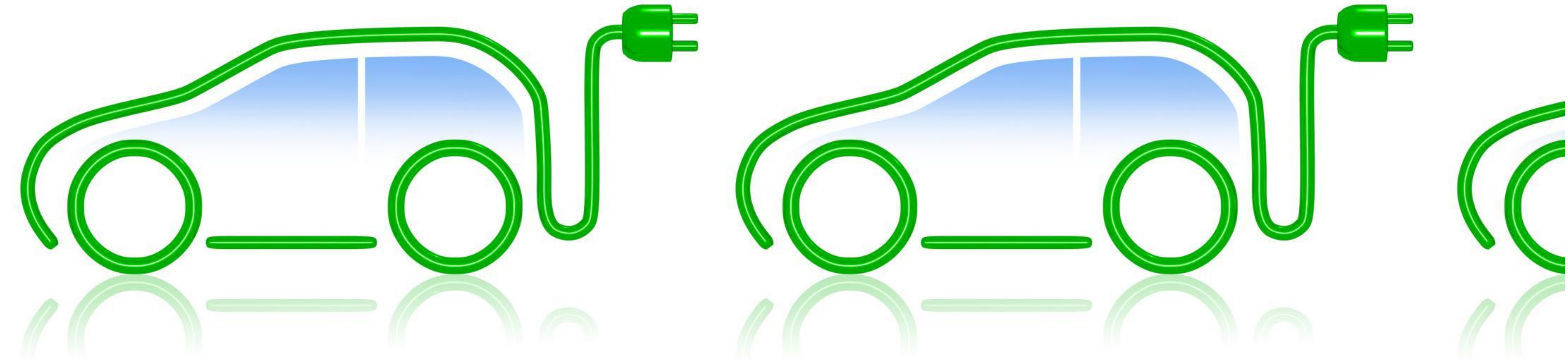
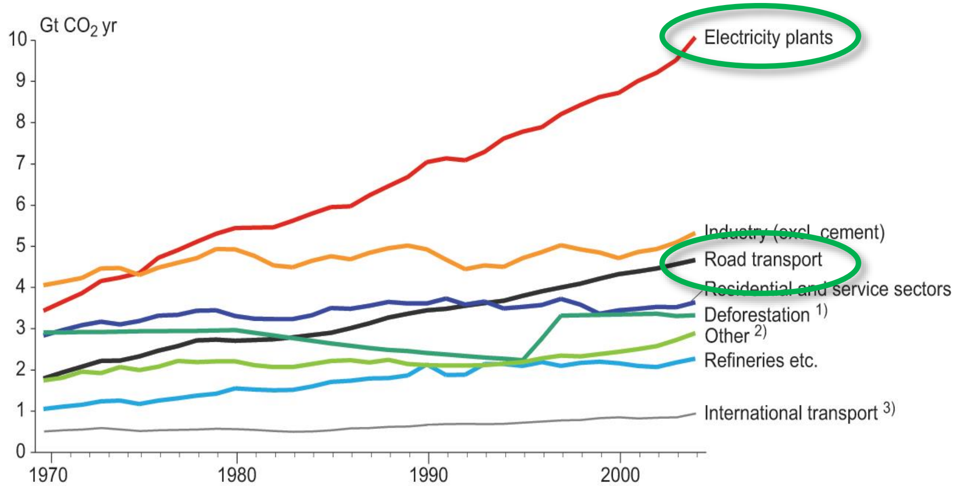


Impact of vehicle-to-grid and second-life application selection on environmental impact of electric vehicle batteries considering degradation

Varun Duggal, Martin Beuse, Prof. Tobias S. Schmidt

Battery technology presents a solution for key sectors in the attempt to mitigate climate change

Sources of global CO_2 emissions



Source: Contribution of Working Group III to the Fourth Assessment Report of the IPCC, 2007
1) Including fuelwood at 10% net contribution.
2) Other domestic surface transport, non-energetic use of fuels, cement production and venting/flaring of gas from oil production.
3) Including aviation and marine transport.

Three key roles for batteries in mitigating climate change

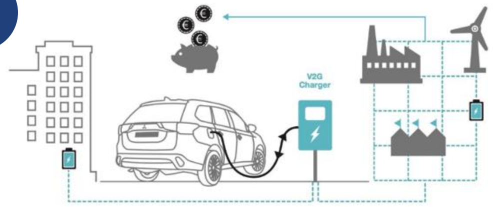
1

Enabling higher shares of intermittent renewable energy sources

2

Electrifying and thereby decarbonizing road transport (electric vehicles, EVs)

