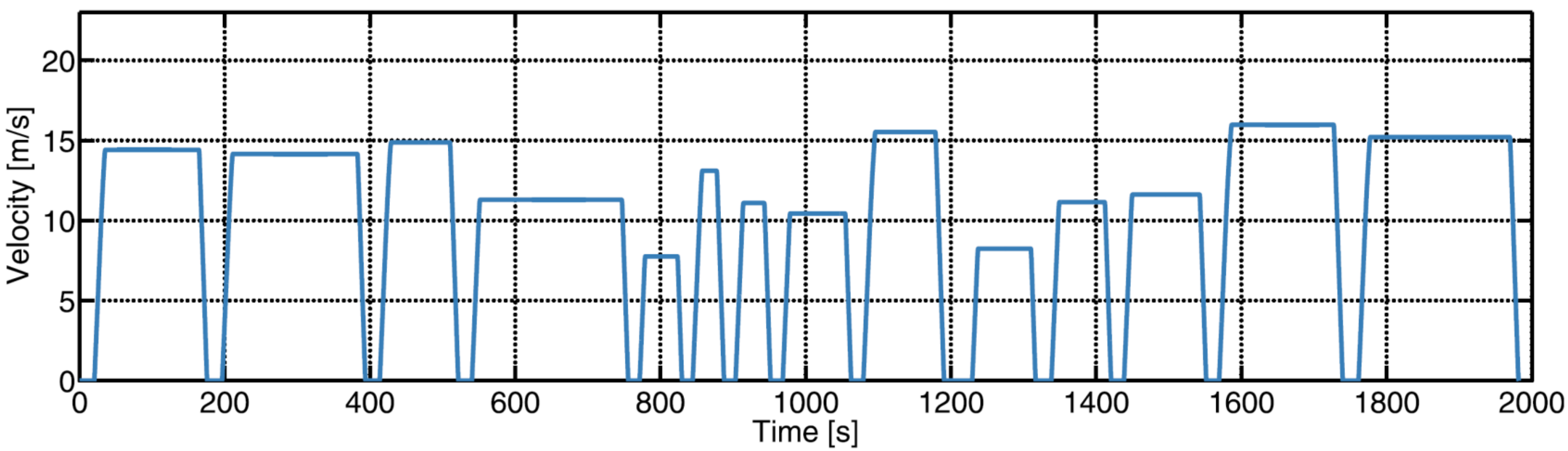




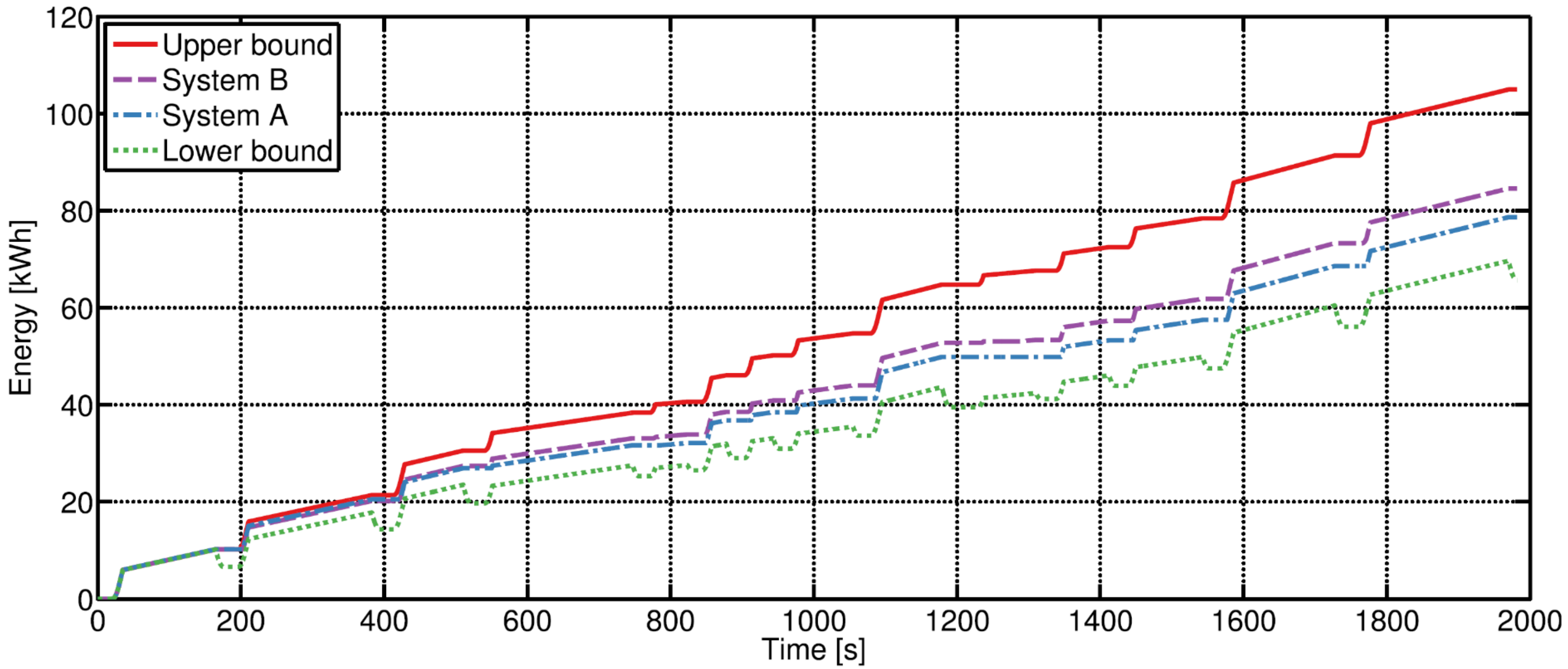
Optimizing Energy Consumption and Operating Cost with FES in LRT

