mardi, 24 avril 2018

Technology and Policy of Electrical Energy Storage

L1 - Introduction to Electrical Energy Storage - TS

- Transformation of the energy system is a socio-techno-economic challenge
- strong correlation between electrification rate and poverty rate
- renewable micro-grids can already be cheaper than baseline technology (diesel)
- resource depletion of non-renewable energy
- transport is sector with highest emissions and highest emissions growth rate
- rising shares of intermittent RET should result in increased role for storage
- rise of electric mobility (still depend on policy support)
- falling prices of batteries

L2 - Energy Storage Applications, Innovation and Policy - TS

- Political system triad:
    - Policy: political content - laws, regulations, frameworks
    - Polity: political structures - civil authorities and institutions
    - Politics: political processes - decision-making, implementation
- When is policy intervention justified?
    - market failures
    - markets are good for near-term optimization only
    - policy about shaping new systems and markets (Evolutionary economics)
    - policy about ensuring fair market transactions (Mainstream economics)
- With more RET (like PV), wholesale arbitrage model does not work well anymore because the cost differential between high and low demand is shrinking.
    - marginal costs of RET very low. Most costs are upfront.
    - there is an incentive to keep technologies with high marginal costs, in order to keep the wholesale arbitrage business model alive
    - actual market does not incentivize introduction of Electrical Energy Storage —> Need Policy
    - Technology push (R&D) or demand pull (price on emissions)

- Energy Systems:
    - long time horizons (coal plant, 40 years - pumped hydro 80 years)
    - large investments (several billion - nuclear plant)
    - strong externalities (pollution)
    - natural monopolies (power grid for ex.)
    - characterized by complexity and uncertainty —> policy intervention

Complexities in policy and politics

- Scarcity of public funds
    - need cost-effective solutions
    - tap into private finance
- Different policy domains have different targets
- Different governance levels, supranational, national, regional etc.
- Aims of energy policy:
    - security of supply
    - affordability
    - sustainability
    - industrial competitiveness

Take home messages

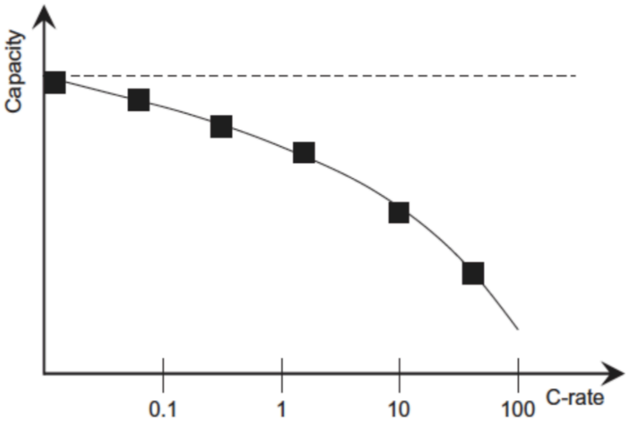
- Policy intervention can have different rationales: Steady state vs transitions
    - policy instrumental for both
- policy-making shaped by financial constraints, politics and polity
- Multi purpose character of storage provides many demand-pull policy intervantion possibilities

Questions

- Policy:
    - “the actions of government and the intentions that determine those actions“
    - “whatever governments choose to do or not to do”
    - “policy is a general term used to describe a formal decision or plan of action adopted by an actor to achieve a particular goal”
- Policy Cycle: Agenda setting - Policy formulation - legitimation - implementation - evaluation - policy maintenance - agenda setting
- Policy mixes are often inconsistent because policy has multiple targets and domains. These can be conflicting

L3 - Battery Basics - VW

- **Reduction**: accepting an electron
- **Oxidation**: giving an electron away
- **Cathode**: positive electrode (LCO)
    - gets oxidized during charge and reduced during discharge
    - gets de-lithiated during charge and lithiated during discharge
- **Anode**: negative electrode (graphite)
    - gets reduced during charge and oxidized during discharge
    - gets de-lithiated during charge and lithiated during discharge
- **C-rate**: the rate at which charge and discharge occurs [1/h]
    - C-rate = current/capacity [A/Ah = 1/h]
    - high C-rate: high speed of charge/ discharge
    - at lower C-rates you can get more capacity into and out of a cell
    - this is **not** degradation!