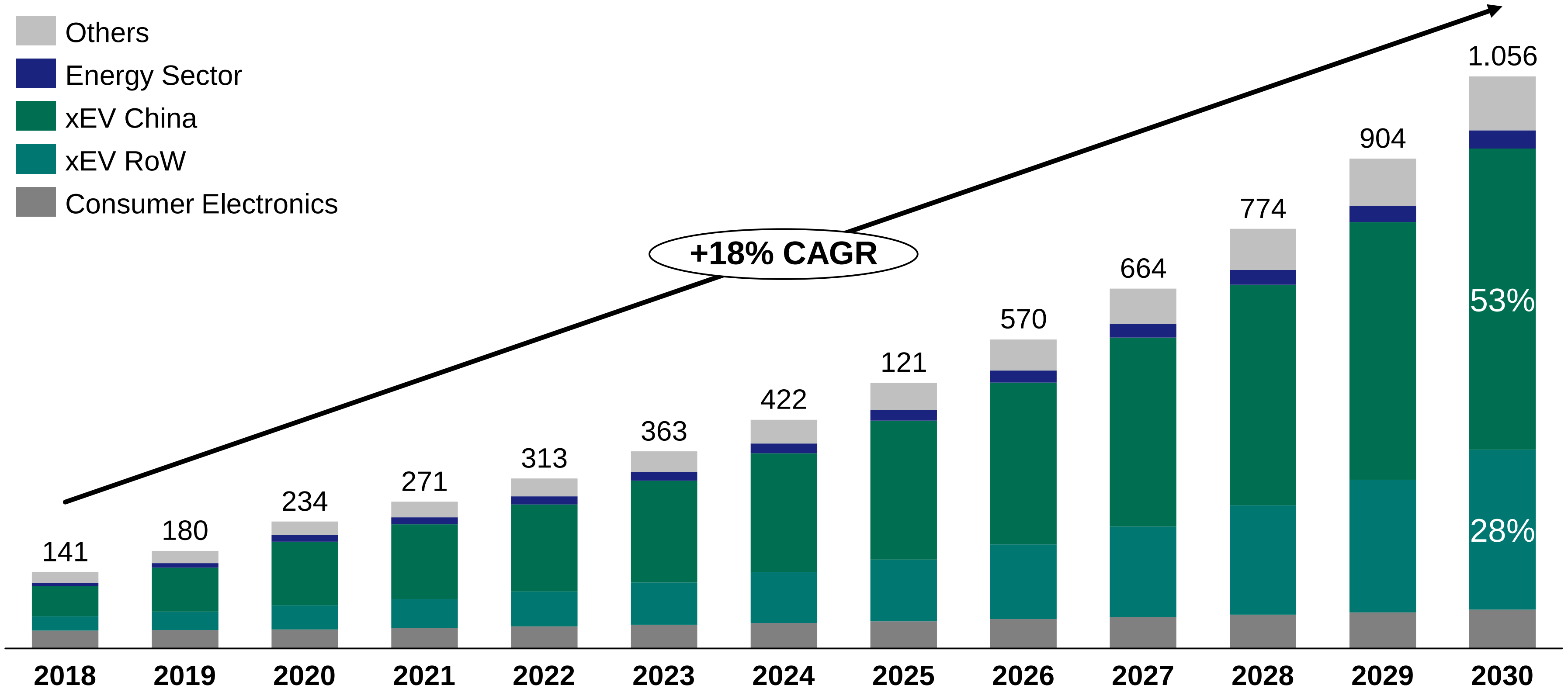
3



Connecting electricity, transport and other end-use sectors, increasing efficiency (e.g., Vehicle-to-Grid, V2G & second-life applications, 2^{nd}-life)

Already in 2019, EVs added more GW p.a., than is available from all Pumped-hydro plants combined globally

Lithium-ion battery capacity additions by application (GWh p.a.) – conservative forecast



Considerations

- Currently installed global **Pumped-hydro storage capacity** <180 GW, **but around 9.000 GWh**
- **Useable capacity** for vehicle-to-grid and second-life applications
- **Regulatory regimes** needed accelerate deployment of V2G