FES assisted traction / braking





Optimizing Energy Consumption and Operating Cost with FES in LRT



Findings

Depending on track, payload, number of vehicles per train and type of FES (based on operating cost over 5 years):

➔ predicted PES: 9.8% to 31.2%

➔ predicted PCS: 0.55% and 11.1%

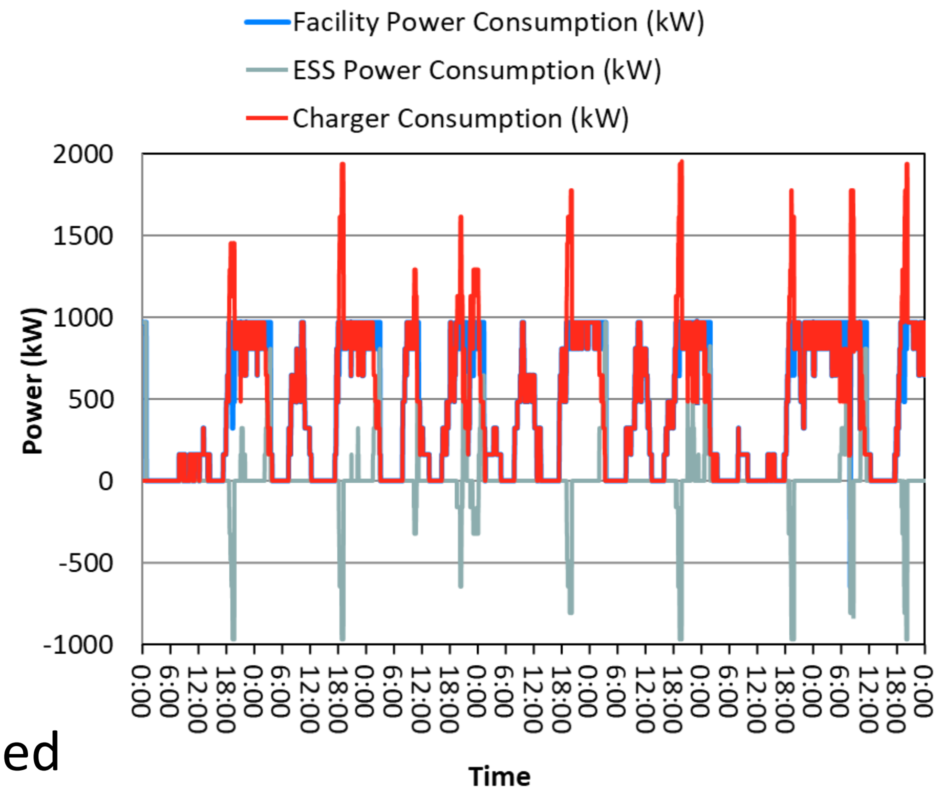
Bus Fleet Charging

- 20% of City of Edmonton GHG emissions come from transit fleet.
- CoE converting diesel bus fleet to battery electric buses (BEB) by 2030, with 40 BEBs already on the roads.
- Bus fleet operation creates potential power surges with challenges for grid connection.
- Integration of FES provides high-power charging capabilities.
- ESS is charged steadily from grid, provides fast charging capabilities when BEB is connected.

Bus Fleet Charging

Modeling of ES integration:

- 1000 kW cap on grid power.
- No disruption in bus service.
- Total of 25 commercial FES units (each 160 kW, 30 kWh).
- Comparison with commercial battery ES (BES) 1.5 MWh.
- Both BES and FES meet system requirements.
- Cost benefit analysis performed for several scenarios (net present value and internal rate of return) ➔ FES always cost advantageous.