- **Capacity**: the charge transferred during the reaction
    - depends on how much active material there is,
    - how many lithium atoms per mol of active material there is
- **Specific Capacity**: Capacity per unit mass
- **Cell voltage**: difference in voltage between cathode and anode
- **Coulombic efficiency**: charge transferred during discharged/ transferred during charge
    - a coulombic efficiency of 99% means that a cell loses 1% of its capacity at each cycle
    - after n cycles, a cell capacity is $CE^n * C_{in}$ —> significant digits are important

- **Ragone plots**: specific energy vs specific power

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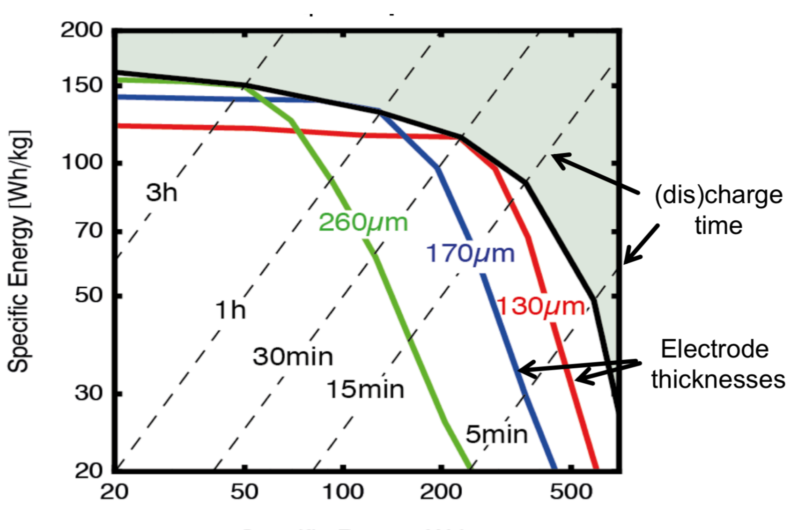
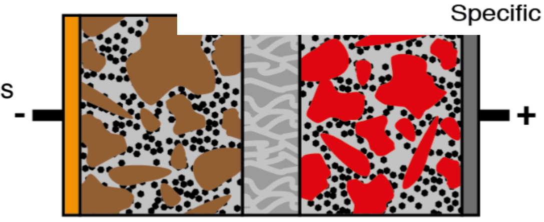
- how quickly can the energy be delivered vs how much energy in cell
- the slope = 1 lines are charge and discharge times
- the current depends on the thickness of the electrode



- **The Electrochemical cell**



Cu Current Collector
Thickness = 10 µm
(but coated on both sides
so effectively **5µm**)
ρ_{Cu}=8.9 g/cm^2
4.45 mg/cm^2

Thickness=10 µm
(but coated on both sides
so effectively **5µm**)
ρ_{Al}=2.7 g/ml
1.35 mg/cm^2

Graphite Anode
Thickness = **50 µm**
Loading= 2.8 mAh/cm^2
8.0 mg/cm^2

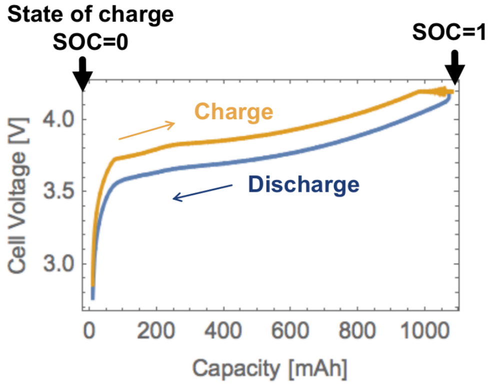
PE Separator
Thickness = **20 µm**
Porosity = 50%
ρ_{PE}=0.95 g/ml
0.95 mg/cm^2

LCO Cathode
Thickness = **70 µm**
Porosity = 30%
ρ_{LCO}=4.2 g/ml
C_{LCO}=136 mAh/g
Loading=2.8 mAh/cm^2
20.6 mg/cm^2