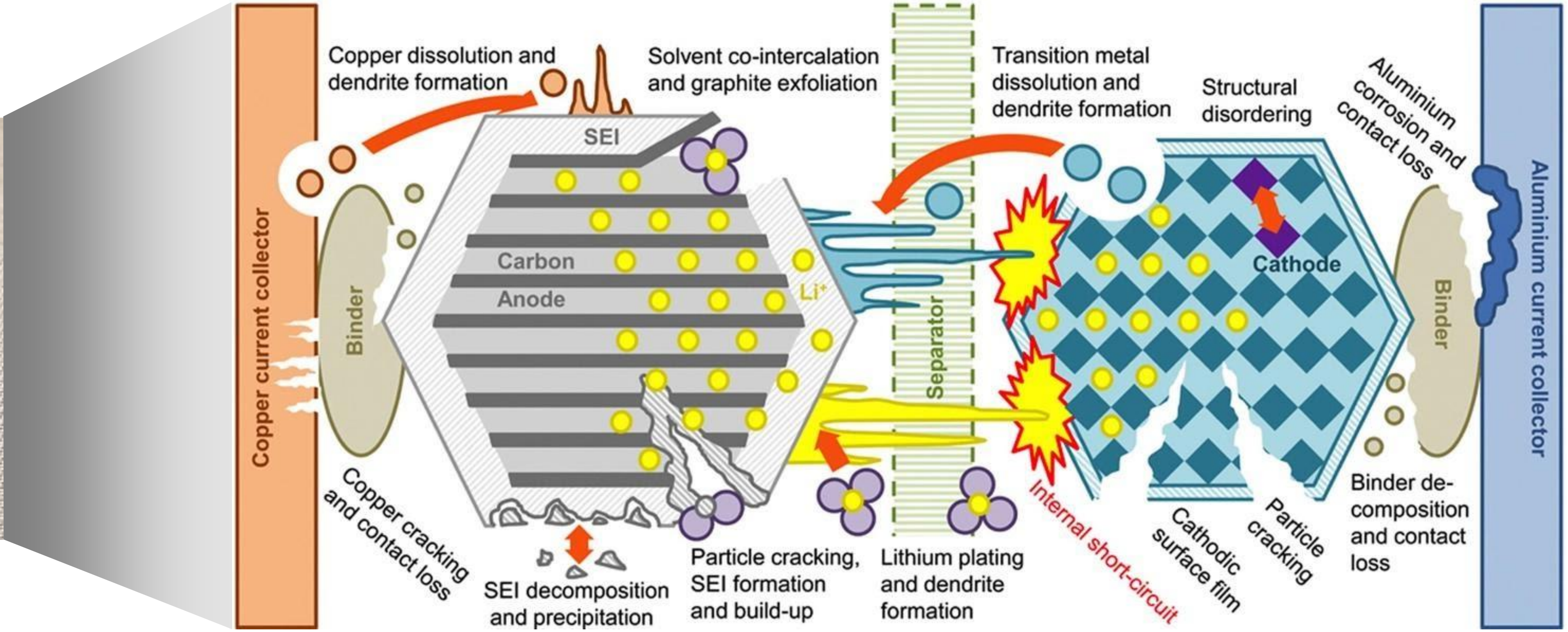
Source: Pillot, C: The rechargeable battery market and main trends 2016-2025, (2018)

Vehicle-to-grid and second-life: Huge potential, but what can be realized?

	What it means	Potential benefits	Considerations
V2G	▪ Provision of services to the electricity system ▪ Charging, and/or discharging electricity from electric vehicle batteries ▪ Using battery's idle time	▪ Higher **utilization** of already existing asset, integrate RETs ▪ **Additional revenues** from service provision, increase EV diffusion ▪ Batteries' manufacturing **CO2 footprint** distributed over increased utility	1 **Additional degradation** from additional use of battery 2 **Throughput over battery lifetime** depending on battery use 3 Battery use: many **different applications** possible for V2G and 2^{nd}-life with different impact on degradation
2^{nd}-life	▪ Provision of services to the electricity system ▪ Repurposing EV batteries into stationary system	▪ Using battery after it does not fulfill performance/ customer criteria for use in EV ▪ Potentially **low-cost storage** capacity (depending on cost for repurposing), enabling RETs	

