REQUIREMENT SPACES FOR SUSTAINABLE TECHNOLOGIES

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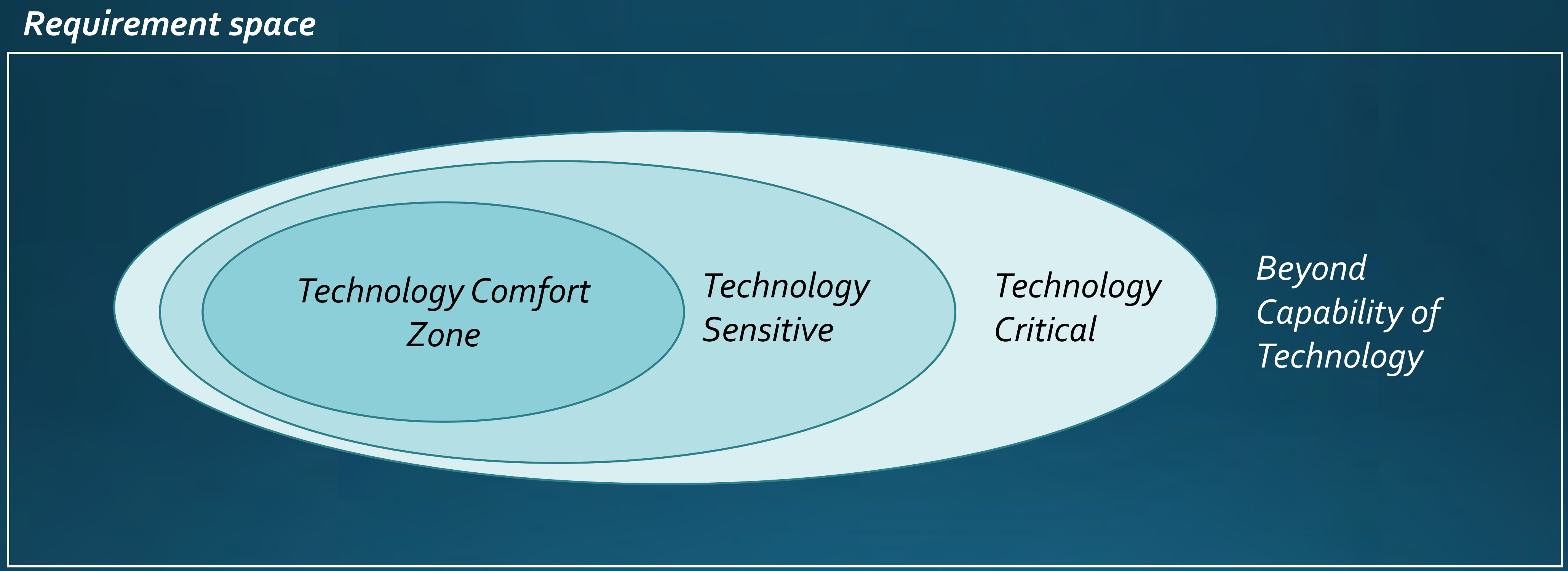
Introduction

- Requirements for more sustainable systems often means that new technological solutions should be introduced. In most cases this is not straightforward.
- Our assumption is that first we need to determine the specific set of achievable requirements for a technology. Secondly, it is also important to understand for what type of system the new technology is viable for.
- In order to illustrate this mapping of domains of valid requirements, we examined the increasing demand for electrical power systems for aircraft and vehicles.

