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Forskningsgruppeleder: E-Mobility and Drives

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**AAU
ENERGY**

**AALBORG
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GYMNASIELÆRERDAGEN 2024

BATTERIER OG ELBILER
AAU ENERGI | 2024.11.27

Kort om mig

Uddannelse

- 2010 Ph.d. AAU Energi. Afhandling "Design of a Fuel Cell Hybrid Electric Vehicle"
- 2005 Civilingeniør Elektrisk Energiteknik, AAU Energi, Specialization: Power Electronics, Electric Machines, and Drives

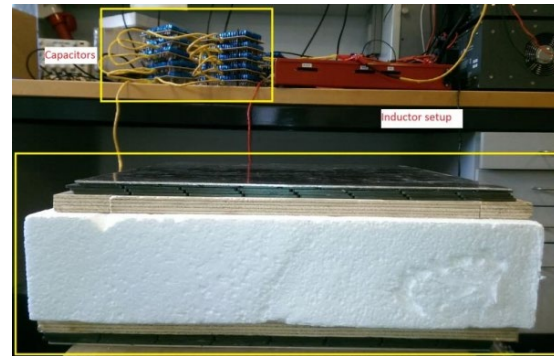


AAU Energi ansættelse

- 2012 - : Lektor
- 2009 – 2012: Adjunkt
- 2008 – 2009: Post doc
- 2005 – 2008: Ph.d. studerende

Arbejdsområder i nuværende stilling

- Undervisning og vejledning på BSc, MSc, og ph.d. programmerne
- Aktiv i følgende forskningsgrupper
 - E-Mobility and Drives
 - Batteries
 - Electro Fuels



Studenterprojekter

- ▶ Studerende går sammen i **grupper** på 5-6 personer og arbejder på et projekt
- ▶ Hver **semester** skal studerende optjene 30 ECTS-point -> **900 timers arbejde pr studerende**
- ▶ Halvdelen opnås fra **projekterne**
- ▶ **Køretøjer** indeholde mange **ingeniørmæssige discipliner**



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Indhold

- ▶ Kræfter på køretøjer
- ▶ Drivsystem og komponenter I elbiler
- ▶ Efteruddannelse
- ▶ Evaluering



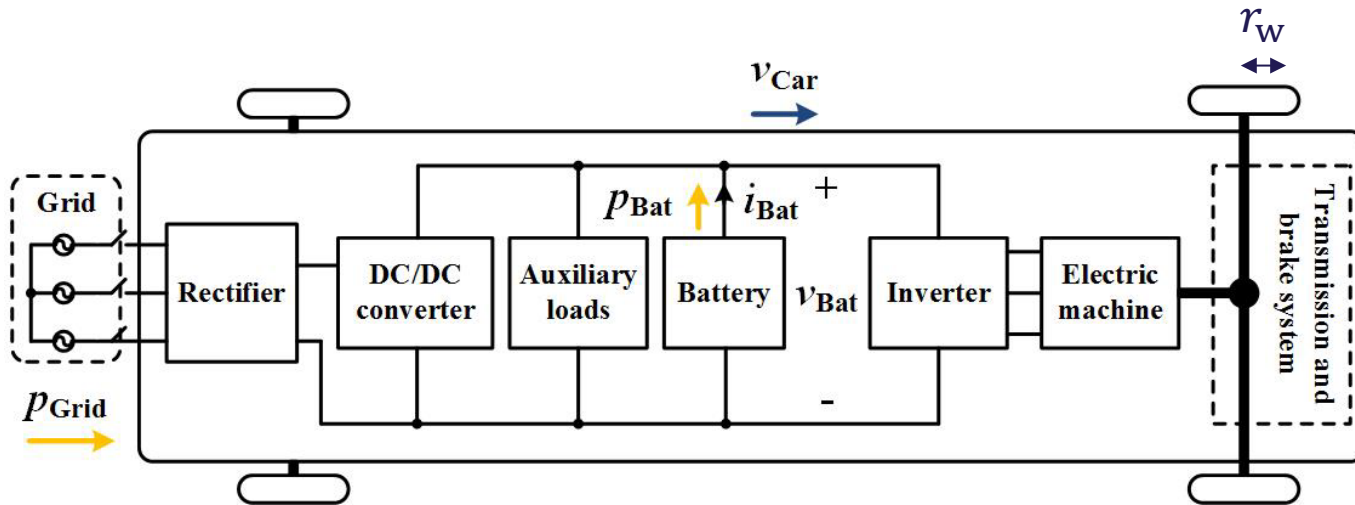
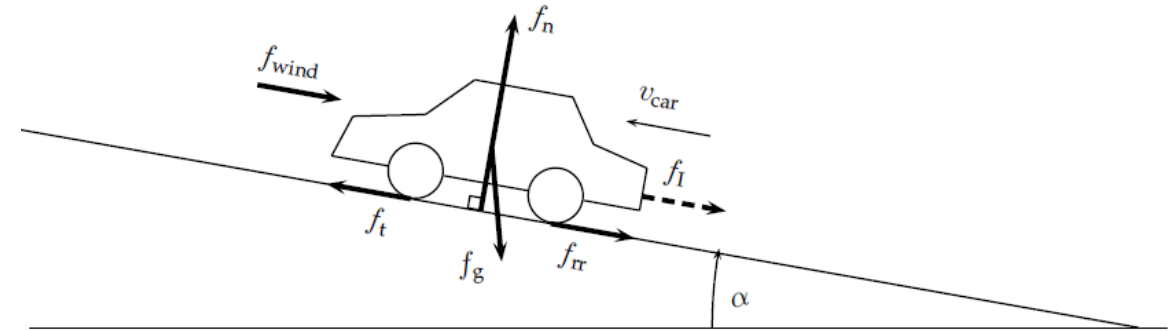
KRÆFTER PÅ KØRETØJER