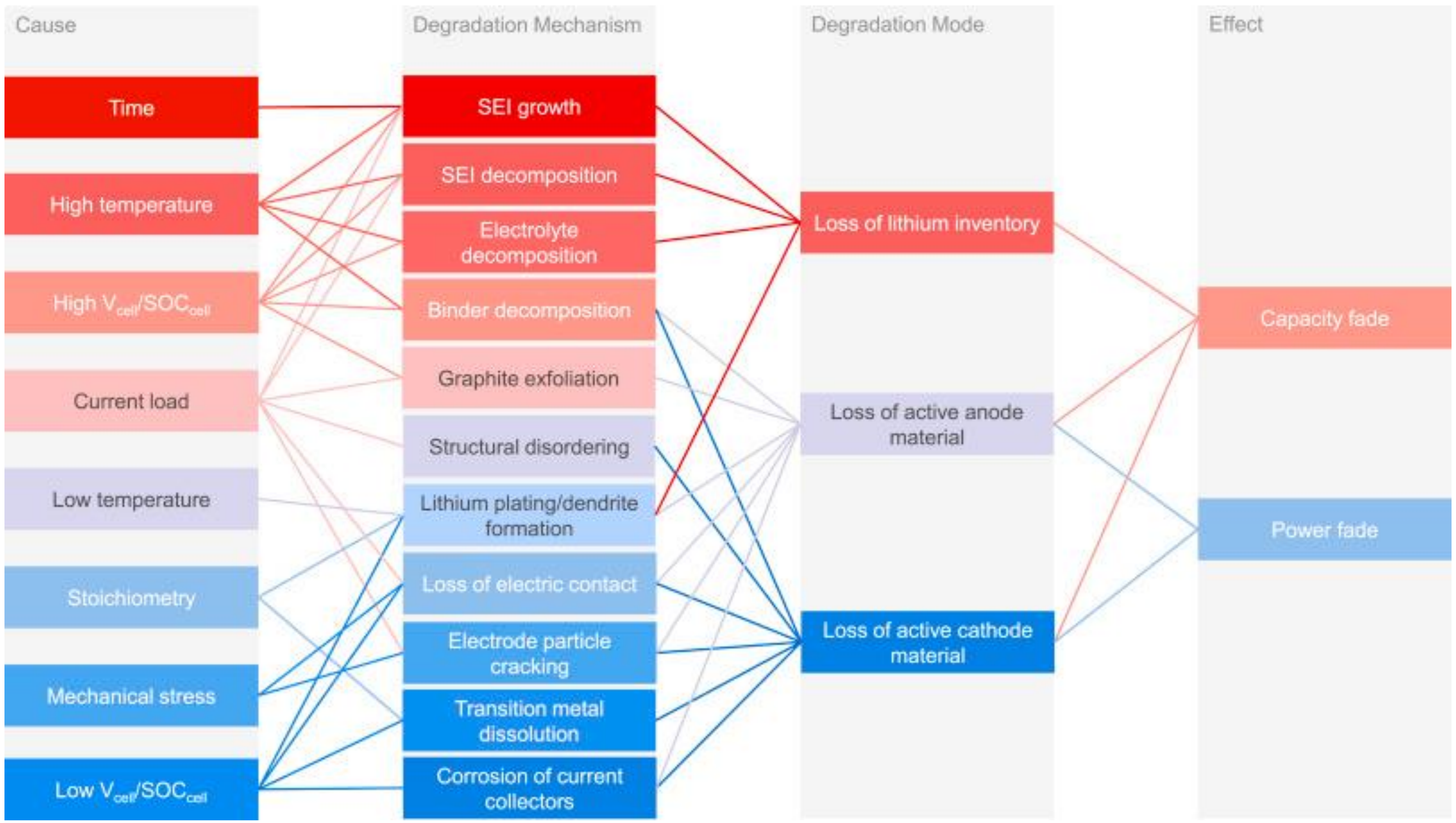
Degradation is key consideration – Lifetime throughput (in kWh) as key performance metric – different applications available

Background: Battery degradation is not an easy problem to model – many mechanisms interact



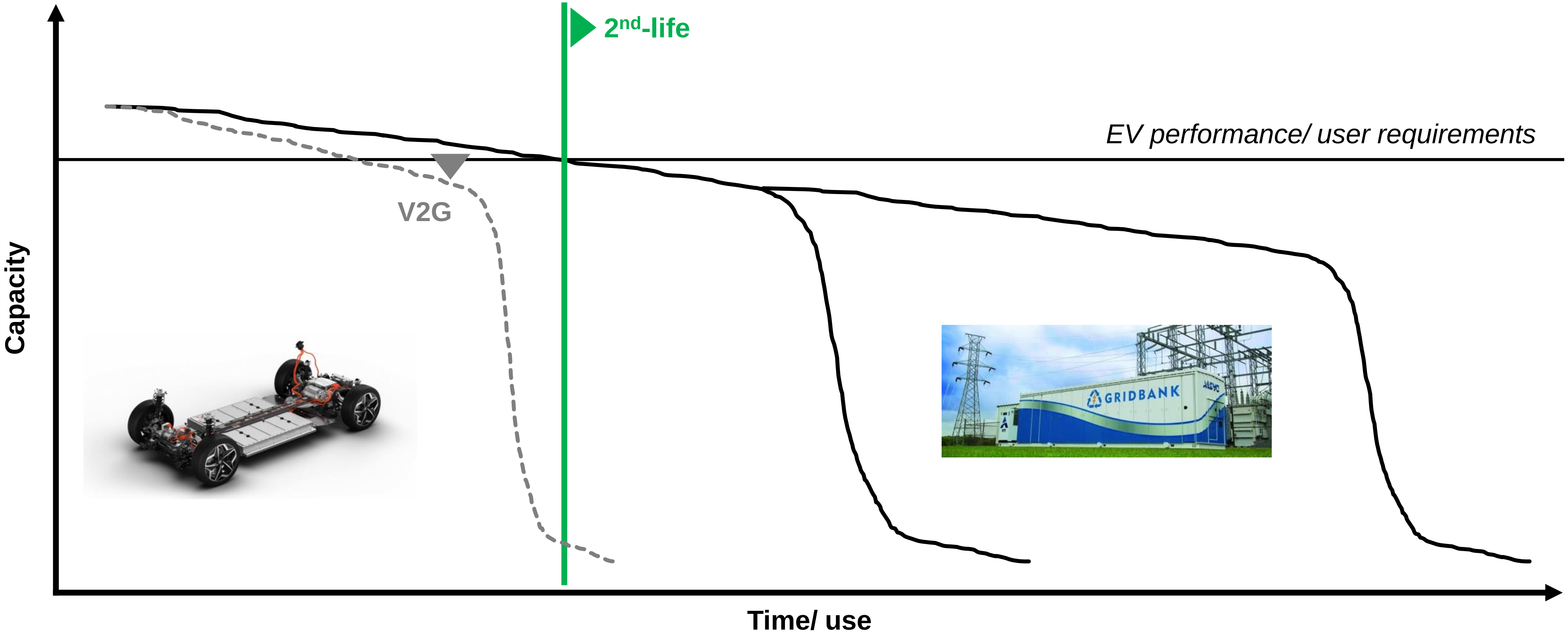
Source: Birkl, C. R., Roberts, M. R., McTurk, E., Bruce, P. G., & Howey, D. A. (2017). Degradation diagnostics for lithium ion cells. Journal of Power Sources, 341, 373-386.