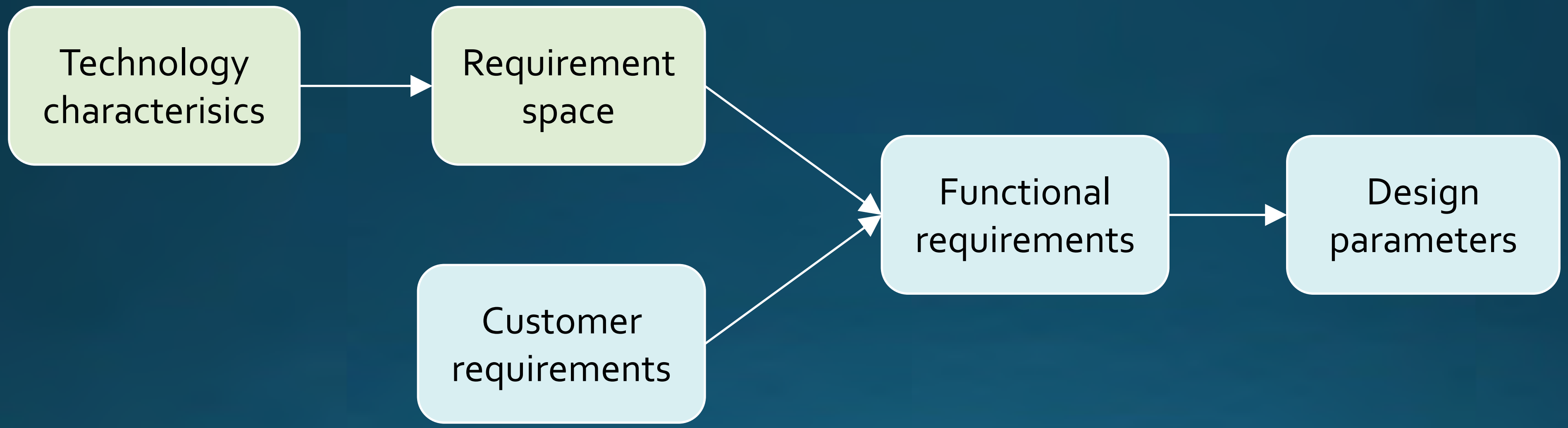
Comparison CO_2 Producers in Sweden

	Alternatives
• Swede's flying 2019 approx. 10 million tonnes CO_2	Hydrogen (burn or fuel cell) / synfuel
• Swede's car use 2019 approx. 10 million tonnes CO_2	Battery
• Heavy road transport 5 million tonnes CO_2	Battery / hydrogen fuel cell
• Work machines 3.5 million tonnes CO_2	Battery / hydrogen fuel cell
• Ships to and from Sweden, 8 million tonnes of CO_2	Hydrogen (burn or fuel cell) / synfuel
• *SSAB's direct CO_2 emissions of 9.8 million tonnes of CO_2*	Hydrogen

Requirement space Framework



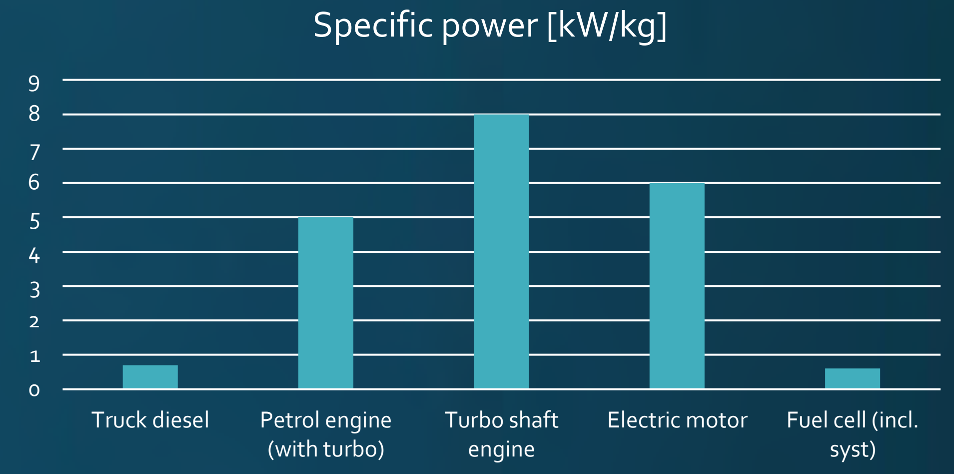
Technology and Requirement Space



The design process with the *Requirement space* as a function of the *Technology characteristics* is indicated.

Specific Power

Truck diesel	0.7 kW/kg
Petrol engine (with turbo)	1-8 kW/kg
Turbo shaft engine	6-10 kW/kg
Electric motor	1-10 kW/kg
Fuel cell (incl. syst)	0.4-0.8 kW/kg
1932 Pratt & Withney	1.2 kW/kg



GeeBee racer
Max speed 476 km/h
1932
Engine 50% of empty weight

Saab 340
Max speed 502 km/h
Cruise 467 km/h
Engine 5% of empty weight

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Specific Energy

Diesel (about the same as petrol and kerosene)	12600 Wh/kg
Battery (Tesla, pack level)	177 Wh/kg
Hydrogen	33000 Wh/kg
Hydrogen pressure storage	1700-3300 Wh/kg

Hydrogen stored is ~5%-10% of storage system weight

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Efficiency

Truck diesel	0.4
Petrol engine (with turbo)	0.25
Turbo shaft engine	0.5
Electric motor	0.95
Fuel cell (incl. syst)	0.4-0.6
Battery	0.96

Fuel cell+electric motor comparable to combustion engine

Technology Comfort Zone, TCZ

- Improvement in the technology coefficient, ζ, such as e.g. tensile strength, specific energy or power, should have a strong effect on system performance p
- The change in a design parameters, x, such as component size, should have a lower effect on system performance p.
- A low sensitivity from design parameters, x, to cost, c, making it cheap to increase performance through design parameters.