Electrolyte **4.0 mg/cm^2**
ρ_{El}=1 g/ml **0 µm thick**

- the lithium content of both electrodes changes during cycling, more lithium in an electrode —> potential gets closer to Li —> potential gets smaller
- Charge: Li from cathode to anode, potential anode - -, potential cathode ++
- Discharge: Li from anode to cathode: potential anode ++, potential anode - -

- **State of charge** (SOC)
  - potential of electrodes change during cycling
  - potential of cell thus changes during cycling, and depends on the state of charge.
  - there is a voltage hysteresis



- Theoretical Gravimetric capacity: computable from Faraday constant and number of moles and molar weight.

    - tradeoff between needed size and mass of the cell
- **Cell degradation**
    - Calendar life: does a cell retain properties when sitting on a shelf?
    - Cycle life: how does cycling influence capacity?
    - Losses can be electrochemical (due to side reactions), mechanical (due to stress) or thermal (due to heating)

L4 - Battery Materials - VW

- **Porous Electrode:**
    - about 35% of the volume of the electrode filled with liquid electrolyte
    - 3 components:
        - **active material**: stores lithium - 90% wt%
        - **Carbon black**: improves electronic conductivity and lowers resistance and heating of the electrode- ~3-5 wt%
        - **Polymer binder**: for mechanical stability and adhesion to the current collector - ~ 5-10 wt%
- **Active materials**:
    - classification: how do they react with lithium?
    - expand volume when litigated (graphite 10%, Silicon 400%). Volume expansion is bad because it can make active material inactive, due to mechanical disconnection.
    - **Intercalation/Insertion**: lithium moves into unoccupied sites in a crystal lattice. The crystal lattice dilates but does not change structure. For example when graphite gets lithiated. —> **Lithiation of Graphite**
    - **Alloying/Formation**: when lithiation leads to creation of alloys which crystal structure is different from the initial structure of the compound in the active material. —> **Lithiation of Silicon**
    - **Conversion/Displacement**: lithium displaces a component from the active material from a compound. The reaction is not always reversible. —> **Lithiation of iron fluoride**
- **Electrolyte**
    - a source of lithium and transport for lithium ions
    - solvent and salt, ex: LiPF6: Cation Li^+, Anion PF_6^-

    - Lithium ions are transported via **migration** (PF_6^- move in opposite direction) or **diffusion** (PF_6^- move in same direction) through the electrolyte.
    - **Lithium transference number**: describes relative ability for cation and anion to move, typical is 0.4, i.e. 4 Li+ in one direction for 6 PF6- in other direction.
  - a low conductivity means a high resistance, a high voltage drop and more heat generated
  - electrode microstructure affects conductivity and diffusion through porosity and tortuosity
- **Separators**
  - polymer membrane that prevents electronic contact between cathode and anode but allows ionic transport.
  - continuous network of pores with diameter of ~50nm, thickness roughly 16 microns, porosity ~ 40%
  - safety measure, shutdown of separators. In the case of a thermal runaway, the inner layer melts first
- **Lithium Plating**: if the potential at an electrode drops below 0V vs Li, lithium can plate the electrode. It happens during fast or low temperature charging where high voltages are required to compensate for slow kinetics.
- Lithium Titanate (LTO) vs graphite
  - LTO attractive as anode because has low voltage profile at 1.5V vs Li, lithium plating is unlikely. Has a high C-rate and is thermally stable.
  - Graphite has voltage plateau close to 0V vs Li, risk of lithium plating, during fast charge for example
  - graphite electrodes don’t work well above 2C, LTO does
  - LTO has lower specific capacity than graphite —> heavier battery, more useful for grid stabilization application where weight is not critical.

