Advanced Vehicle Cost and Energy-Use Model (AVCEM) - Overview, Recent Developments, and Preliminary Findings

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Outline

- Overview
- Overview of *AVCEM*
- Relevance
- Conceptual framework and boundaries of analysis
- The *AVCEM* model
- Sample results
- Focus on battery cost and performance
- Research agenda
- Summary (accomplishments)

Overview

- Timeline
  - March 2015 through December 2019 (might extend)
- Budget
  - ~ $593,000 total allocated so far
  - ~ $437,000 DOE share
  - $0 FY18-19
  - Need ~$240,000 to complete project
- Technical Targets
  - Estimating total social cost of advanced vehicle technologies
- Partners
  - UC Davis
  - Informal discussions with ANL, NREL
  - Formal work with Technical University of Munich

AVCEM

The Advanced-Vehicle Cost and Energy-Use Model

A detailed, integrated model of vehicle design, energy use, manufacturing cost, lifetime operating cost, and lifecycle external and oil-use costs, for H2 and methanol fuel cell vehicles, pure battery EVs, hybrid EVs, and alternative fuel ICEVs.

Overview of *AVCEM*

- Estimates lifetime consumer and social cost of advanced vehicles.
- Lifetime social cost = consumer cost + other social costs.
- Consumer costs:
  - All initial vehicle costs, amortized over the life of the vehicle.
  - The present value of all component replacement costs, amortized over the life of the vehicle.
  - Periodic maintenance and repair costs.
  - Fuel costs.
  - Insurance costs.
- Other social costs:
  - External costs -- air pollution, climate change, noise, oil use (lifecycle).
  - Adjustments for non-costs transfers (taxes and fees, producer surplus).

Closer view of *AVCEM*

- Only fully integrated and detailed publicly-available model of vehicle design, energy use, manufacturing cost, overhead costs, operating costs, external costs, and other non-market costs (?).
- Includes detailed sub-models of performance, cost and lifetime for fuel-cells, batteries, and hydrogen storage systems and stations.
- Realistic, conceptually correct treatment of financial parameters, with attention to difference between social and individual perspectives.
- Allows detailed analysis of wide range of factors relevant to consumers and to society, in a comprehensive, internally consistent framework.
- Detailed representation of the full range of relevant parameters allows testing of specific research uncertainties, and comparisons with other studies.
- Can determine the lifetime cost impact of key design assumptions such as hybridization of fuel cell with battery, range, performance, use of air conditioning, drive cycle assumptions, and so on.
- Complete documentation being developed.

Relevance

Relevant to any transportation energy policy where cost matters.

Conceptual framework

Consider three perspectives on cost: social, business, personal

A. Applications, methods, analytical boundaries

Perspective -->	*Social*	*Business*	*Personal*
Applications	Evaluating transportation projects, policies, and scenarios; affecting prices of transportation goods and services; prioritizing transportation research and funding	Evaluating actual expenditures in commercial and government fleets	Modeling consumer behavior
Estimation methods	Social cost-benefit or welfare analysis; damage-function analysis	Financial accounting	Econometric analysis; surveys
Boundary of analysis	Large-scale social, economic, and environmental systems	Firm or industry; take markets as given	Whatever matters to people in this context

B. Cost elements and parameters that vary by vehicle or powertrain

Perspective --> **Cost element or parameter ↓**	***Social***	***Business***	***Personal***
Vehicle cost	Included	Viewed together as full vehicle retail price (cost+profit+taxes), and considered jointly with vehicle loan payments	
Automaker profit	Not included, because producer surplus is an intra-society transfer from consumers to producers		
Vehicle sales tax	Not included, because taxes are an intra-society transfer from consumers to government		
Vehicle loan payments	Includes only the cost of administering the loan; principal is part of "vehicle cost;" loan interest is a transfer from consumers to lenders (social discount rate is used instead)	An ordinary periodic cost to be discounted by the relevant discount rate	Considered informally, rather than in a full, explicit financial accounting?
Vehicle resale value	Includes only the actual (very small) transaction costs; the rest is a transfer between consumers	Same as social perspective ?	Considered, but only informally?
Period of first ownership	Relevant only via its effect on the timing of the resale transaction cost (trivial impact)		Considered informally in regards to effect on vehicle resale value?
Vehicle lifetime	Lifetime to scrappage		

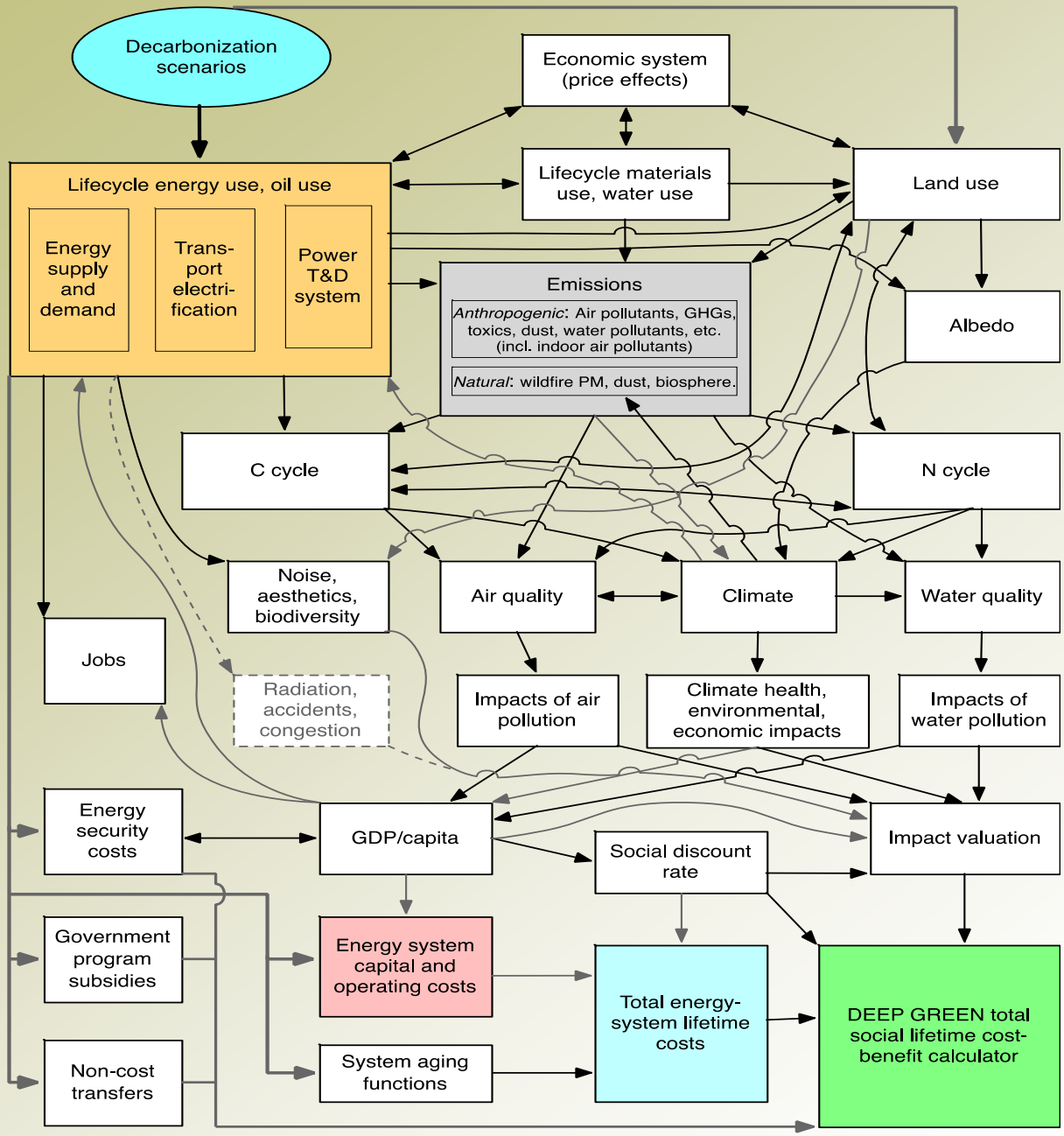
B. Cost elements and parameters that vary by vehicle or powertrain, cont.