Technology sensitivity

Performance

$$p = f_p(x,\zeta)$$

$$k_{0,p,i} = \frac{x_i}{p}\frac{\partial p}{\partial x_i}$$

Cost

$$c = f_c(x,\zeta)$$

$$k_{0,c,i} = \frac{x_i}{c}\frac{\partial c}{\partial x_i}$$

How many percent the performance can be increased if cost is increased one percent.

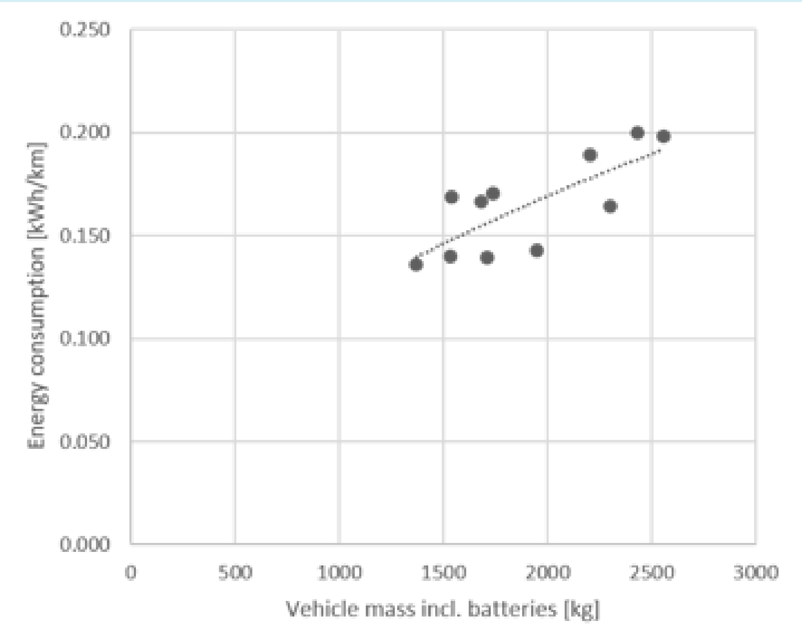
Cost benefit factor

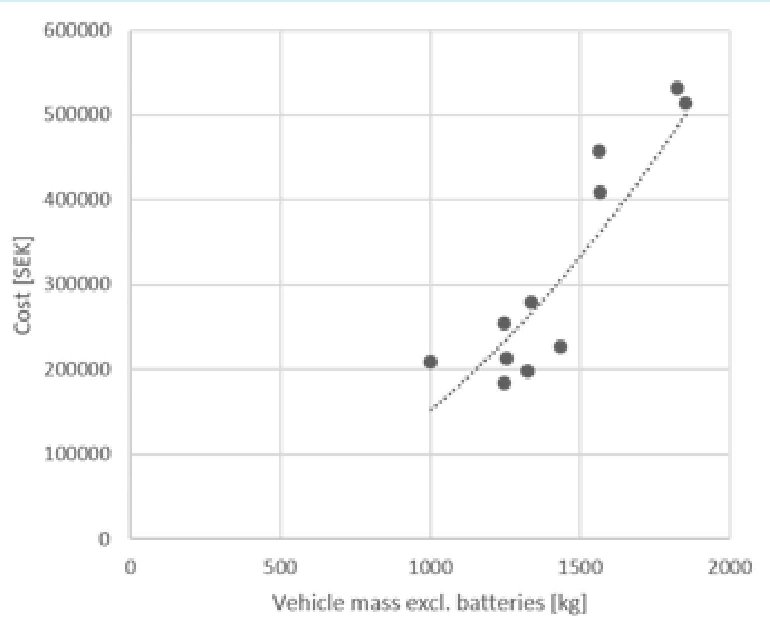
$$\kappa_i = \frac{k_{0,p,i}}{k_{0,c,i}} = \left(\frac{x_i}{p}\frac{\partial p}{\partial x_i}\right)\left(\frac{x_i}{c}\frac{\partial c}{\partial x_i}\right)^{-1} = \frac{c}{p}\left(\frac{\partial p}{\partial x_i}\right)\left(\frac{\partial c}{\partial x_i}\right)^{-1}$$