For our assessments: Modelling capacity and power fade is key



Source: Birkl, C. R., Roberts, M. R., McTurk, E., Bruce, P. G., & Howey, D. A. (2017). Degradation diagnostics for lithium ion cells. Journal of Power Sources, 341, 373-386.

Typical degradation curve over time/ use: Beware of the “aging knee”



Source: Visualization idea from T. Grandjean, The University of Warwick

Modeling Approach

Application Profiles

- Primary EV application simulated using realistic **World Harmonized Light Vehicles Test Cycles (WLTC)** at varying usage intensities.
- Secondary **vehicle-to-grid and second life** applications simulated using **Primary Frequency Control and Wholesale Arbitrage profile**.

Electrical Model 1

- Uses power profiles to simulate **cell current, voltage, temperature and SOC**.
- **Thevenin equivalent circuit model** with temperature dependent components used to simulate cell performance and losses.

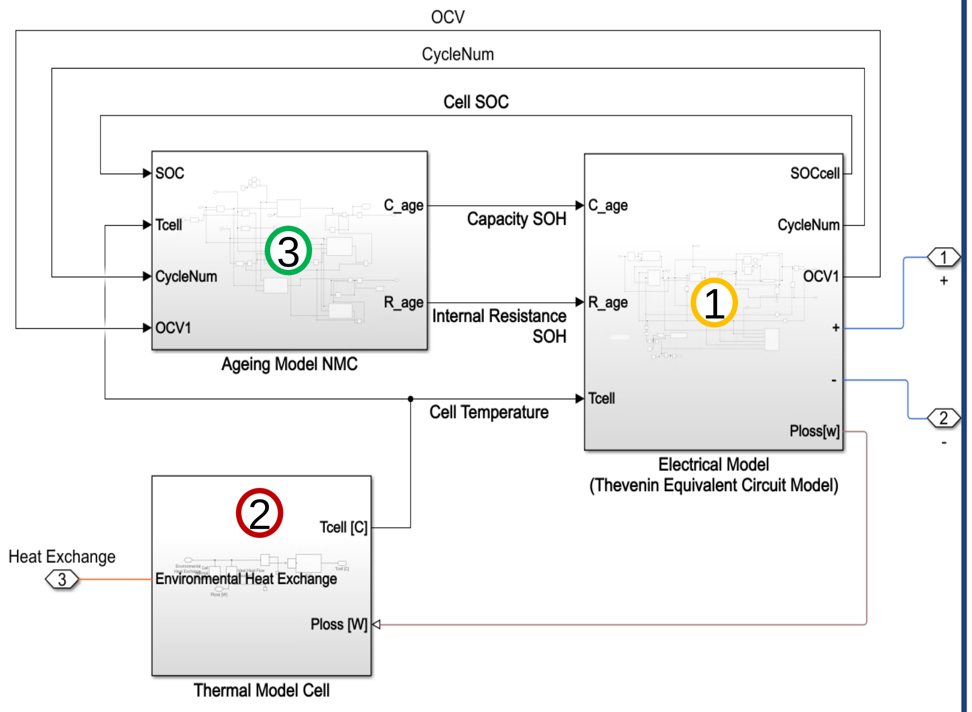
Thermal Model 2

- 1-D thermal model uses ohmic losses to determine **cell temperature** with context to surrounding cells and environment.