Perspective --> Cost element ↓	*Social*	*Business*	*Personal*
Battery replacement	Included formally		Considered informally
Vehicle efficiency			
Energy cost	Included	Included formally based on full energy prices (cost+profit+taxes)	Considered informally, based on full energy prices (cost+profit+taxes), in conjunction with vehicle efficiency
Energy firm profit	Not included, because producer surplus is an intra-society transfer from consumers to producers		
Energy taxes	Not included, because taxes are an intra-society transfer from consumers and producers to government		
Corporate income taxes	Not included, because taxes are an intra-society transfer from producers to government	Included formally based on actual prices	Considered informally, based on actual prices
Insurance	Includes only actual cost; excludes industry true profit (producer surplus) in premiums	Included based on actual premiums paid	Perhaps considered informally
Maintenance and repair	Included; must avoid double-counting repair costs covered by warranties and insurance premiums; costs must be consistent with vehicle usage and lifetime; costs for EVs will decrease with scale and learning		
Engine oil	Included		Probably not explicitly considered in purchase or use decisions
Inspection fees			
Replacement tires			
External costs	Included	Not included	

C. Cost elements and parameters that do not vary (much) by vehicle or powertrain

Perspective --> **Cost element or parameter ↓**	**Social**	**Business**	**Personal**
Parking	Included		Probably not explicitly considered in purchase or use decisions
Accessories			
Tolls and fines	Not included, because they are a transfer from consumers to government.	Included	
Registration fees			
Annual VMT, base-line travel benefits*	Included		Perhaps considered informally
Inflation, cost escalation			
Discount rate	Social discount rate; mainly the opportunity cost of foregone productivity growth	Interest foregone on short-to-medium term, relatively safe savings and investments	Implicit discounting of the future due to risk aversion, uncertainty, and limited time to fully enjoy benefits of transportation
Motor-vehicle infrastructure and public services	Not included, because they do not vary by vehicle technology; they would be included in a cost-benefit analysis comparing motor-vehicles with other transport modes, such as trains		