Electric Vehicle Modelling

	year	Price incl tax	Price excl tax	Price without battery	El power [kW]	empty weight [kg]	min weight [kg]	empty weight-batt [kg]	Battery fraction	Battery weight [kg]	Battery capacity [kWh]	Electric range [km]	kWh/100km
BMW i3	2019	419000	335200	208600	125	1270	1370	1002	0.267584	268.0941	42.2	310	13.6
Nissan Leaf 40	2019	397000	317600	197600	110	1580	1680	1326	0.191659	254.1176	40	240	16.7
Nissan Leaf 62	2019	461500	369200	183200	160	1640	1740	1246	0.316088	393.8824	62	364	17.0
VW e-Golf	2019	403000	322400	226400	100	1640	1540	1437	0.1415	203.2941	32	190	16.8
Tesla Model 3 SR	2019	531700	425360	254360	211	1611	1711	1249	0.289953	362.1176	57	409	13.9
Tesla Model 3 LR	2019	649600	519680	279680	211	1847	1947	1339	0.37963	508.2353	80	560	14.3
Tesla S SR	2019	830000	664000	409000	581	2108	2208	1568	0.344388	540	85	450	18.9
Tesla S LR	2019	946000	756800	456800	581	2200	2300	1565	0.406015	635.2941	100	610	16.4
Tesla X SR	2019	923000	738400	513400	386	2330	2430	1854	0.257061	476.4706	75	375	20.0
Tesla X LR	2019	1039000	831200	531200	386	2459	2559	1824	0.348353	635.2941	100	505	19.8

Electric Vehicle Modelling





Cost is increasing much more than proportionally to size. This means that for a large car a battery of the same fraction of vehicle weight will be a smaller fraction of the total cost.

$$E_{cons} = a_E {m_{tot}}^{b_E} = 0.004397 {m_{tot}}^{0.5163} \text{ [kwh/km]}$$

$$c_0 = a_c {m_0}^{b_c} = 0.00192661 {m_0}^{2.599} \text{[SEK]}$$

Vehicle Modelling

$$R = \frac{E_b}{E_{cons}} = \frac{\varsigma_b m_b}{a_E (m_0 + m_b)^{b_E}} = \frac{35.25 m_b}{(m_0 + m_b)^{0.5163}} \quad [\text{km}]$$

Range

$$c_t = c_0 + c_b = a_c {m_0}^{b_c} + k_{bc} m_b = 0.00192661 {m_0}^{2.599} + 444.6 m_b \quad [\text{SEK}]$$

Cost

$$\Psi = \frac{m_b}{m_0}$$

Design parameter

$$\kappa = \frac{R}{c_t} \left(\frac{\partial c_t}{\partial \Psi} \right) \left(\frac{\partial R}{\partial \Psi} \right)^{-1} =$$

$$= \frac{k_b m_0 (1+\Psi)^{1.5163}}{(\Psi + 9.695 \times 10^{-6} {m_0}^{1.599})(-0.5163 {k_b}^2 {m_0}^2 (1+\Psi)^{0.5163} + (1+\Psi)^{1.5163})}$$