Simulation of FES integration

Islanded Micro-grids

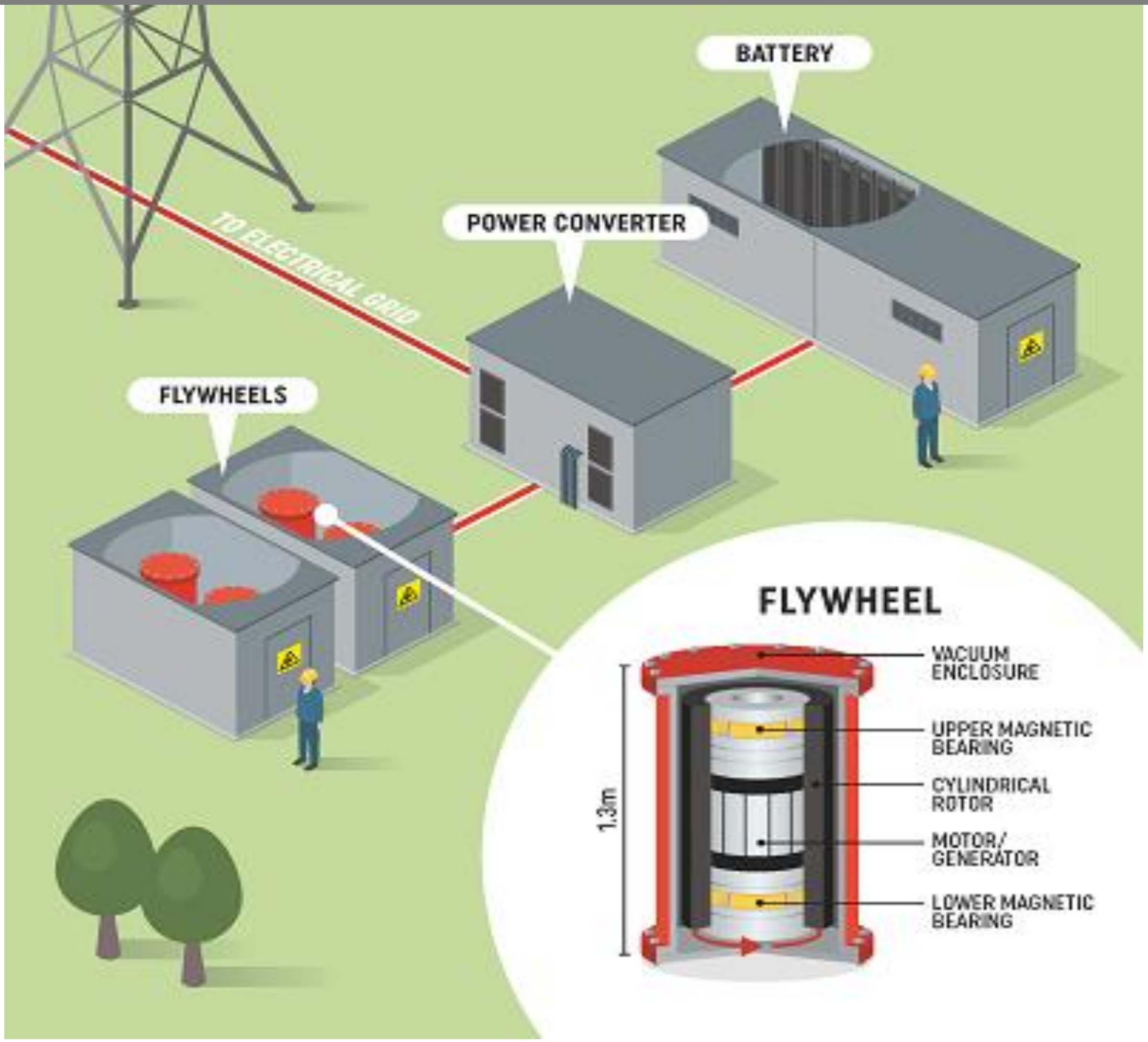
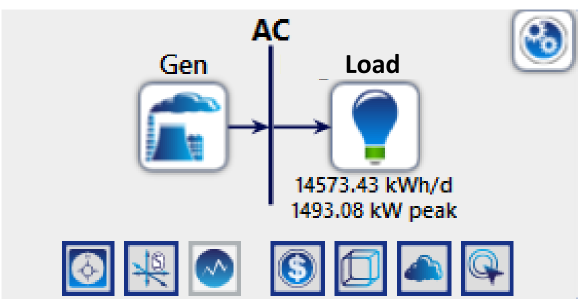


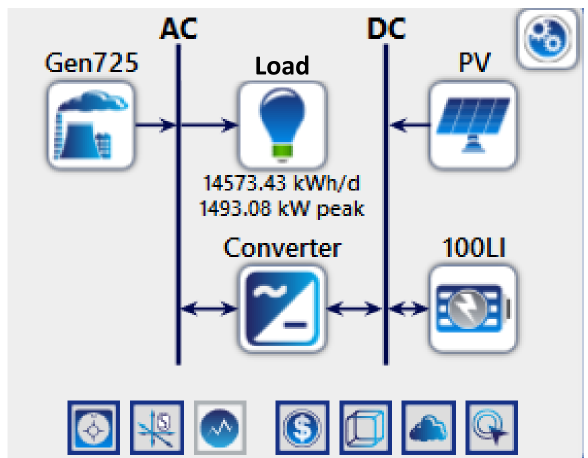
Image source: University of Sheffield

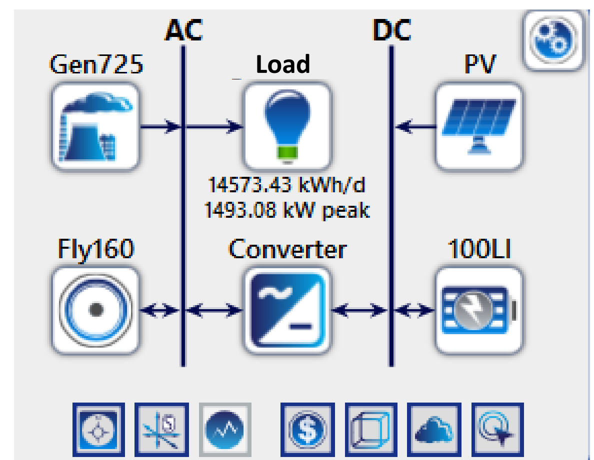
Islanded Micro-grids

Modeling of standalone micro-grids (business or small community):

- Scenario 1: Fossil fuel based base power.
- Scenario 2: Base power augmented by solar PV and BES.
- Scenario 3: BES and FES hybrid alternative.