BOUNDARY OF ANALYSIS: WITHIN *DEEP GREEN* MODELING SYSTEM

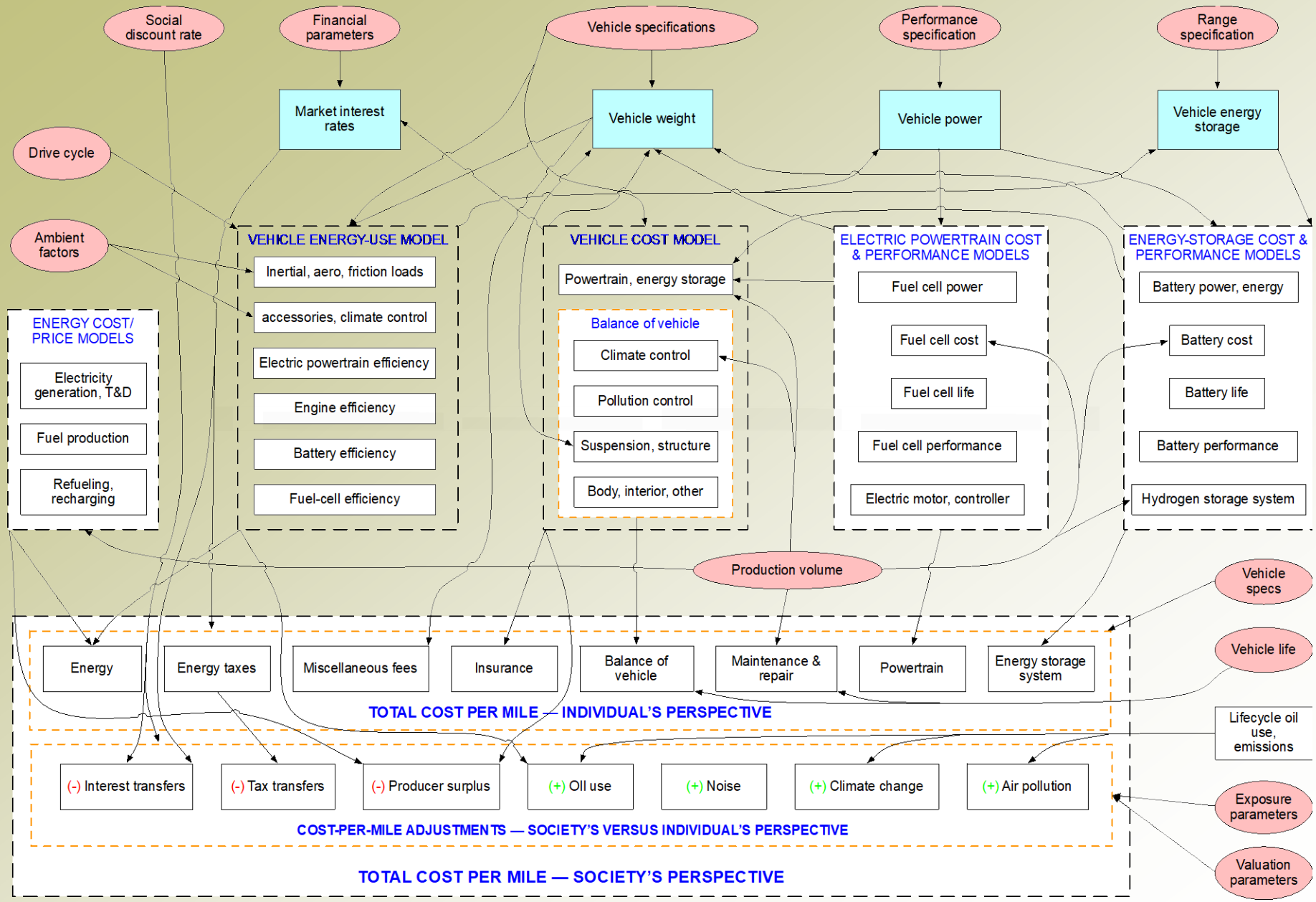


Fuel/feedstock/vehicle combinations in *AVCEM*

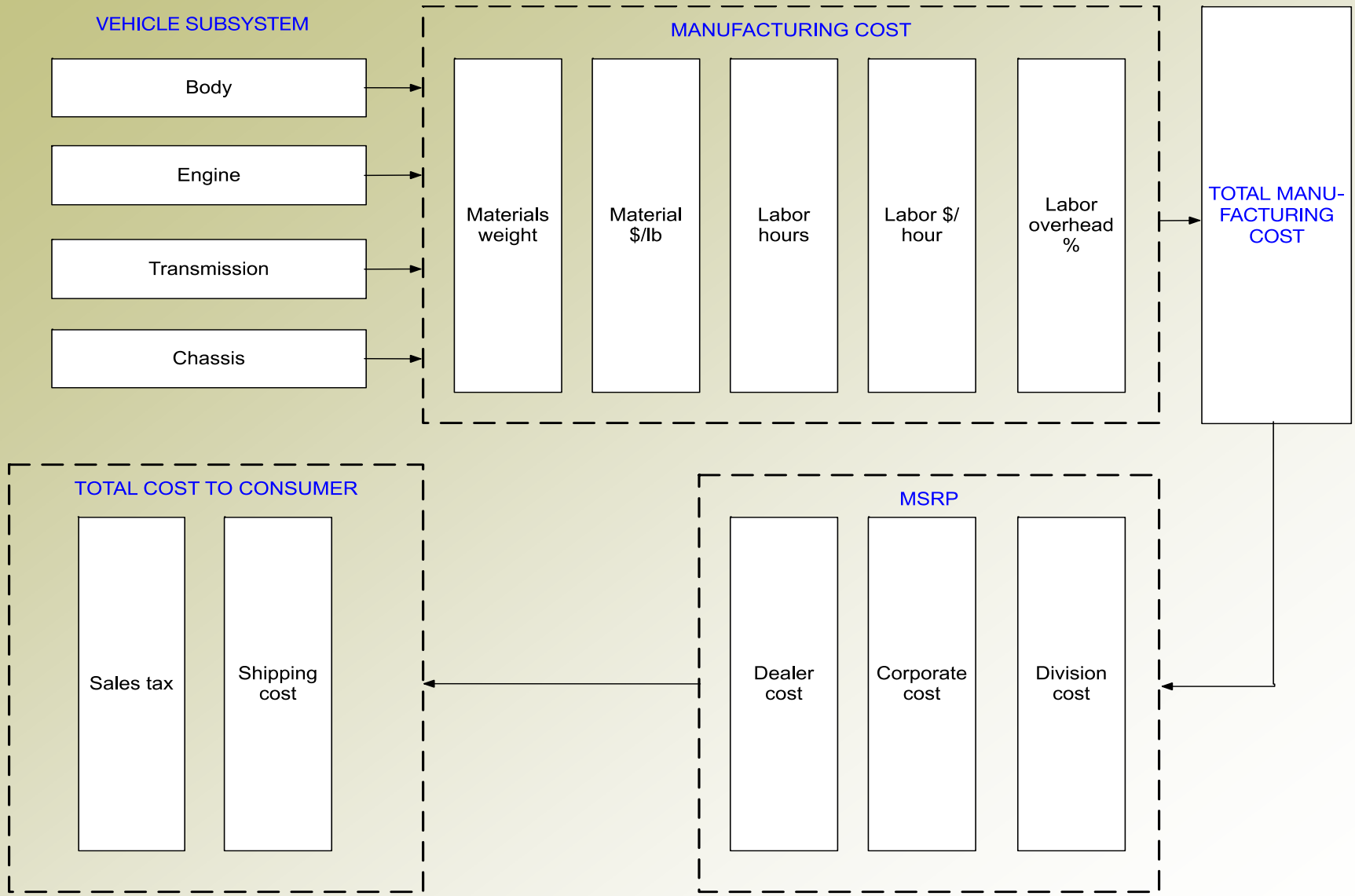
Fuel –> ↓ Feedstock	*Gasoline*	*Methanol*	*Ethanol*	*Methane (CNG, LNG)*	*Propane (LPG)*	*Hydrogen (compressed)*	*Hydrogen (liquefied)*	*Hydrogen (hydride)*	*Elec-tricity*
Petroleum	**ICEV HEV**				**ICEV**				
Coal		**ICEV FCEV**				**ICEV FCEV**	**ICEV**	**ICEV**	
Natural gas		**ICEV FCEV**		**ICEV**		**ICEV FCEV**	**ICEV**	**ICEV**	
Wood, grass		**ICEV FCEV**	**ICEV**			**ICEV FCEV**	**ICEV**	**ICEV**	
Corn			**ICEV**						
Power generation						**ICEV FCEV**	**ICEV**	**ICEV**	**BPEV**

ICEV = internal combustion engine; HEV = hybrid electric vehicle; FCEV = fuel-cell electric vehicle; BPEV = battery-powered electric vehicle. All FCEVs can be hybridized with a peak-power battery.

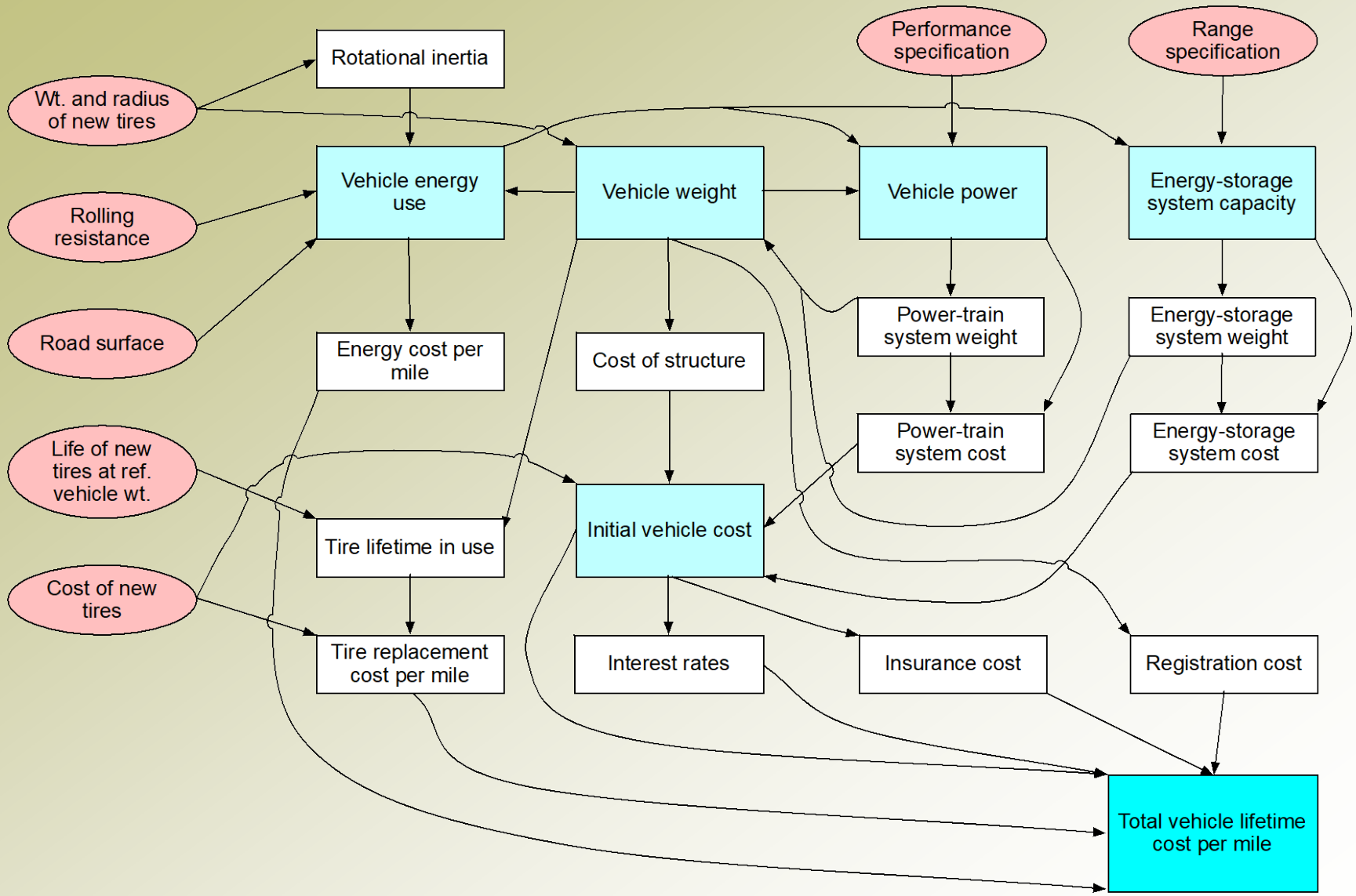
Structure of *AVCEM*



AVCEM: Consumer cost of vehicles



Example of calculation logic in *AVCEM*



Quantitative comparison: social lifetime cost, 2020

Compact car, Li-ion battery, FUDS cycle (present value of costs)