Expressions for range and cost are combined to formed the cost benefit factor

Technology Zones

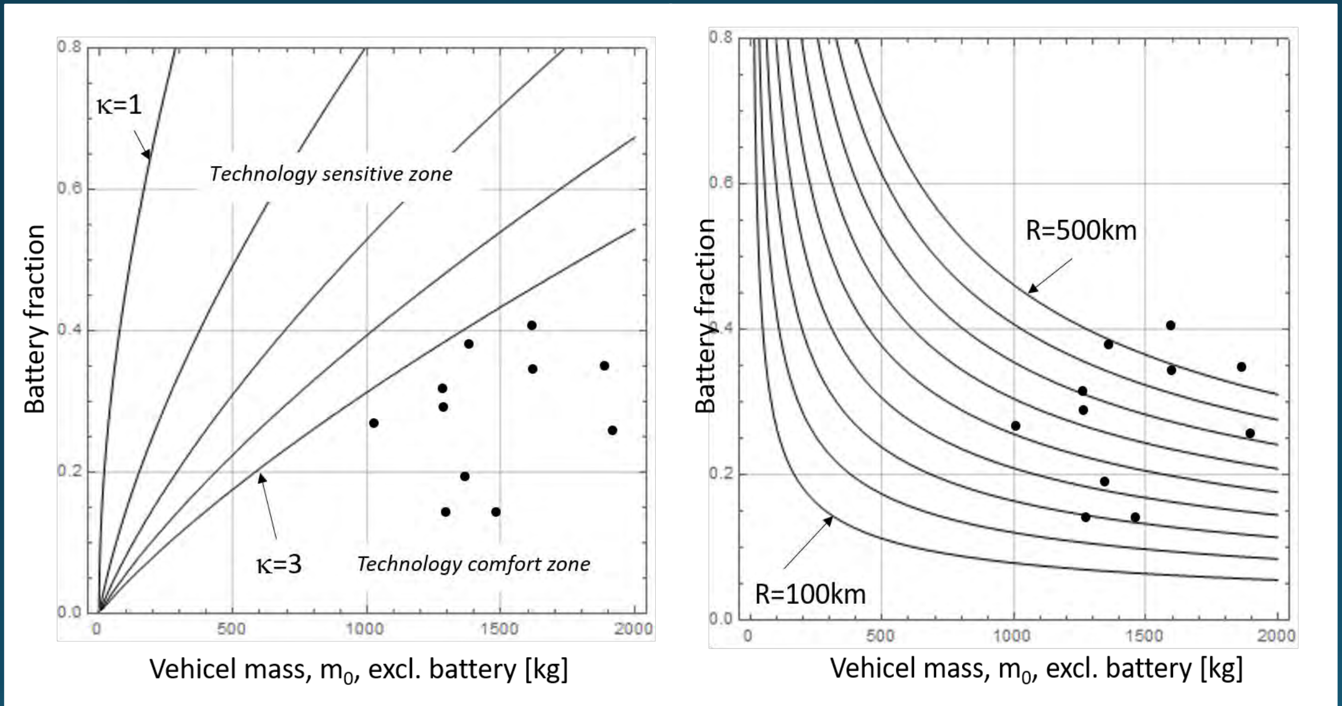
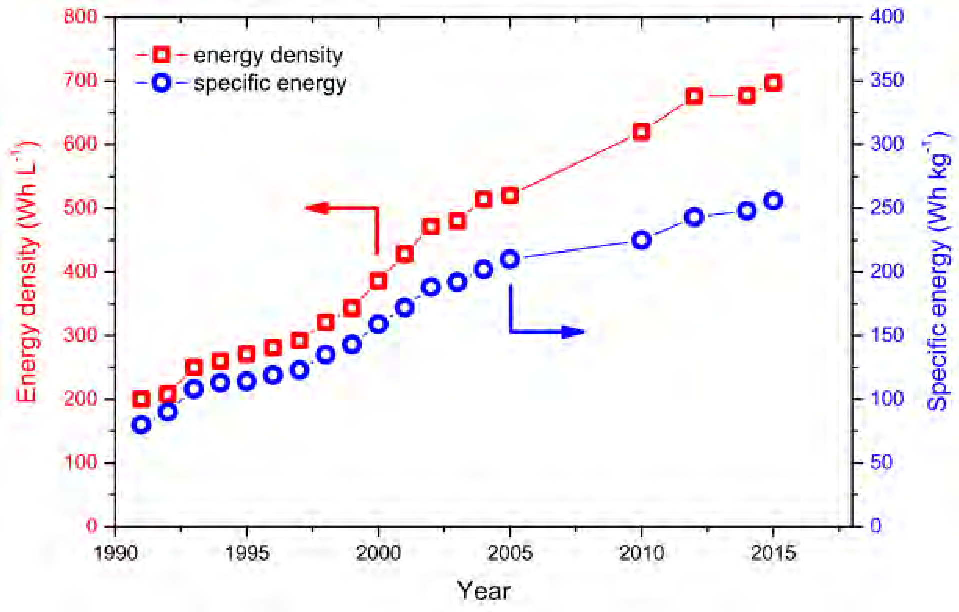
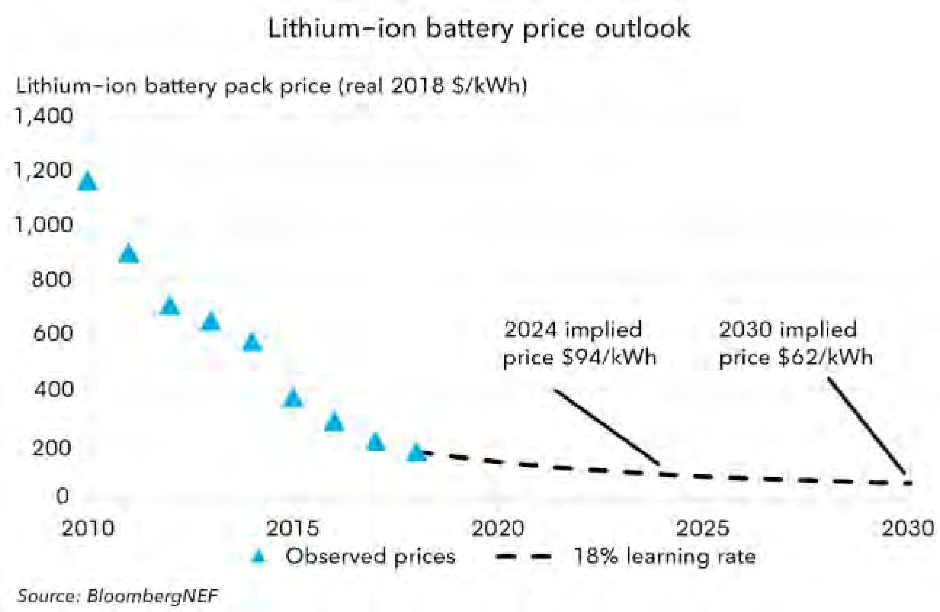