L5 - Battery Manufacturing - VW

Key trends in battery manufacturing:

  - mixing material with different properties
  - structuring of material for optimal performance
- Fragmented market, many steps and actors, mining companies, material producers, battery manufacturers
- **Steps in Manufacturing**

  - **Slurry mixing**: making the porous electrode. Take the active material, polymer binder and carbon black and mix them.
    - Important because there needs a good distribution of carbon black and binder mixture in the electrode
    - Not mixed enough, it can prevent ionic transport
    - mixing process should be optimized for each type of active material
  - **Electrode coating**: putting the slurry mix on Cu or Al foils (current collectors) and then the wet film is dried in ovens
  - **Electrode calendering**: compression of the dried electrode to obtain desired thickness and porosity
  - **Slitting**: cutting the electrodes to the desired shape
  - **Winding**: depending if pouch cell, prismatic cell or cylindrical cell, arranging in the adequate formation
  - **Filling and Sealing**: in a dry room, fill the electrolyte in the electrodes.
    - long process, ~5 hours. Multiple fillings needed due to the bad wetting of electrolyte
    - Next direction: ceramic separators to optimize this step
  - **Cell Formation**: first charge and discharge cycle, build up solid electrolyte interphase (SEI). SEI protects active materials from further reactions with electrolyte components
    - key for cell's stability, lifetime and safety
  - **Testing**: test voltage and capacity
- Nanoparticle active materials:
  - shorter diffusion length and times and electronic conduction length
  - low bulk density, requires more binder and conductive additive
- **Future directions**:
  - aqueous based slurry processing
  - better electrolyte wetting: ceramic separator
  - Thicker electrodes: potential problems are the drying which is longer and more complicated for manufacturing and the longer path length for lithium ions for the battery operation
  - improvement to current processes likely before any disruptive change

L6 - Batteries for E-Mobility - VW

Levels of Vehicle Electrification

- **micro hybrids** (low voltage hybrids) - 12, 24V
  - powers auxiliary systems
- **mild/Strong hybrids HEV** - hundreds of V
  - charge during breaking, discharge during acceleration
- **plug-in hybrid EV PHEV**
  - all electric drive possible, battery charged externally or internally
- **full electric vehicle BEV**
  - battery fulfills all driving requirements

- **Reduction of CO2?**
  - 400 kWh needed to make 1 kWh battery
  - need more than 400 cycles to have positive environmental impact
  - CO2 emissions depend of course on energy mix
- **Battery selection for EV**
  - General criteria: vehicle type, size, mass, environmental conditions (temperature)
  - Criteria for selecting power requirement: acceleration requirements and drag
  - Criteria for selecting energy requirement: desired electric range, which other features need to run on electric
  - Power determines C-rate and Energy determines Capacity
  - Design parameter: P/E (Power over Electricity)
    - EV: ~ 2 P/E, need high E to enable long driving distances —> P/E low
    - PHEV: ~ 10 P/E
    - HEV: ~ 20 P/E electric drive impossible, don’t need high E
    - P and E are not independent but it’s a good indicator of what criteria is needed for a specific application
- Installed energy != usable energy
  - HEV and PHEV: work in charge sustainable mode, around 50% SOC
  - EV and PHEV: charge depleting mode, larger SOC

- **Series and Parallel connections**
  - batteries in series, voltage is additive but current the same
  - parallel batteries, voltage the same and current divided among cells
  - for a given current, parallel has a higher capacity
- **Key problems and challenges for EV batteries**
  - longer cycle life
  - lower cost
  - faster charge
  - Lithium Ion is the most likely short-term scenario due to the balance between energy, power and life.

L7 - Battery Materials and Recycling - VW

- Lithium ion is an area of high growth and investment
- Lead Acid still important
- Lithium Ion Battery Market:
  - Automotive, Grid, Power tools
- Lithium Ion Batteries will start to drive worldwide mining. Will become a metal sustainability problem.
- **Drivers for Recycling**:
  - Economic profitability
  - Legal obligations
  - government incentives
  - energy saving
  - reduction of ecological footprint
- Pb acid batteries —> over 99% of Pb-acid batteries recycled in USA and europe
- Lithium Ion Battery Recycling?
  - Are there enough batteries to support large scale recycling?
  - No standardized pack size/shape or materials —> way more complicated than for Pb acid.
  - What battery industry can do is designs that allow easy separation of parts. And standardization of formats and materials
- Complexities and Unknowns of Li-Ion battery recycling