Gasoline	Ethanol	BPEV-120	HEV-35	H2-300	COST ITEM
0	0	0	0	0	Blank -- not used
0	0	2,094	2	0	Purchased electricity (accounts for regenerative braking from fuel cell, power to heat battery, mai
0	0	951	0	0	Space heating fuel for EVs
0	0	18,369	19,373	613	Battery and tray and auxiliaries (Li-ion)
0	0	192	0	0	Off board battery-charging wiring and equipment
0	0	0	0	4,159	Fuel-cell stack and auxiliaries
0	0	0	0	0	On-board fuel reformer
20,854	20,704	17,576	19,023	16,890	Vehicle, excluding battery, fuel cell, and hydrogen storage
13,103	13,314	0	10,658	14,318	Motor fuel, excluding excise taxes and electricity*
see "vehicle"	62	0	0	2,660	Fuel-storage system
11,204	10,952	13,222	12,199	12,552	Insurance (calculated as a function of VMT and vehicle value)
14,527	14,527	10,755	15,232	11,929	Maintenance and repair, excluding oil, inspection, cleaning, towing, but including time costs
259	259	0	178	0	Engine oil
669	668	615	629	422	Replacement tires (calculated as a function of VMT and vehicle weight)
2,862	2,862	2,862	2,862	2,862	Parking, tolls, and fines (assumed to be the same for all vehicles)
1,248	1,241	0	1,470	1,149	Registration fee (calculated as a function of vehicle weight)
1,717	1,717	605	1,816	605	Vehicle safety and emissions inspection fee
2,867	2,867	2,867	2,867	2,867	Federal, state, and local fuel (energy) excise taxes
971	971	971	971	971	Accessories (assumed to be the same for all vehicles)
70,282	70,144	71,079	87,281	71,996	Total private (consumer) lifetime cost
1,806	1,498	0	603	0	Dollar value of air pollution external costs (lifecycle of fuels and vehicles) (best estimates)
0	0	0	0	0	Blank
619	619	464	489	441	Dollar value of noise external costs (best estimates)
19	1	0	15	0	Dollar value of oil use external costs (best estimates)
19,389	11,827	0	3,411	0	Dollar value of climate change external costs (lifecycle of fuels and vehicles) (best estimates)
-2,867	-2,867	-2,867	-2,867	-2,867	Taxes and fees that are transfers, not resource costs
-4,914	-679	-548	-3,997	-730	Producer surplus on fuel (wealth transfer in excess of resource cost)
-928	-919	-1,435	-1,481	-1,069	Producer surplus (qua "true corporate profit) on vehicle price
83,405	79,624	66,692	83,454	67,772	Total social lifetime cost
n.a.	2.86	3.03	5.96	3.20	Breakeven gasoline price, private-cost basis ($/gal)^
n.a.	2.20	-0.13	2.90	0.06	Breakeven gasoline price, social-cost basis ($/gal)^

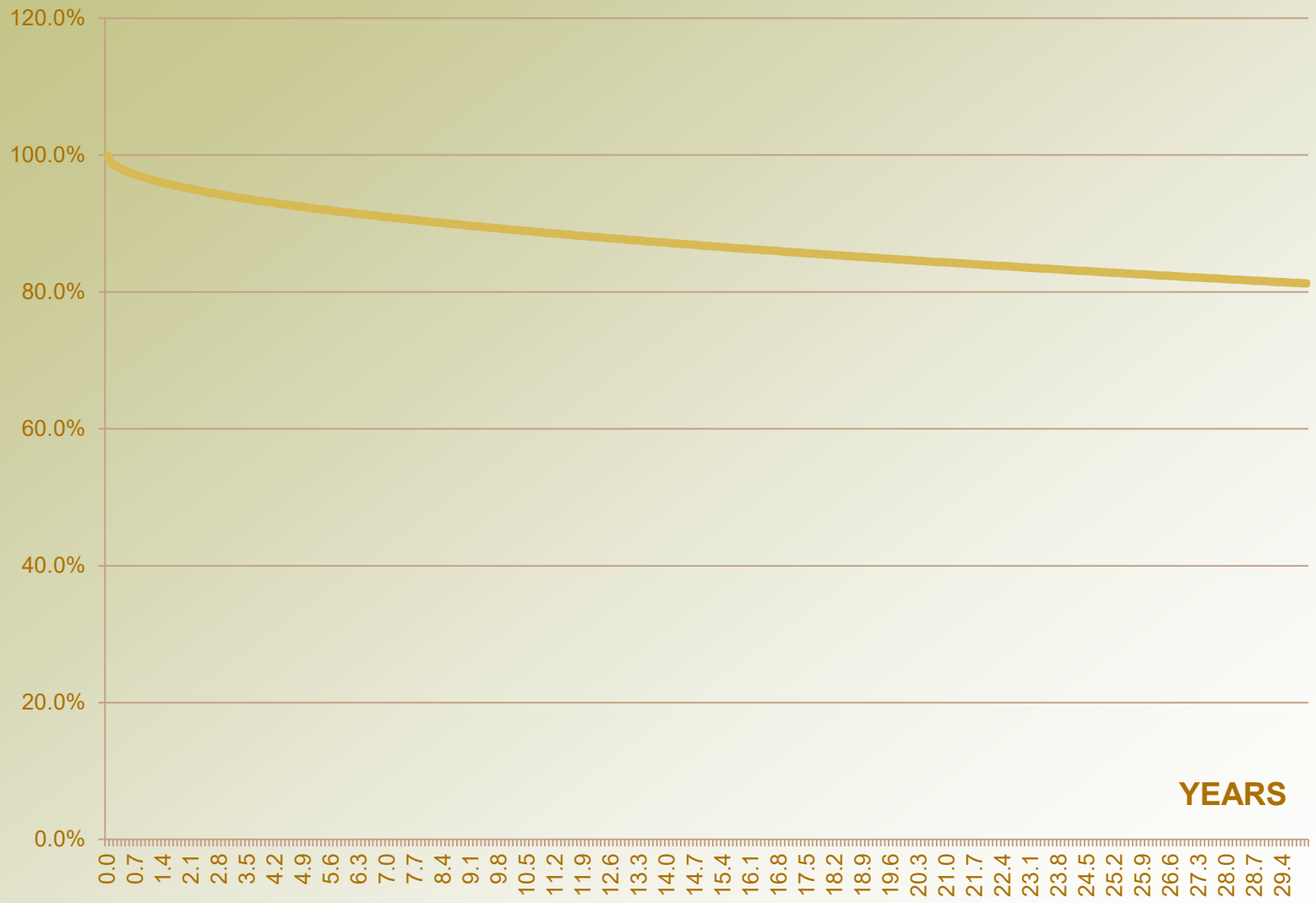
Source: Advanced Vehicle Cost and Energy-Use Model (AVCEM).