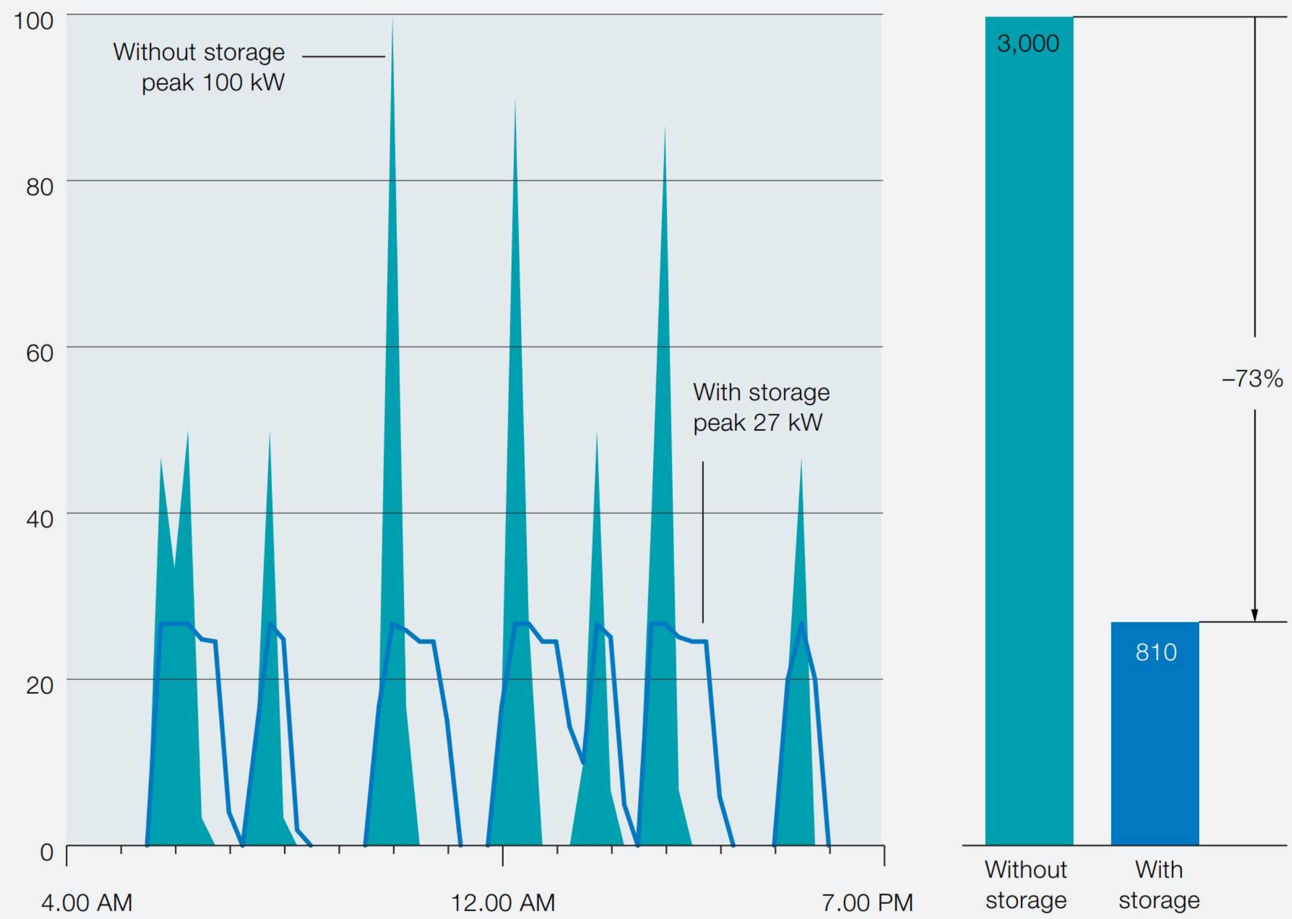


➔ BES/FES hybrid system typically most cost effective.
➔ GHG emission not necessarily reduced by hybrid system.
➔ System optimization inevitable for specific conditions.

EV Charging Network

Electric-vehicle-station load profile by time-of-day comparison,[1] kilowatt (kW)

Demand charges, $ (monthly)



[1] This assumes (i) the station has four direct-current fast-charging 50 kW chargers; (ii) 11 charging sessions occur during the time period profiled (4AM to 6PM); (iii) there is at least one instance where two cars charge simultaneously; (iv) the demand charge rate is $30 per kW; and (v) the battery-storage system is 150 kWh and can discharge at up to 75 kW.

S. Knupfer, J. Noffsinger, S. Sahdev. How Battery Storage Can Help Charge The Electric-Vehicle Market. McKinsey&Company, 2018.

EV Charging Network

- ES needed to mitigate grid limitations, reduce demand charges.
- FES capable of high-power charging and discharging without ES degradation. Temperature independent operation.
- FES-based fast charging systems are in emerging.
- Claimed significantly reduced Global Warming Potential compared to Li-Ion BES.

Image source: Chakratec

Overview FES Design Needs

Recall FES challenges:

1. High capital cost in terms of capacity
2. High self-discharge (t > minutes, hours)

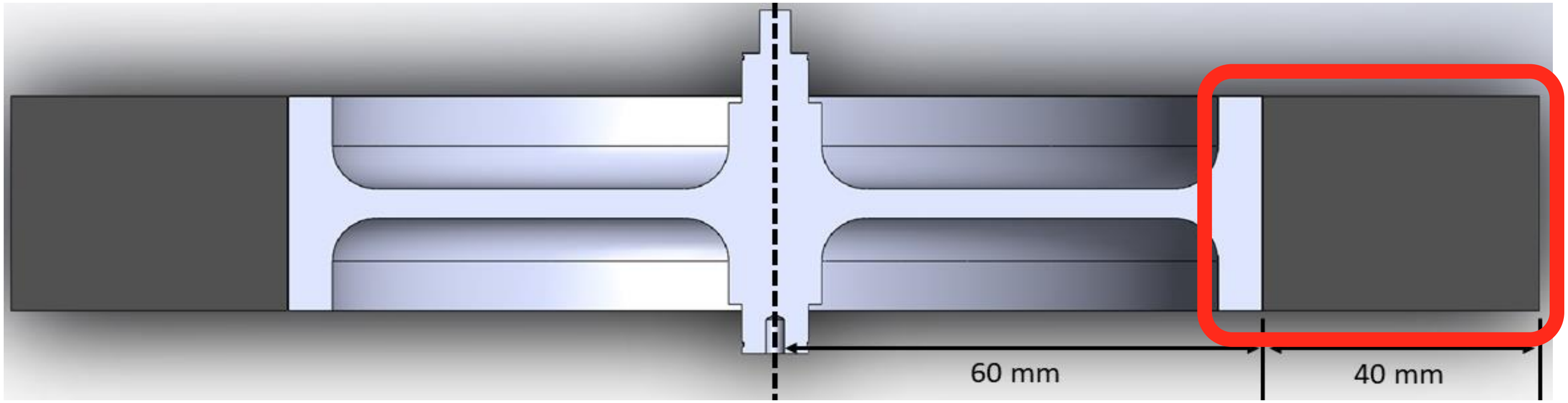
➔ Improved FES designs: Fabrication and material innovation