  - current recycling models depend on high cobalt content of cathode
  - large growth expected from EV market —> will make battery recycling easier to organize and legislate
  - new cathode technologies with less cobalt are entering the market
  - will it be economic to recycle cobalt-containing batteries in 2030-2035
  - Problem is the time structure, build them now but recycle them in X years.
- What can be done:
  - Policymakers: Li-ion battery recycling is a must, policy instruments needed to ensure security of supply by recycling.
  - R&D: battery design for recycling: easy and automated disassembly
  - Industry: explore recycling cell level, automated disassembly

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L8 - Next Generation - VW

- **Alternative to Lithium ions**
  - **Lead acid** (**Pb Acid**): liquid electrolyte water + sulfuric acid —> limits voltage of cell
    - mobile ion is H+
    - used for large scale storing
    - middle voltage, low specific energy, low energy density
  - **Nickel metal hybride** (**NiMH**):
    - in most PHEV (Prius), electrolyte is aqueous and basic (KOH in water)
    - low voltage, high specific energy, high energy density
  - Li Ion has highest voltage, specific energy and energy density
    - non aqueous electrolyte
- development of batteries driven by market predictions
- most of the cost is in the active material
- Success of new technologies very much dependent on emerging market demands
- Incremental improvements to technology currently the favored approach
- **Trends in Lithium Ion Battery Development**:
  - higher energy density, consider graphite - Si composite (remember trade-off expansion of Si and energy density)
  - cheaper materials: it's the most efficient way to reduce pack price

    - use less cobalt (which is expensive) and more magnesium (cheaper)
  - higher voltage —> opportunity for higher density
    - more nickel in positive electrode, it can get the voltage up to 4.8V but might not operate properly at those voltages
    - higher voltage achieved only by getting potential of cathode higher, because there is the limit of 0 V vs Li which should not be crossed in the negative electrode —> lithium plating.
  - faster charge: improve ion conductivity in electrolyte
    - make lithium ion path length as straight and short as possible —> Production becomes the major challenge
- **Solid State Batteries**
  - replace liquid electrolyte with solid materials that can conduct lithium ions
  - Problems with liquid electrolytes:
    - very long to infill the liquid electrolyte in the battery
    - it's organic (carbonated) and thus combustible
  - Challenge in manufacturing: can't infill a solid electrolyte
  - Cracking: expansion of common cathode and anode is 10 to 15%, might lead to cracking of the solid electrolyte
  - In principle safer because no combustion possible, but cracks are a problem

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L9 - Technological Learning - TS

- Innovation is not linear, the invention - innovation - diffusion model is too simple
  - must take technological learning into account: learning by searching, learning by doing, learning by using and knowledge spillover from other technologies
- Knowledge is non-rival, non-excludable, cumulative and sticky (hard to transfer from one actor to another)
- Learning curve is not historical learning, historical learning is **cost vs time**, learning curve is cost vs **cumulative installed capacity**
  - Learning rate: by what percentage costs reduced if capacity increases by 100%
- Knowledge spillover from other technologies can be highly important for innovation
- Exploration vs Exploitation
  - Exploitation means going down the learning curve by using the technology

  - Exploration means shifting the learning curve through R&D for example.

Role of technological complexities

- Complexity: number of parts, how they interact, how many parts should be replaced if only one is defective
  - of design: relationship between the parts —> Wind turbine
  - of production process: —> PV cell
- Grid-scale battery storage is complex wrt. manufacturing and design
- Batteries are complex, you can't just change the anode like that
- Technologies with few « tacit knowledge » generally have rather flat learning curves, mainly driven by economies of scale
- With technological learning, barriers to entry are raising.

Learning in Li-ion industry value chain

- Interactive learning between actors along industry value chain important
- Batteries learn most from other batteries —> Knowledge spillovers within sector
- But Spillovers between batteries rather limited: internal technologies across batteries quite different
- Li-ion battery technology is multi-component technology produced in different sectors

Take home messages

- Technological change is complex and hard to predict - learning curves are an imperfect estimation tool
- policy plays key role in technological change, the better we can predict TC, the better we can design policies
- learning patterns differ between technologies. Policies should be technology-specific

Questions

- key difference between packs used for BEV and hybrid vehicles is that BEV have high-energy battery packs (for range) and hybrids high-power energy packs
- Learning rates for Li-ion battery packs in BEV around 9%
- At battery cost of 150USD/kWh, BEV become competitive with engine/diesel cars. (depends on oil price)
- Other factors should be taken into account, like charging infrastructure, policy incentives etc.