FOCUS: ANALYSIS OF BATTERY PERFORMANCE, COST, AND LIFETIME

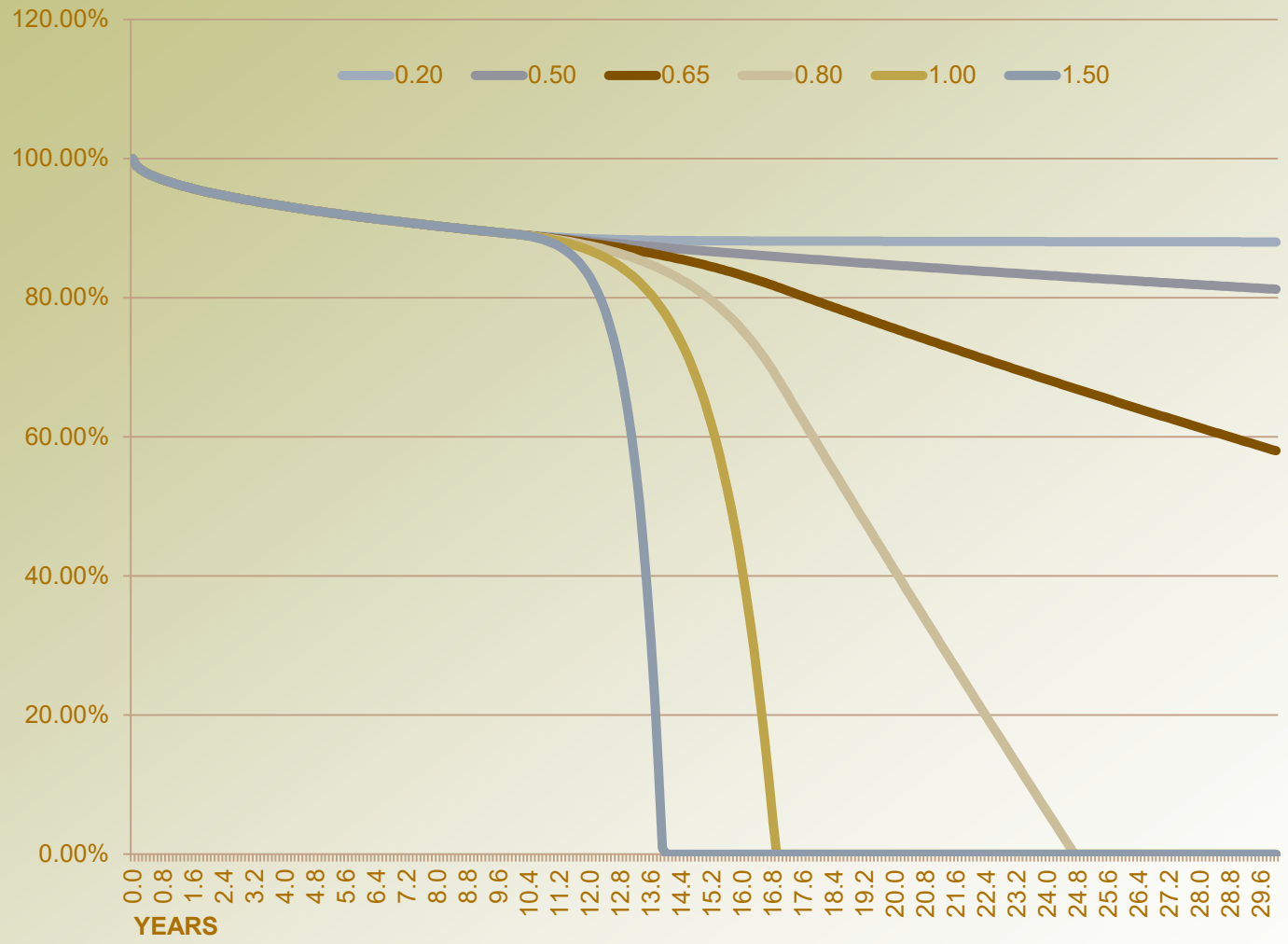
Li-ion chemistry anode/cathode	Performance model	Manufacturing cost model	Lifetime model
graphite/nickel-cobalt-aluminum (NCA)	UCD-EVPSL (tests of Gaia cell) and other data	Reduced form version of ANL BatPaC model	Revision and expansion of NREL lifetime model w/TUM
graphite/iron-phosphate (FP)	UCD-EVPSL (tests of A123 cell) and other data	Reduced form version of ANL BatPaC model	Simple extension of revised NREL model w/TUM test results
titanate/ manganese-oxide (MO)	UCD-EVPSL (tests of Altairnano cell)* and other data	Reduced form version of ANL BatPaC model	
graphite/ manganese-oxide (MO)	Based on NCA battery	Not included in present analysis (available in BatPaC however)	Simple extension of revised NREL model w/TUM test results
graphite/nickel-manganese-cobalt (NMC)	Based on NCA battery	Reduced form version of ANL BatPaC model	Simple extension of revised NREL model

* Cathode chemistry from Heinzmann (2010). UCD-EVPSL = University of California, Davis, Electric Vehicle Propulsion Systems Laboratory; ANL = Argonne National Laboratory; NREL = National Renewable Energy Laboratory; TUM = Technical University of Munich.

AVCEM BATTERY LIFETIME: CAPACITY VS. TIME, NO CYCLING, ORIGINAL NREL MODEL



AVCEM MODIFICATION TO NREL BATTERY LIFETIME:
Capacity vs. time, different post-cutoff values of Z



Collaborative work

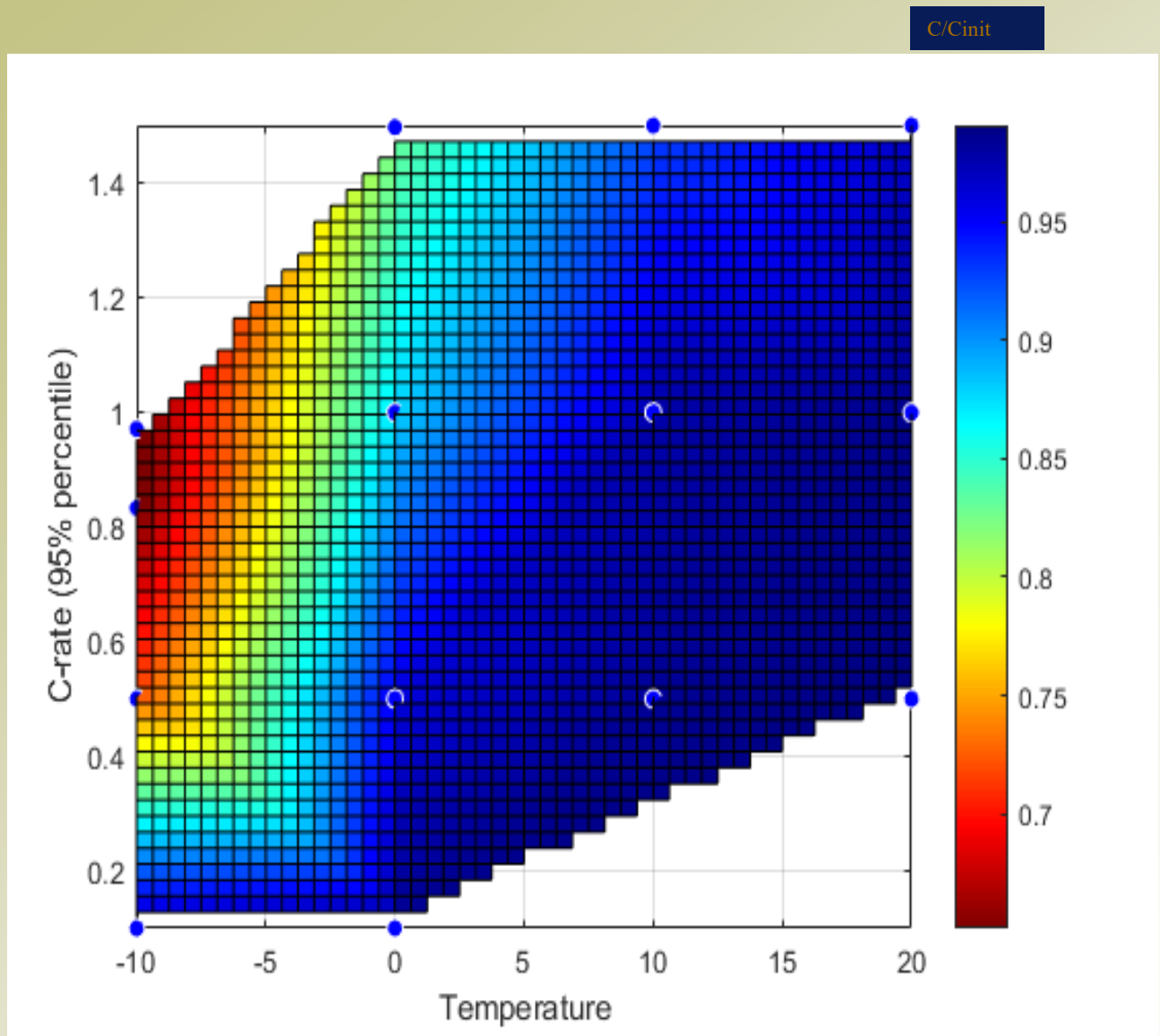
AVCEM/TUM battery testing: Capacity fade induced by lithium plating

Michael Baumann
Technical University of Munich

Visiting scholar
Transportation Sustainability Research Center
UC Berkeley
(M.A. Delucchi host)

November 2017- March 2018

Experimental results (2)



- Capacity fade for different temperatures and C-rates.
- The chart also indicates the maximal reachable Crates at the shown temperatures.