- Structure optimization (rotor)
- Study of long-term operation (~20 years)
- Electrical machine integration
- (Improvements in electrical machines)
- (Innovative bearing systems)

Structure Optimization

Rotor design (storage capacity)

- Dimensions
- Number, material, size of rims
- Hub geometry and material
- Fabrication and assembly



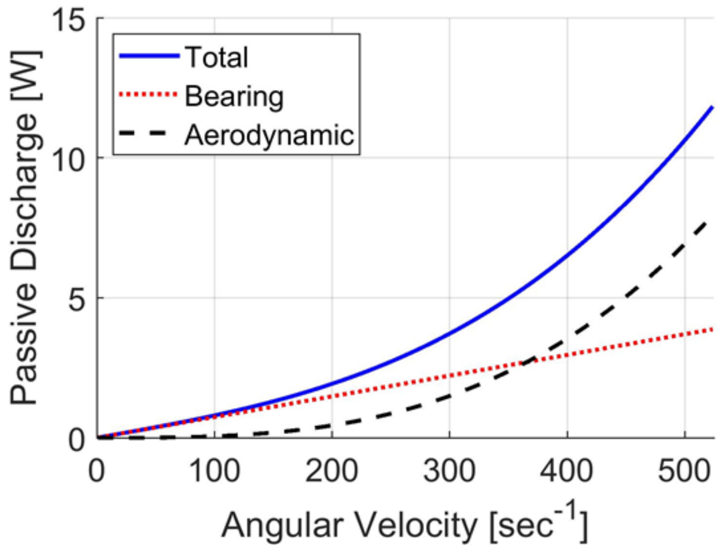
Rotor cross-section view

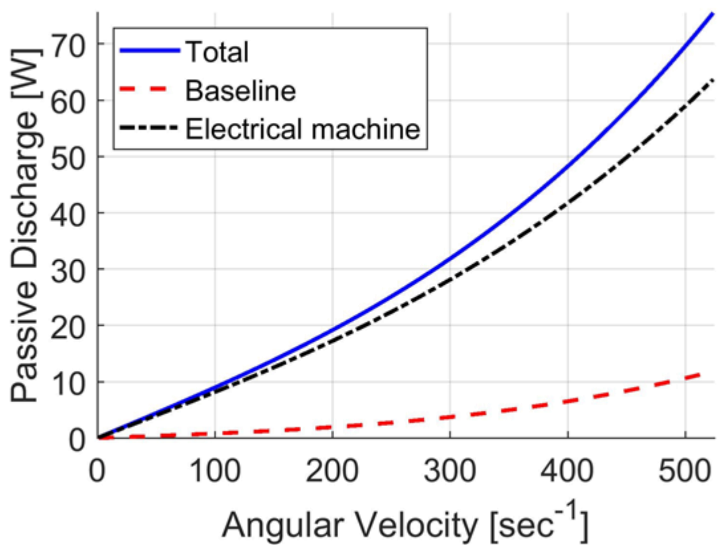
FES Self-discharge

Collaborator: M. Secanell (UA)

FES self-discharge caused by frictional forces acting on flywheel:

- Aerodynamic drag $P_{\mathrm{AD}} = C_{\mathrm{AD}}\omega^3$
- Bearing rolling friction $P_{\mathrm{MB}} = T_{\mathrm{MB}}\omega$
- Electromagnetic forces $P_{\mathrm{MB}} = T_{\mathrm{EM}}\omega + C_{\mathrm{EM1}}\omega + C_{\mathrm{EM2}}\omega^2 + C_{\mathrm{EM.AD}}\omega^3$