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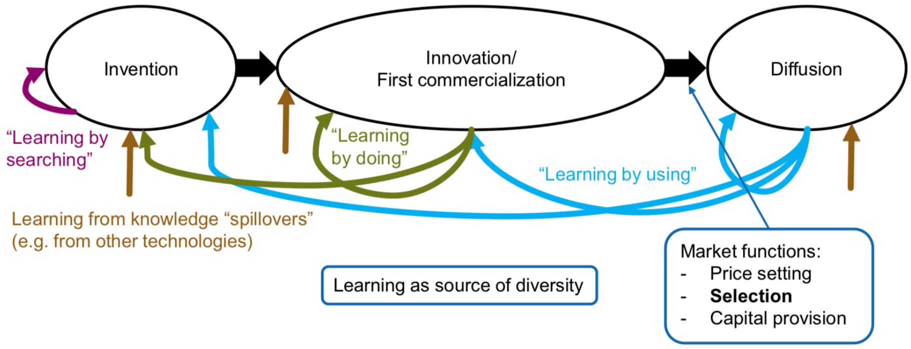
L10 - Constructive Controversy - TS

Complexities in policy making

- different policy domains have different (and potentially conflicting) targets

Role of deployment in innovation

- technological change has a non-linear model



- **Path dependency:**
  - lock-ins: a sector is trapped into a specific technology (fossil fuels, combustion engine)
  - alternative technologies can stayed locked-out: they have little chance to increase their market share without market shifts
  - Early technology adoption can create lock-ins. Costs are key adoption criterion
  - Policies can be technology specific (through subsidies for ex.) or technology neutral (carbon tax). In second case, market picks best technology

Market vs Policy for « best technology chooser »

- **Market**:
  - lead to success of cheapest technology
  - are efficient (prices closest to cost)
  - better informed and closer to technology, better access to information than policymakers (but zero empirical evidence yet)
  - pick on short-term basis (long term is ~18 months for markets)
  - can lead to oligopolies and become inefficient
- **Policy**:

  - too much competition leads to death of innovation —> no slack, due to uncertainty in innovation
  - can provide « safe islands » for technology startups
  - can target long-term good
  - not well placed to predict learning curves
  - can publicly finance technology assessment and put efficient patenting system in place
- **Market & Policy mix**
  - complex, costly and slow
  - How technology neutral or specific should a policy be

L11 - Learning and Multi-Purpose Technologies - TS

Technology specific/neutral policies

- The question to ask is « how neutral/specific should the policies be? »
- **Take advantage of different hierarchy levels**:
  - economy: carbon tax, cap & trade policies
  - sector: Sectoral emissions trading
  - Technological field: renewable portfolio standards
  - Technology (PV, batteries): Feed-in tariffs
  - Sub-technology (c-Si PV, Lithium-ion): Feed-in tariffs
- Policies can only be specific on **one** hierarchy level

Multi Purpose Technologies (MPT)

- batteries are MPT
- applications of MPT differ in terms of user groups / value drivers /rival technologies
- Policymakers can decide in which market to intervene through **application-specific** deployment policies

Stationary Batteries

- Key technical parameters:
  - **power capacity**: how much wattage does storage have?
  - **discharge duratio**n: how long is battery used?

  - **cycle frequency**: how often is battery used?
  - specific energy and energy density mostly relevant for mobile applications
- Competition varies strongly across the battery landscape depending on those three key parameters
- Different technologies lead in different applications —> lock-in risk across entire landscape
  - Application specific policy can also lead to technological lock-in

Designing Deployment Policies

- Picking application by policymakers can result in lock-in
- Application neutral deployment policy can also result in lock-in
- Policymakers should consider MP characteristic to avoid random technology lock-in and limit policy cost
- For example use sequential approach taking advantage of profitability gap
  - support different applications in a certain timely order
- Also combining applications can pump up profitability