Research agenda for AVCEM

- Task 1. Conceptual framework
- Task 2. Scope of the analysis
- Task 3. Comprehensive, detailed literature review
- Task 4. Analysis of discounting
- Task 5. Update analysis of financial parameters
- Task 6. Update analysis of variable manufacturing cost
- Task 7. Further analysis of retail cost vs. manufacturing cost
- Task 8. New battery cost model
- Task 9. New battery lifetime model
- Task 10. New fuel-cell cost, performance, and lifetime model

Note: Future work subject to change based on funding levels

Research agenda for AVCEM, cont.

- Task 11. Revise energy use of internal-combustion engines (ICEs)
- Task 12. Validate EV energy-use model
- Task 13. Finish external costs of air-pollution and climate change
- Task 14. Revise external costs of oil use
- Task 15. Costs and benefits of vehicle-to-grid (V2G)
- Task 16. Update renewable-hydrogen refueling-station cost
- Task 17. Update other parameters (alternative-fuel vehicles, insurance, maintenance and repair, etc.)
- Task 18. Analyze consumer and social lifetime cost
- Task 19. Develop user-friendly model interface

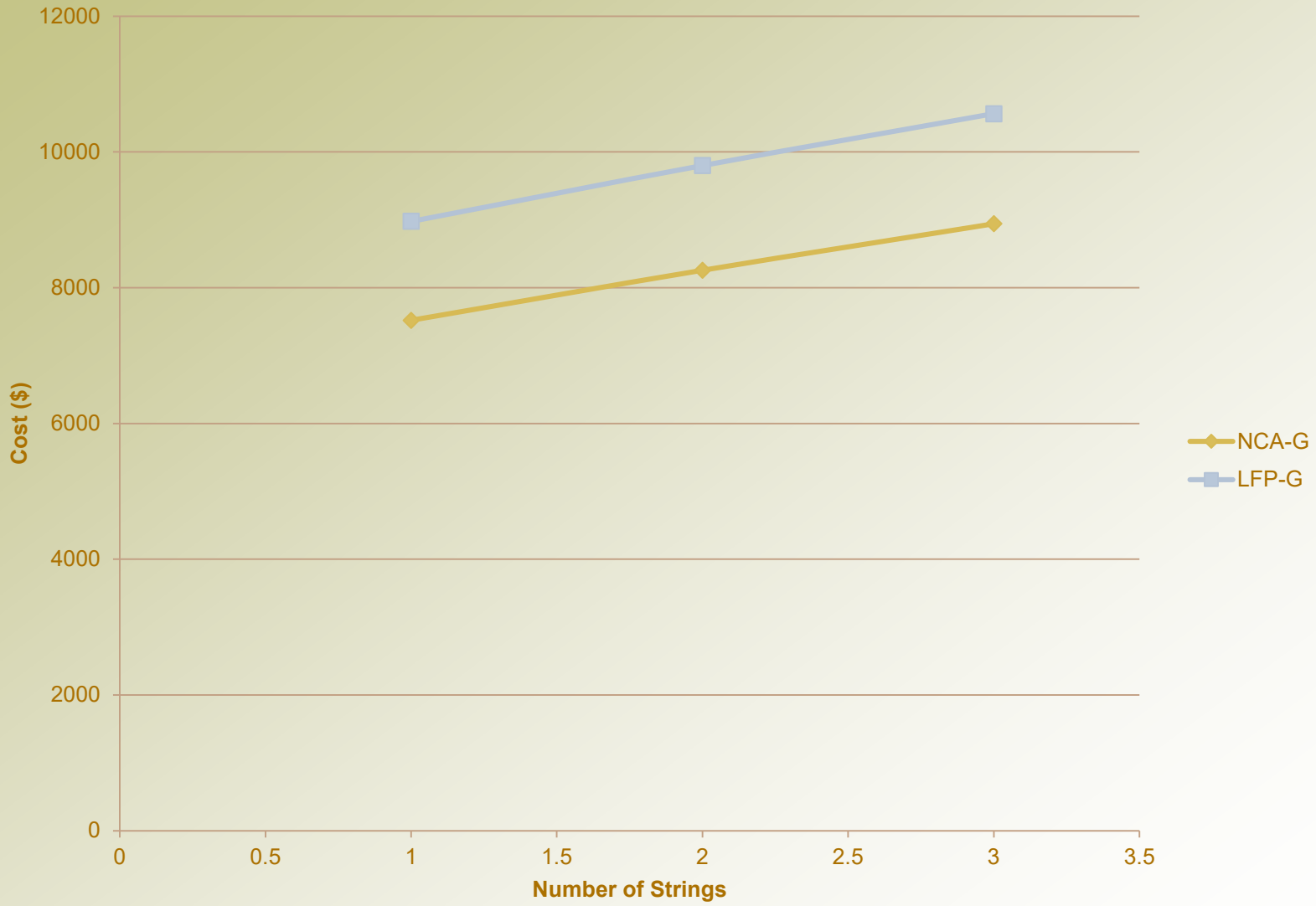
AVCEM FY18 Accomplishments, Next Steps

Task	Expected products	Highlights and status; next steps
1. Conceptual framework	• Part of documentation and journal articles.	Draft completed (summary presented here).
2. Scope of analysis	• Part of documentation and journal articles.	Begun to formulate how *AVCEM* fits into a more comprehensive energy-economic-environmental modeling system such as DEEP GREEN.
3. Literature review	• Model documentation. • Journal article.	Completed detailed review of over 100 articles through 2010. Next steps are to review articles after 2010.
4. Discounting analysis	• Model documentation. • Journal article.	Finalized the conceptual framework and formal analysis of the discount rate. Continued writing paper and AVCEM documentation report.
5. Financial parameters	• Model documentation.	Revised methods of analysis and updated financial parameters to most recent (ca. 2018) data.
6. Manufacturing cost	• Part of documentation and journal articles.	Updated some parameters related to wages and materials costs.
7. Retail vs. Manufacturing Cost	• Model documentation. • Journal article.	Organized materials for paper and AVCEM documentation report. Next steps are to continue documentation and collaborate with ANL.
8. Battery Cost	• Incorporation into AVCEM and documentation.	With UC Davis, performed validation of reduced-form of ANL BatPac model. Collaborated with German colleagues who are developing a similar cost model. Continued writing paper and AVCEM documentation report.
9. Battery Lifetime	• Model documentation. • Journal article.	Battery testing lab in Germany completed aging tests. We began devising new functional forms to fit the new battery test data. Next steps are to continue to review and revise the battery lifetime model and paper and draft report.