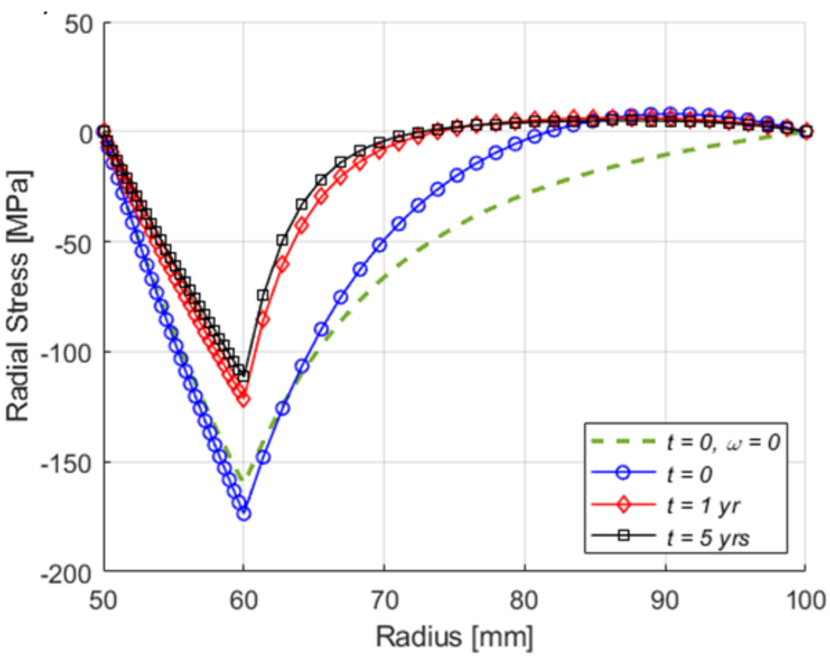


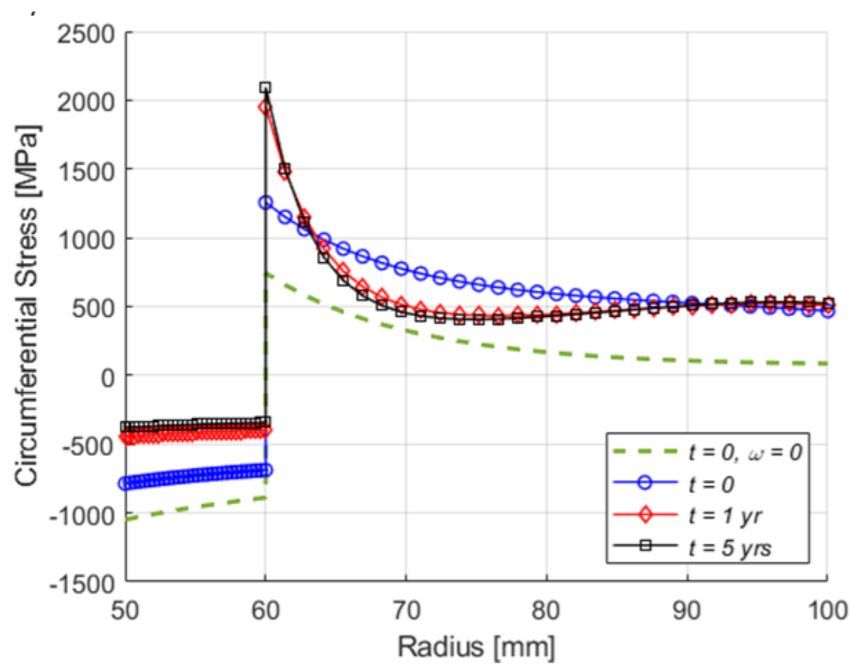


Experimental passive discharge with decoupled (left) and coupled electrical machine (right)

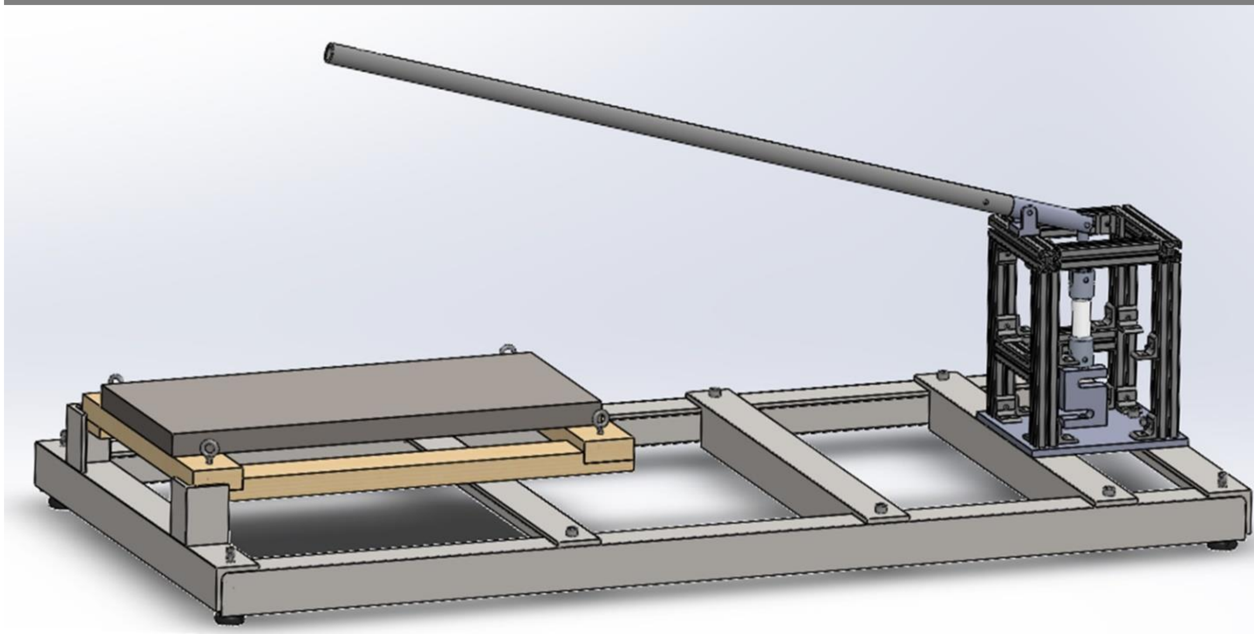
Study of Material Viscoelastic Behavior

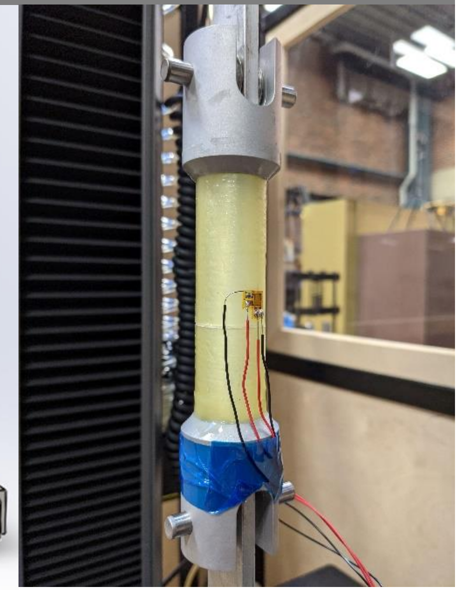
- Rotors experience high-stress loading.
- Stresses depend on material properties, operating conditions.
- Stress relaxation and material aging are of concern.