Diagram of the technology zones (left) and range (right). The curves to the left show lines with constant cost benefit factor. Note tNote tNote that larger cars can have a higher battery fraction and hence range.

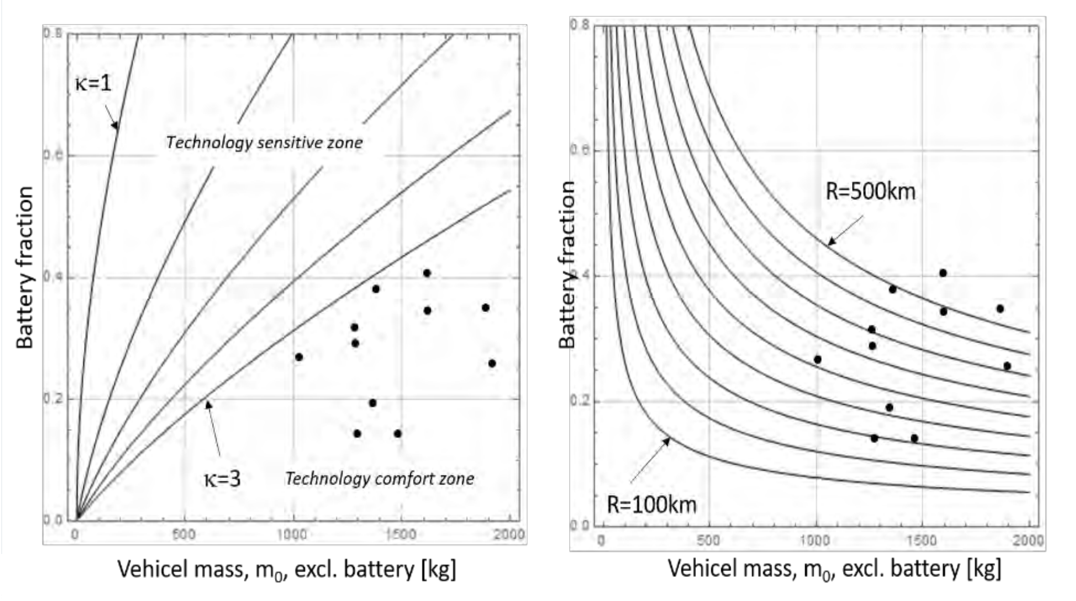
Technology Forecasting: Electric Cars

- Assuming incremental refinement of Li-ion technology
- (Placke et al., 2017) suggests about 3 Wh/kg/year.
- A cost reduction of 8 %/year