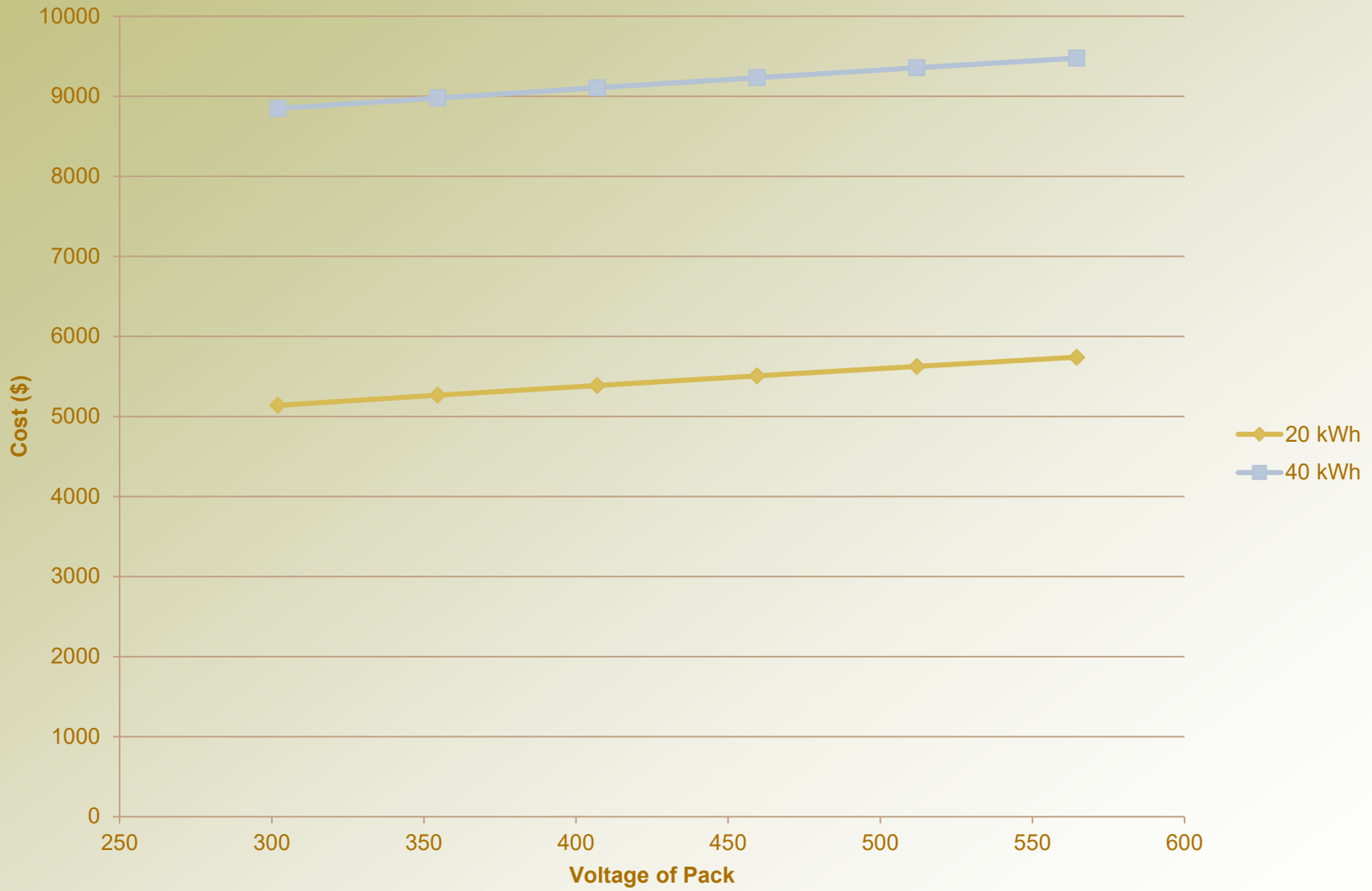
Task	Expected products	Highlights and status; next steps
10. Fuel cell cost and lifetime	• Model documentation. • Journal article.	Completed beta stand-alone version of new integrated model of fuel-cell performance, cost, and lifetime. Next steps are to finalize and integrate into *AVCEM*.
11. Energy use of ICEs	• Part of documentation and journal articles.	Developed new functional form predicting energy use of ICEs as a function of readily available engine parameters; fit function to data. Next step is to improve fit to data.
12. Energy use of EVs	• Part of documentation and journal articles.	Took second-by-second data from test vehicle at UC Davis. Next step is to download ANLs comprehensive EV energy-use data.
13. External-cost of pollution and climate change	• Model documentation. • Journal article.	Updated analysis of air-pollution damages and valuation functions. Finished organizing materials for AVCEM documentation report.
14. External costs of oil use	• Model documentation. • Journal article.	Completed analysis of producer surplus associated with global oil production. Developed framework for estimating OPEC pricing behaviour. Next steps are to develop estimates of costs and incorporate into AVCEM.
15. CBA of V2G	• Incorporation into AVCEM and documentation.	Analyzed costs of electricity generation, transmission, and distribution system for use in grid models with AVCEM.
16. Renewable H2 station	• Incorporation into AVCEM and documentation.	Expanded and updated analysis of hydrogen refueling stations.
17. Update other parameters	• Incorporation into AVCEM and documentation.	Updated some parameters related to insurance and maintenance and repair.
18. Estimate social cost	• Model documentation • Journal article	To be done after model is completed.
19. Develop user-friendly interface	• Publicly available, user-friendly version of AVCEM	To be done after model is completed.
20. Documentation and articles	• See above	• See above

TECHNICAL BACK-UP SLIDES

AVCEM version of BatPaC: Cost vs. number of strings



AVCEM VERSION OF BATPAC: LFP-G COST VS. PACK VOLTAGE

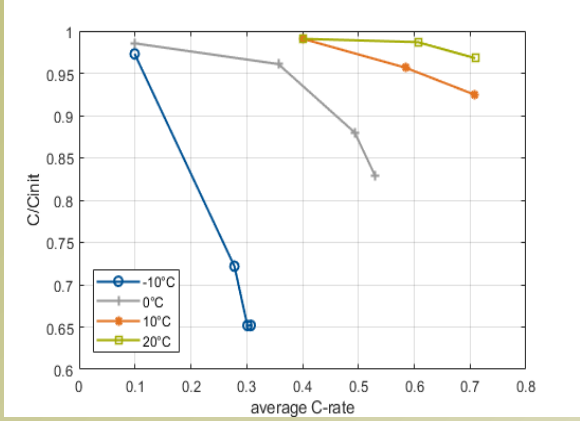


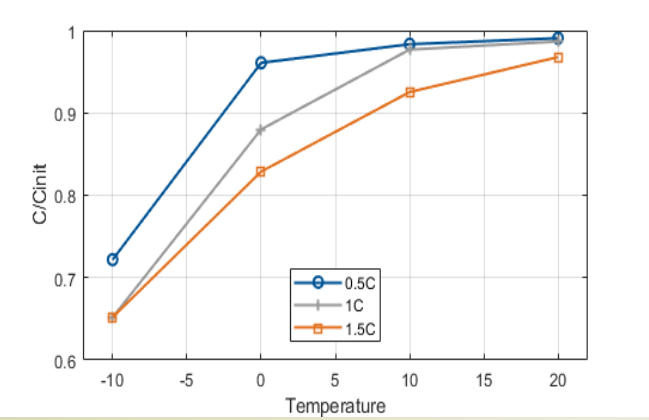
TUM battery test matrix

Temperature **-20 to 0°C**			Crate			
Vmin	Vmax	DOD/EndSOC	0,1C	0,5C	1C	1,5C
2,5V	4,12V *******	90/90	*			
		60/60	**	5	12	15
		30/30	**	6	13	16
3,33V	4,12	90/95	1	7	14	17
3,59V		60/95	2	8	*****	18
3,84V		30/95	**	9	***	***
2,50V	4,07	90/90	3	10	*****	19
3,57V		60/90	****			
3,79V		30/90				
2,50V	4,02	85/85	4	11	*****	20
3,57V		60/85	****			
3,79V		30/85				
3,37V	4,2	90/100	******			
3,62V		60/100				
3,88V		30/100				