Study of Material Viscoelastic Behavior





- Transverse-to-fibers material properties are poorly characterized, especially for viscoelastic behavior.

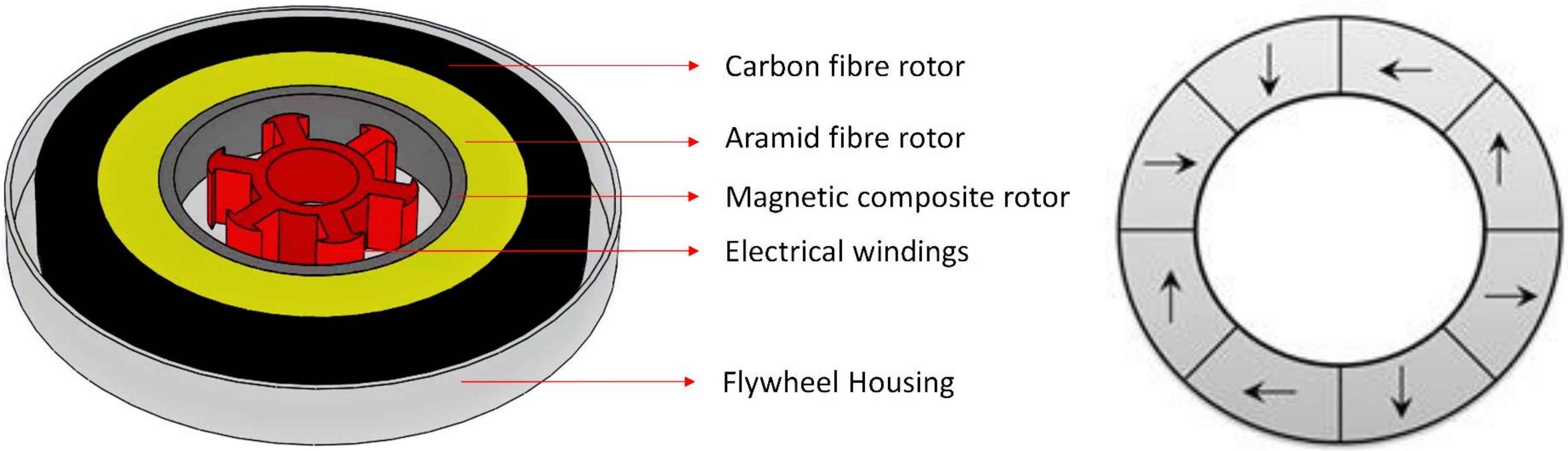
➔ **Approach: Time-temperature superposition principle**

- Long-term behavior is typically difficult to characterize:
  - Suitable specimen configuration and fabrication
  - Long time horizons
  - Need for specialized testing equipment

Electrical Machine Integration

Collaborator: A. Qureshi (UA)

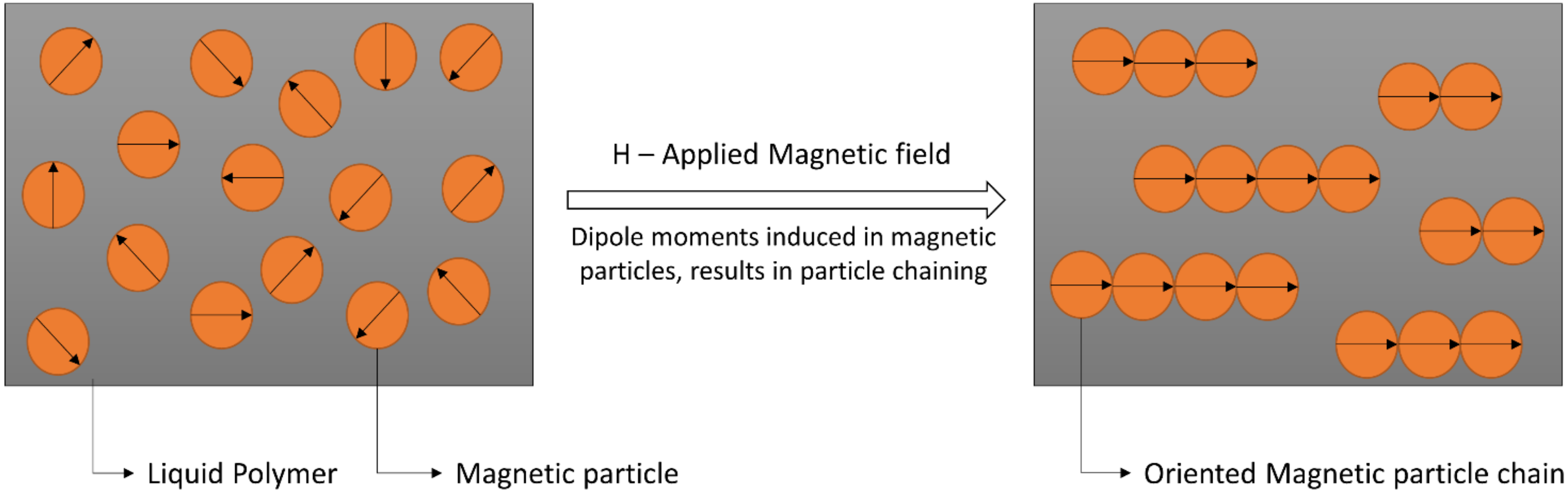
- ➔ Eliminate externally coupled electrical machine
- ➔ Design ring (arc) shaped polymer bonded permanent magnets
- ➔ Develop innovative manufacturing technologies to create field-structured permanent magnets