Electric cars forecasting to 2024



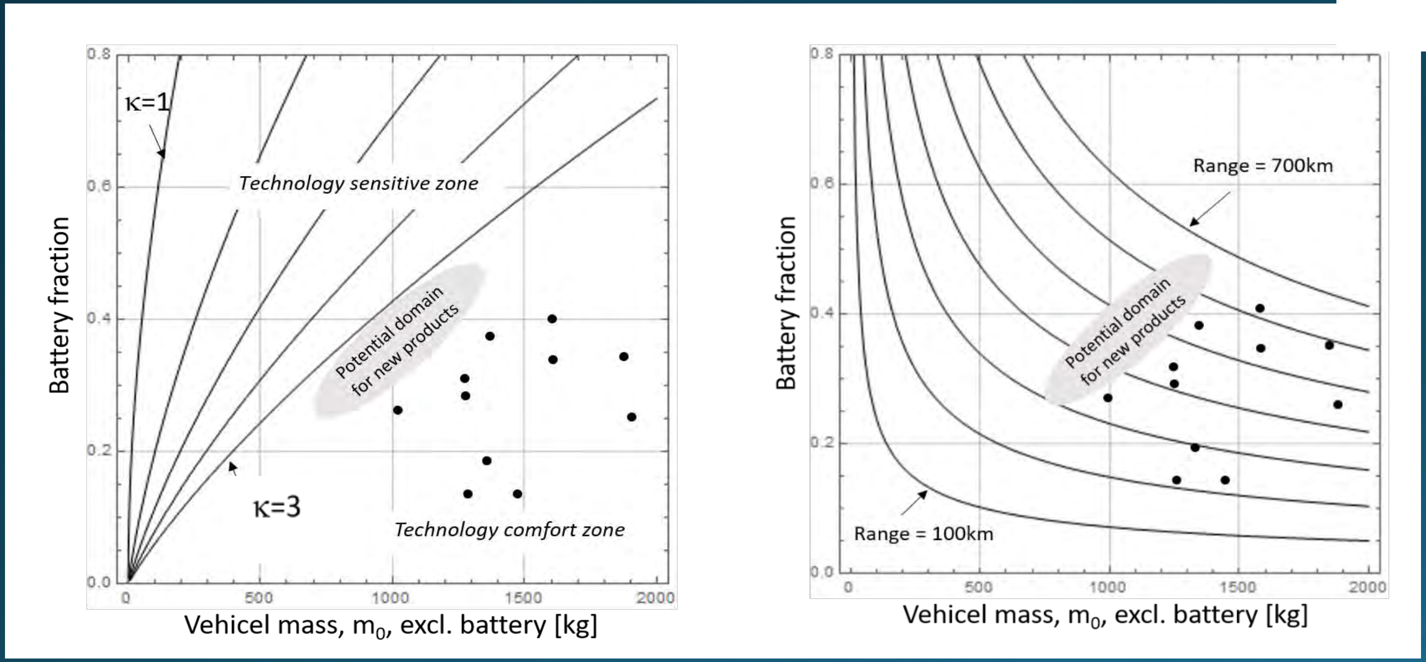


Diagram of the technology zones (left) and range (right) estimated for 2024. The curves show lines with constant κ between 1 and 3. There is a new area where new products are likely to be located.