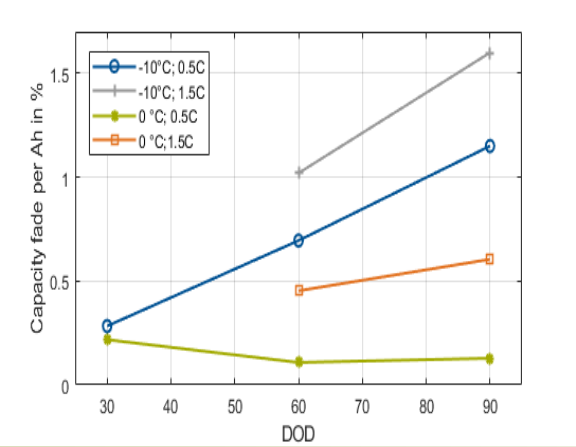
* (1)	Covered with 7-10 (not exactly, but only a 5% SOC offset)
** (2)	No capacity fade at screening tests
*** (3)	Would result in an immediate CV-Phase
**** (4)	Reduced due to limited channels
***** (5)	Limited channel count, therefore 3 out of 4 currents had to be picked. 1C screening tests were similar to 1.5C
****** (6)	No 4.2V, because capacity fade was similar for all screening tests between 4.1-4.2V
****** (7)	Voltage Limit for CV-Phase. Cut-off criteria will be the Ah-Throughput for the desired DOD

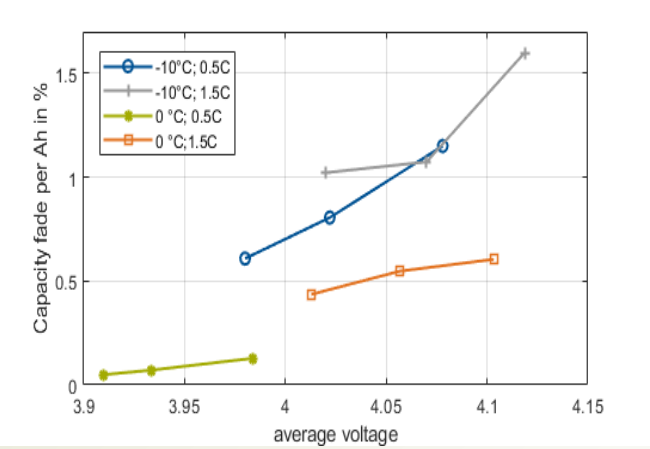
TUM battery testing: experimental results (1)





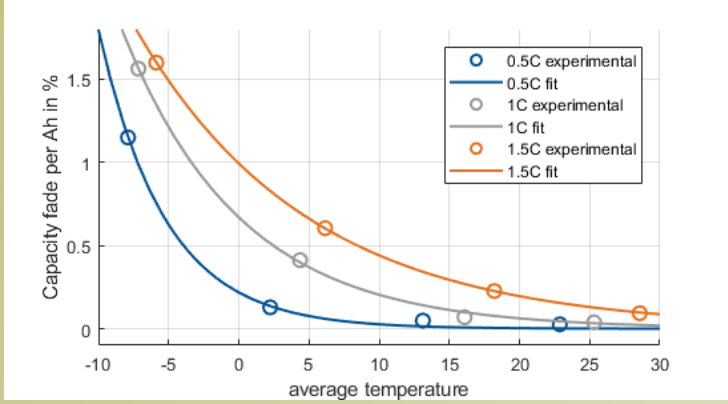
Capacity fade for a variation of the impact factors „average C-rate“ and „Temperature“

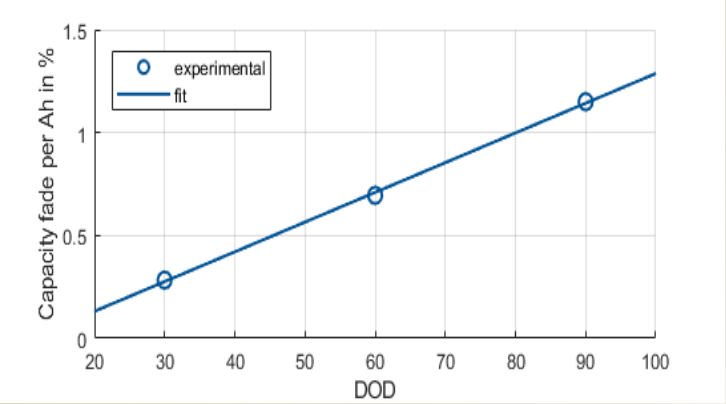


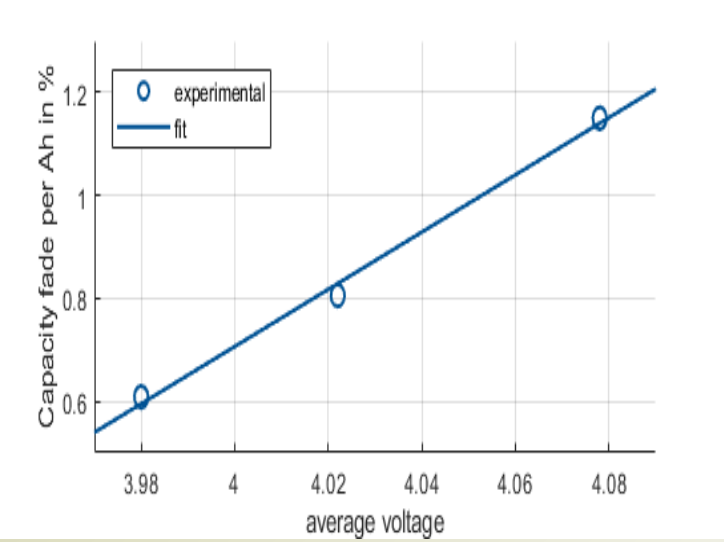


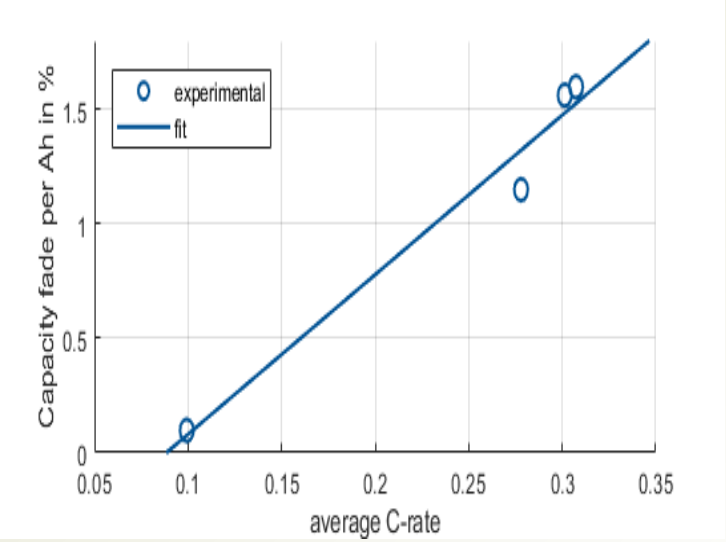
Capacity fade per Ah for a variation of the impact factors „DOD“ and „average voltage“

Empirical Modelling









- Fit of capacity fade per Ah for different impact factors.
- Exponential fit: Temperature
- Linear fit: DOD, average voltage, average Crate