Ageing Model 3

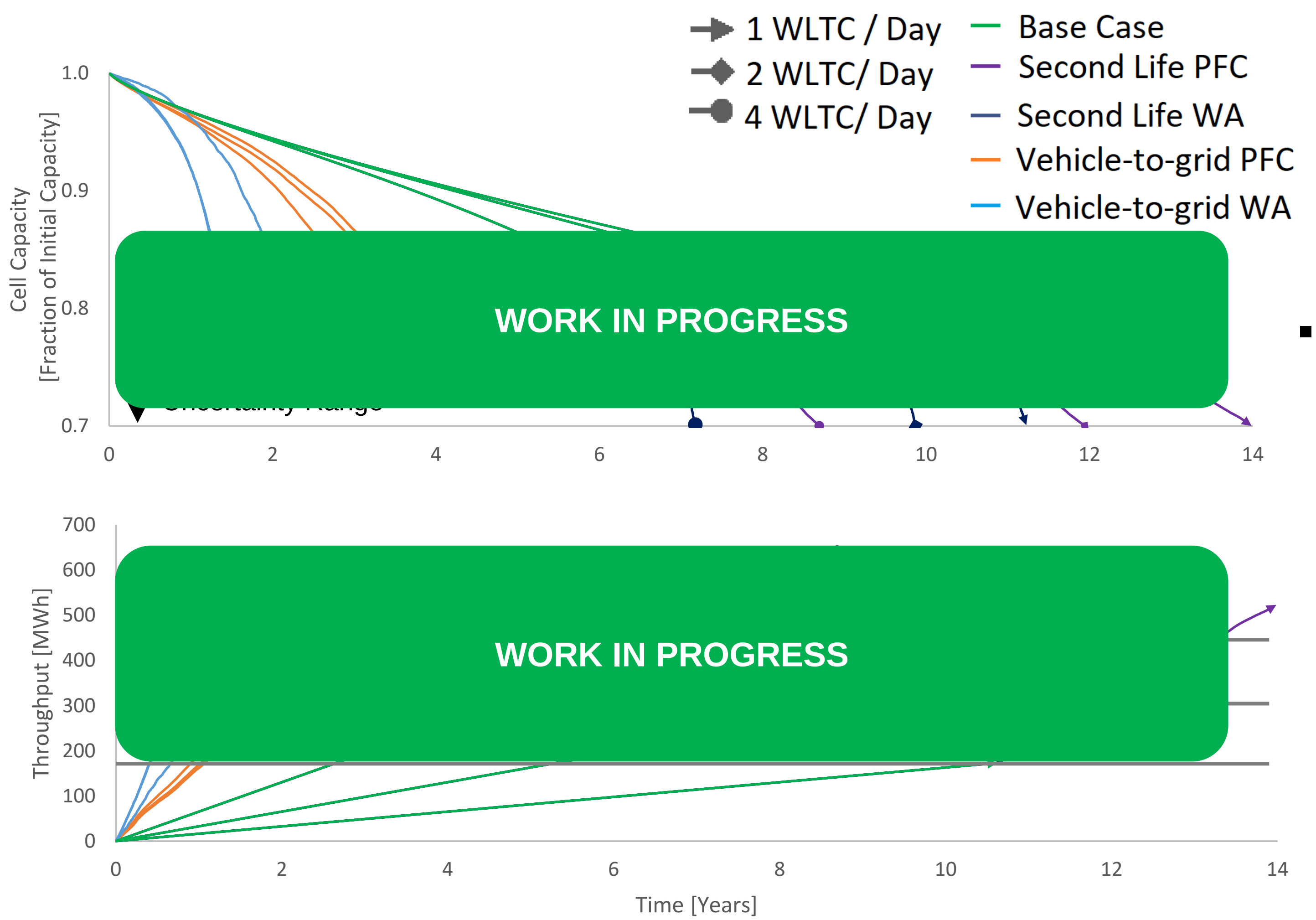
- Uses cell **cycling profiles**, SOC, temperature and voltage to simulate **capacity and power fade** over cell lifetime in terms of **calendar and cycle ageing**.
- **Semi-empirical model** is derived from Schmalstieg et al.[2] and Batteries2020 Project[3].