Rotor arrangement (left) and permanent magnet configuration (right)

Electrical Machine Integration

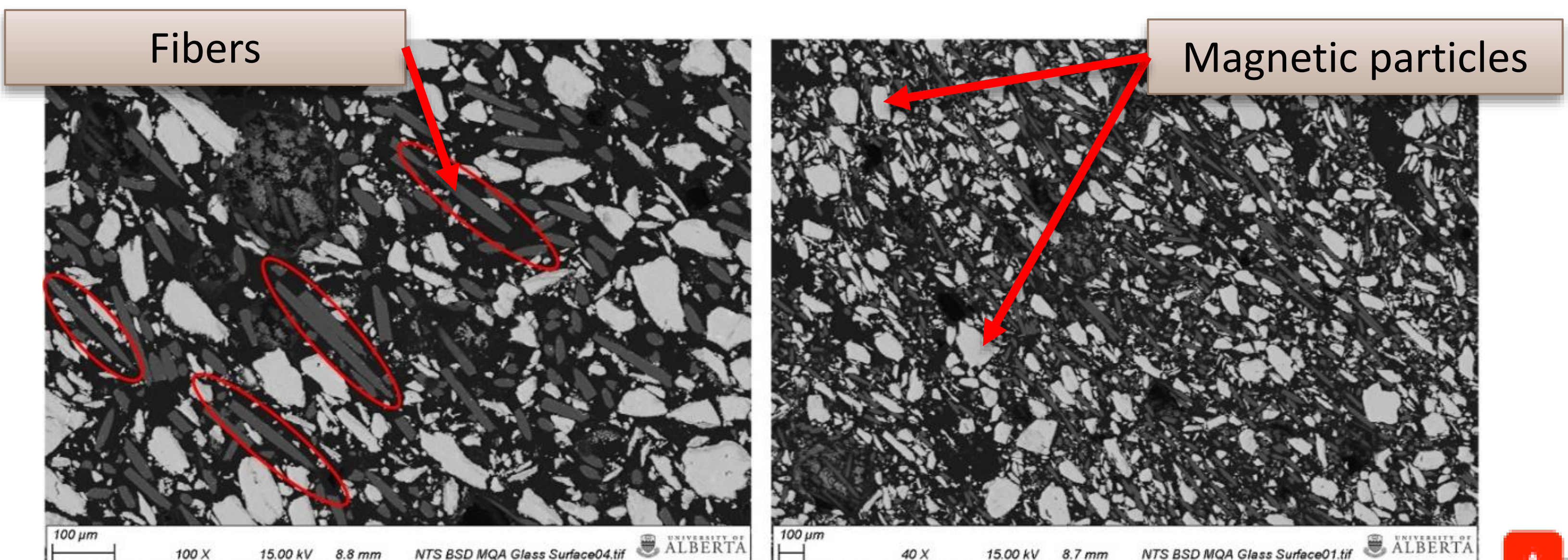
- ➔ Enhance magnetic properties (residual magnetism) by magnetic particle structuring
- ➔ Fabrication by magnetic field induces particle structuring
- ➔ Current developed permanent magnets exhibit 0.3 Tesla in remanence (target ~0.7 Tesla)



Electrical Machine Integration

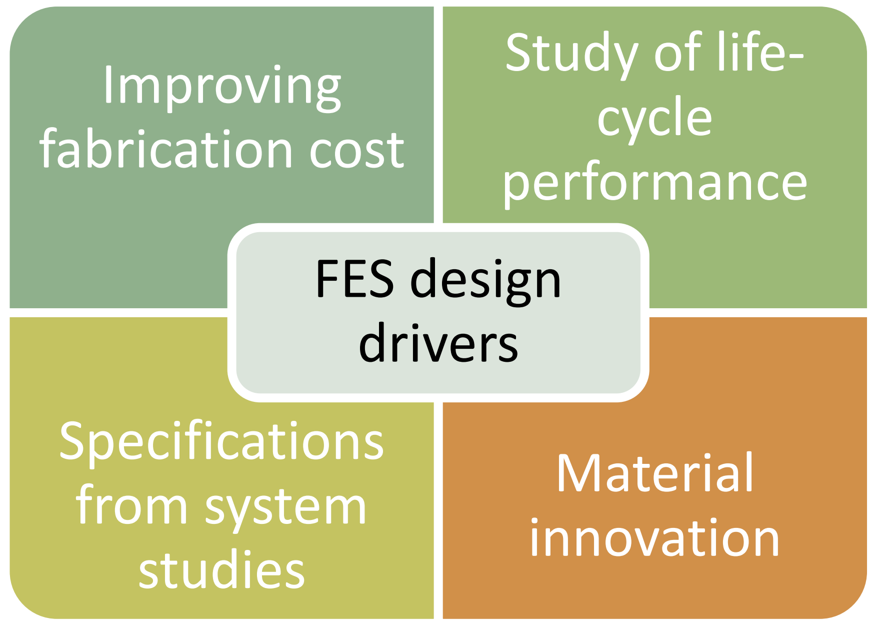
Design parameters:

- Magnetic materials (e.g. rare earth and/or ferrites)
- Polymer systems (Heat curable and heat/UV curable resins)
- Assistive materials (Reinforcing fibers, processing additives)
- Fabrication method (Additive manufacturing)



Where Do We Go From Here?

- ES essential to reducing GHG (e.g. renewables integration, electro-mobility).
- FES attractive for smart grid support system, ancillary services (e.g. EV charging).
- Comparatively mature technology, but marginalized by BES commercial interests and popularity.



- Research and development needed to drive application-specific design optimization and innovation.
- Further potential for hybrid ES with FES.
- Academic research needed on FES system integration (e.g. EV charging networks) to assess potential and inform FES design.