The criticality of technology for electric aircraft

Aircraft range

$$R = \frac{\varsigma_b}{g}\eta\left(\frac{L}{D}\right)\frac{W_b}{W_0}$$

$$W_1 = W_0 - W_b$$

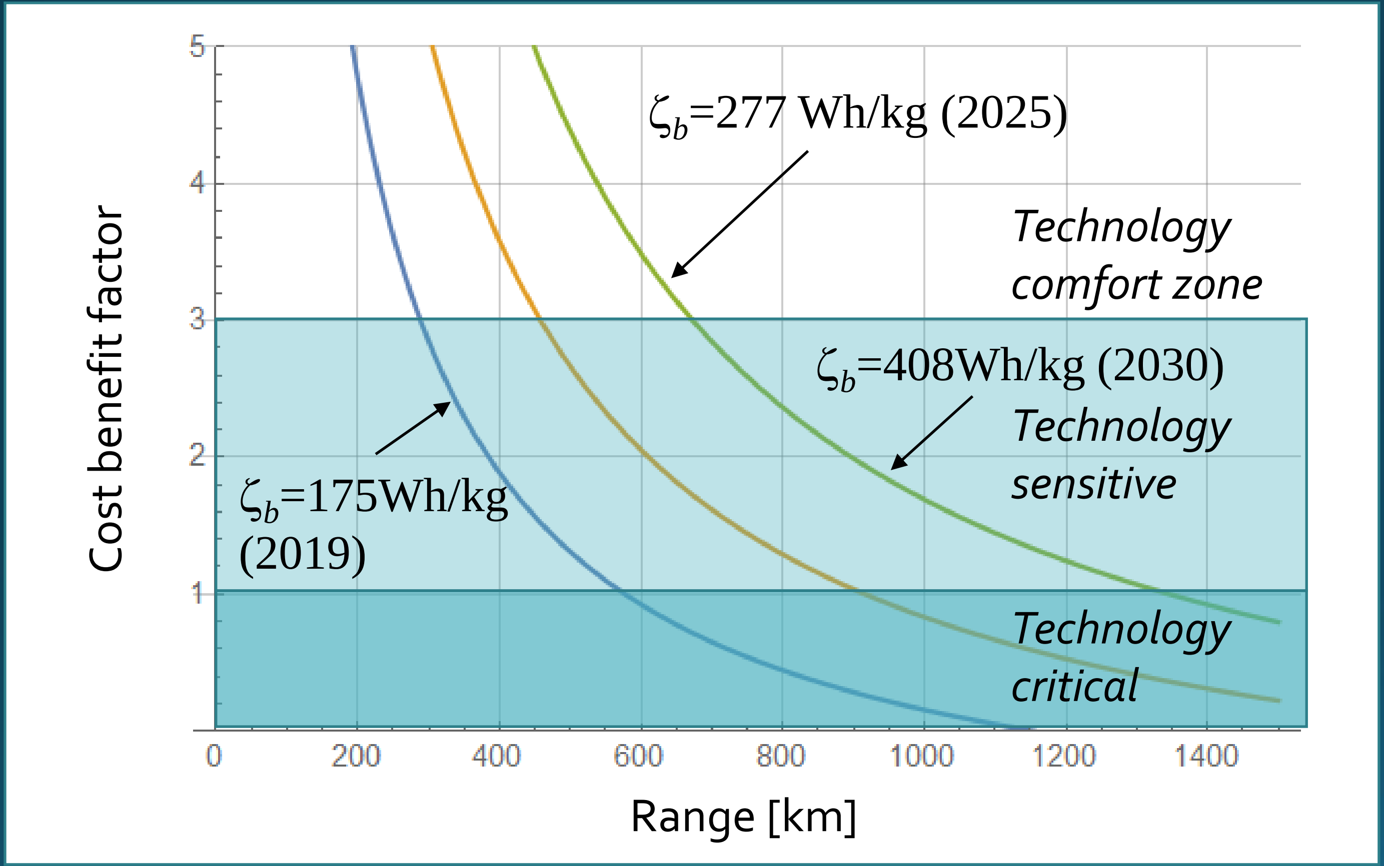
$$\Psi = W_b / W_1$$

Assuming cost proportioinal takeoff weight

$$R = \eta\frac{\varsigma_b}{g}\left(\frac{L}{D}\right)\frac{\Psi}{1+\Psi}$$

$$\kappa = \frac{k_{0,p}}{k_{0,c}} = \Psi^{-1}$$

Electric Aircraft Range Forecasting



The cost benefit factor as a function of (theoretical) range. The curves represent 2019 technology and with estimated technology level 2025 and 2030. Long term improvement assumed to be an optimistic 8%/year.

Electric Trucks

Cars are rapidly going into the technology comfort zone for batteries.

Long haul trucks requires 4.5 h driving and 45 min rest.

Would require charging of >0.5MW.

Short and medium range trucks could use battery. *Technology comfort zone*

A 40 ton long haul truck could do this with about 2 ton of batteries (4 with reserves). 10% should be doable if required. *Technology comfort zone.*

Fire safety?

- Hydrogen storage and Fuel cells could be a viable option.
- System weight would be between that for a diesel truck and a battery truck
- Electric roads? ...not likely, huge investment (60-100 billion SEK in Sweden)...

Electric Construction Machines

- Excavators have an average power much less than trucks.
- A workday on a battery charge could be done. There is a counterbalance weight anyway… *Technology Comfort Zone*
- Construction on sites often without a charging infrastructure.
- Fuel cell is interesting.

Aircraft

- Burning hydrogen directly in the engines.
- Hydrogen storage system is a problem especially for long haul (low energy density, J/m^3)
- Airbus points at this for short and medium range aircraft.

Airbus long haul concept from 2001

- Battery is hardly relevant
- An optimistic theoretical range is about 560km with 50% takeoff weight with batteries. Commercial range means that an alternative airport should be reached and an extra 45 min loitering, severely restricting the operations making it CO_2 irrelevant.
- *Technology critical/impossible*

Aircraft with Fuel-Cells

Fuel cells have low power density making it useful for only slow aircraft (commuters). *Technology sensitive*

They have to compete head-on with hydrogen burning aircraft of comparable efficiency.

Business case have to build on secondary aspects, e.g. maintenance.

Conclusion

- In this presentation, we have demonstrated the concepts of :
  - Cost-benefit factor which is used to define:
    - Technology comfort zone
      - Where technology can readily be used.
    - Technology sensitive zone
      - Where product benefit strongly from technology improvements.
    - Technology critical zone
      - Where technology needs to be developed to be useful for the product.
- This is used to map requirement spaces, where feasible products can be realized.
  - It is particularly useful in select technologies for the green transformation.