Integrated electrical, thermal and ageing model for 20Ah NMC pouch cell



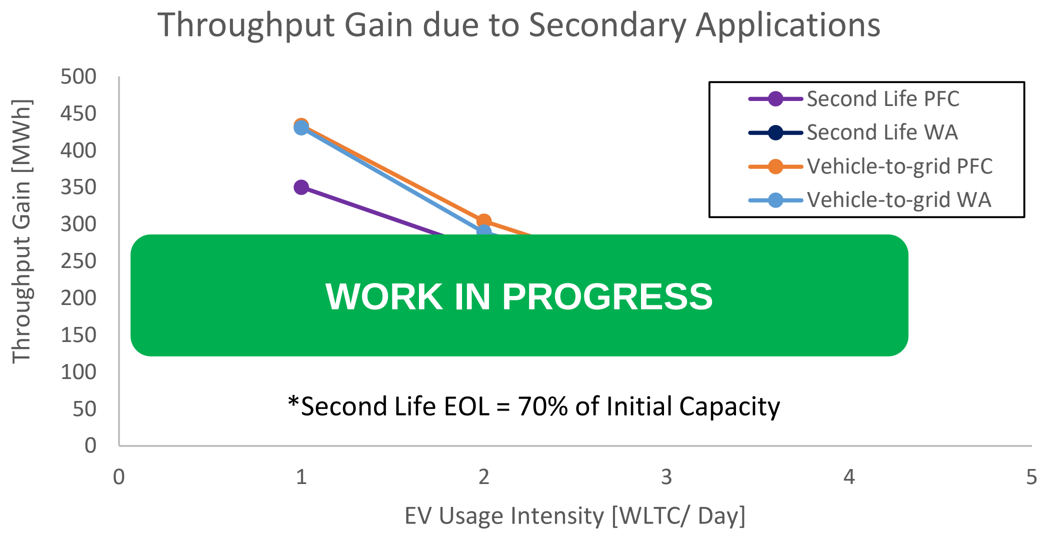
2. Schmalstieg, J., Käbitz, S., Ecker, M. & Sauer, D. U. A holistic aging model for Li(NiMnCo)O2 based 18650 lithium-ion batteries. *J. Power Sources* **257**, 325–334 (2014).
3. Timmermans, J. M. *et al.* Batteries 2020 - Lithium-ion battery first and second life ageing, validated battery models, lifetime modelling and ageing assessment of thermal parameters. *2016 18th Eur. Conf. Power Electron. Appl. EPE 2016 ECCE Eur.* (2016) doi:10.1109/EPE.2016.7695698.

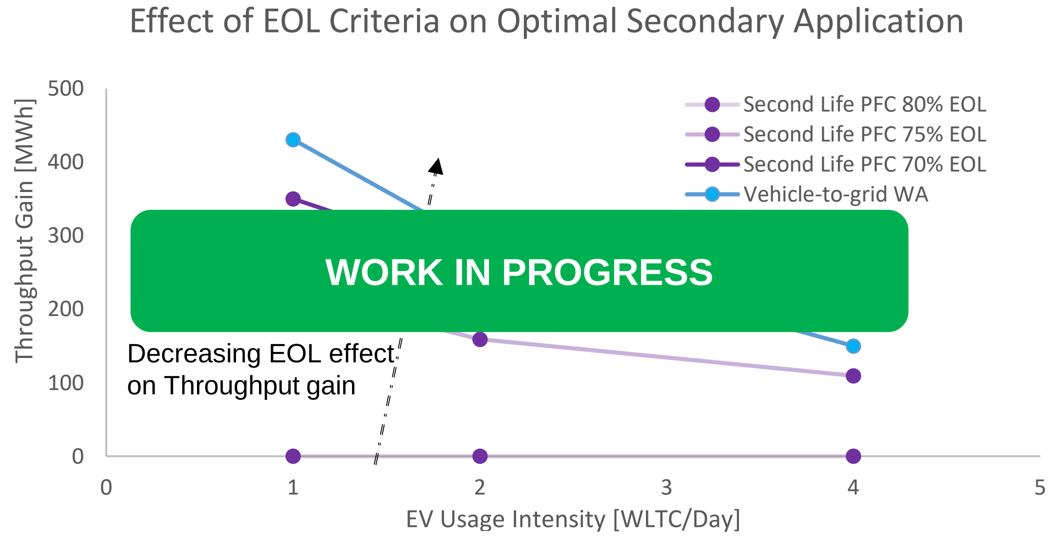
Results: Important to balance calendar and cycle ageing



- **Cell lifetime and throughput must be decoupled for picking ideal secondary application.**
  - Throughput increase rates vary, indicating optimal application is function of usage intensity and end-of-life.
- **Cycle ageing and calendar ageing effects on cells must be balanced to pick optimal secondary application for a given EV usage intensity.**
  - Calendar ageing relatively immutable with application, optimality of secondary application determined by cycle ageing trend.
  - End-of-life (EOL) criteria also impacts application viability. Unable to predict using this model.

Results: Optimal secondary application depends on EV usage intensity and EOL Criteria





- **Cell lifetime and throughput must be decoupled for picking ideal secondary application.**
  - Vehicle-to-grid always leads to a shorter lifetime, and second life always leads to a longer lifetime.
  - Optimal secondary application based on maximum throughput varies by EV usage intensity and EOL criteria, not lifetime.

- **Cycle ageing and calendar ageing effects on cells must be balanced to pick optimal secondary application for a given EV usage intensity.**
  - Heavy use EV cells are best suited to second life, as vehicle-to-grid would make cycle ageing too dominant early on, leading to a lower throughput due to short lifetime.
  - Light use EV cells are best suited to vehicle-to-grid, as it allows more throughput from additional cycling over a shorter calendar aging period and lifetime.

- **These trends persist despite changes in difficult to predict end-of-life criteria.**
  - Model allows simulating impact of assumed end-of-life criteria.

Discussion: Applications matter!

- Important to consider different applications for vehicle-to-grid and second-life use of electric vehicle batteries
- Highest lifetime throughput can be achieved by balancing application and EV use pattern, in addition balance calendar and cycle aging

- However, there are many further considerations. Our model can be one piece in the puzzle:
  - Throughput not the only determinant of CO2 impact: different applications have different effects in the electricity system
  - Profitability to be considered, before influencing business decisions
  - Lithium-ion batteries are improving rapidly: lifetime one key area of research (public & private sector)
  - System design and operating decisions will be considered in sensitivity analyses

- Modelling to be further developed in various ways:
  - Other cell chemistries can be easily incorporated when lab-test data is available
  - End-of-life capacity retention could be viewed as probabilistic
  - Full packs, including cell-to-cell variations can be modelled (but time-intense)

THANK YOU.

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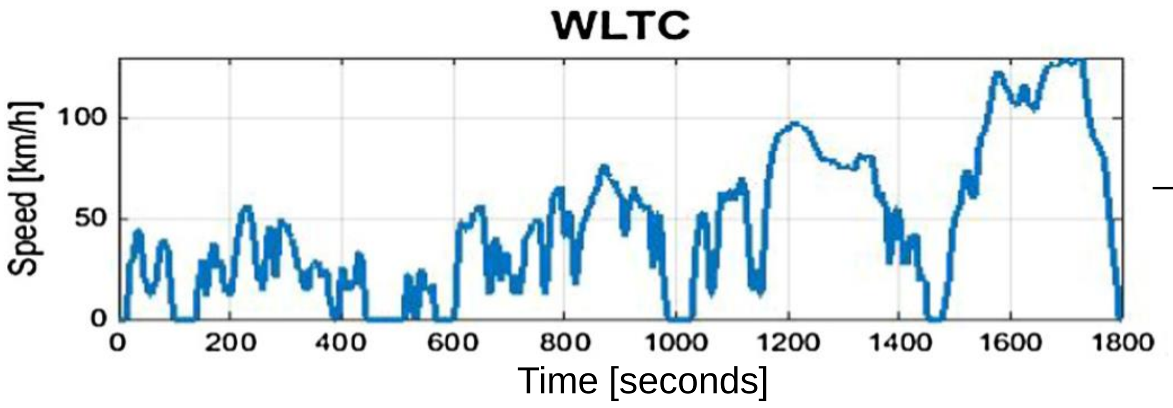
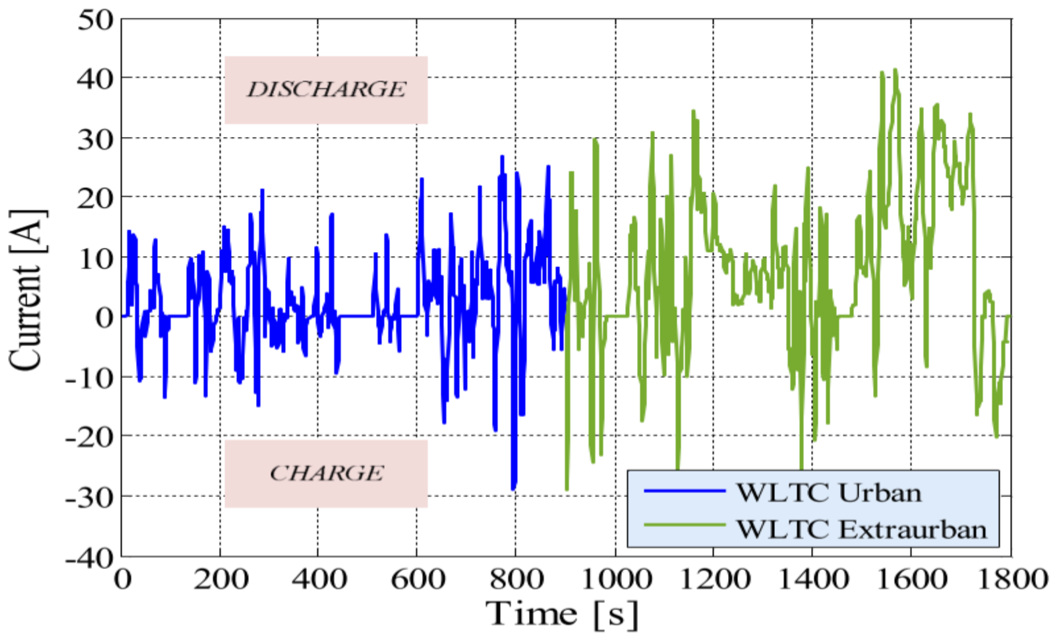
ETH Zurich
Chair for Energy Politics

Prof. Dr. Tobias Schmidt
IFW D 25
Haldeneggsteig 4
8092 Zurich, Switzerland

mbeuse@ethz.ch
+41 79 823 3640

Supplementary: WLTC Profile





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