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Energiflow i drivsystem

- ▶ Kravene til drivsystemet bestemmes af de ydre kræfter på køretøjet
- ▶ Model af hvert element i drivsystemet muliggør energiflow beregning



$$p_t = f_t v_{car}$$

Kobling ml. translationel og roterende domæne

$$\begin{aligned} \tau_t &= f_t r_w \\ &= \tau_{TS} - \tau_{MB} \\ \tau_w &= \frac{\tau_t}{2} \\ \omega_w &= \frac{v_{car}}{r_w} \\ p_t &= f_t v_{car} \end{aligned}$$

Kræfter på køretøjer

▶ Regenerering

- ▶ Inerti
- ▶ Gravitation

▶ Friktion

- ▶ Masse og koefficient for rullemodstand
- ▶ Areal og koefficient for drag

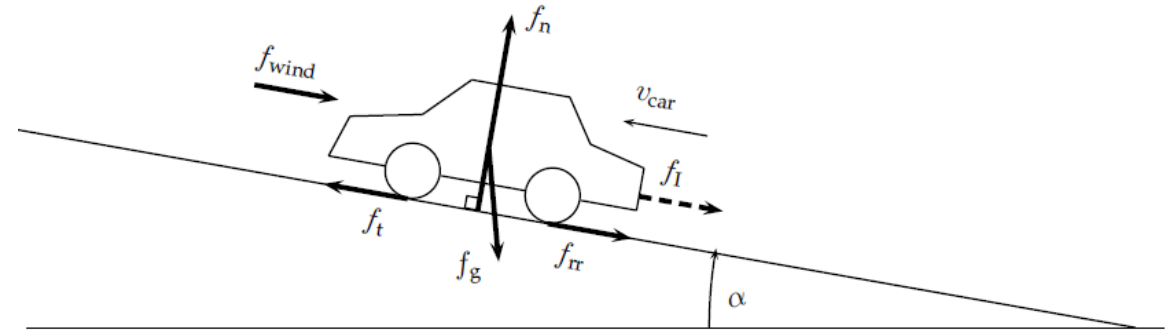
▶ Fremdriftskraft:

$$f_t = \underbrace{M_{\text{car}} \dot{v}_{\text{car}}}_{f_i} + \underbrace{M_{\text{car}} \cdot g \cdot \sin(\alpha)}_{f_g} + \text{sign}(v_{\text{car}}) \underbrace{M_{\text{car}} \cdot g \cdot \cos(\alpha) \cdot c_{rr}}_{f_{rr}} + \underbrace{\text{sign}(v_{\text{car}} + v_{\text{wind}}) \frac{1}{2} \rho_{\text{air}} C_{\text{drag}} A_{\text{front}} (v_{\text{car}} + v_{\text{wind}})^2}_{f_{\text{wind}}}$$

▶ Krævet effekt:

$$p_t = f_t v_{\text{car}}$$

Hastighedens indflydelse: $p_{\text{wind}} \propto v_{\text{car}}^3$



f_t	[N]	Traction force of the vehicle
f_I	[N]	Inertial force of the vehicle
f_{rr}	[N]	Rolling resistance force of the wheels
f_g	[N]	Gravitational force of the vehicle
f_n	[N]	Normal force of the vehicle
f_{wind}	[N]	Force due to wind resistance
α	[rad]	Angle of the driving surface
M_{car}	[kg]	Mass of the vehicle
v_{car}	[m/s]	Velocity of the vehicle
\dot{v}_{car}	[m/s ²]	Acceleration of the vehicle
$g = 9.81$	[m/s ²]	Free fall acceleration
$\rho_{\text{air}} = 1.2041$	[kg/m ³]	Air density of dry air at 20 °C
c_{rr}	[-]	Tire rolling resistance coefficient
C_{drag}	[-]	Aerodynamic drag coefficient
A_{front}	[m ²]	Front area
v_{wind}	[m/s]	Headwind speed

Indflydelse af aerodynamisk design

Mercedes VISION EQXX

- ▶ 100 kWh batteri
- ▶ CW-værdi (drag koefficient) på 0,17
- ▶ 1008 km ved rigtig kørsel
 - ▶ koldt og regnfuldt vejr, alm. vej + motorvej
 - ▶ 15 % tilbage på batteriet
- ▶ 87 Wh/km



<https://mercedes-benz-mag.dk/banebrydende-langt-elbilenvision-eqxx-koerer-mere-end-1-000-kilometer-paa-en-opladning/>

Mustang Mach E

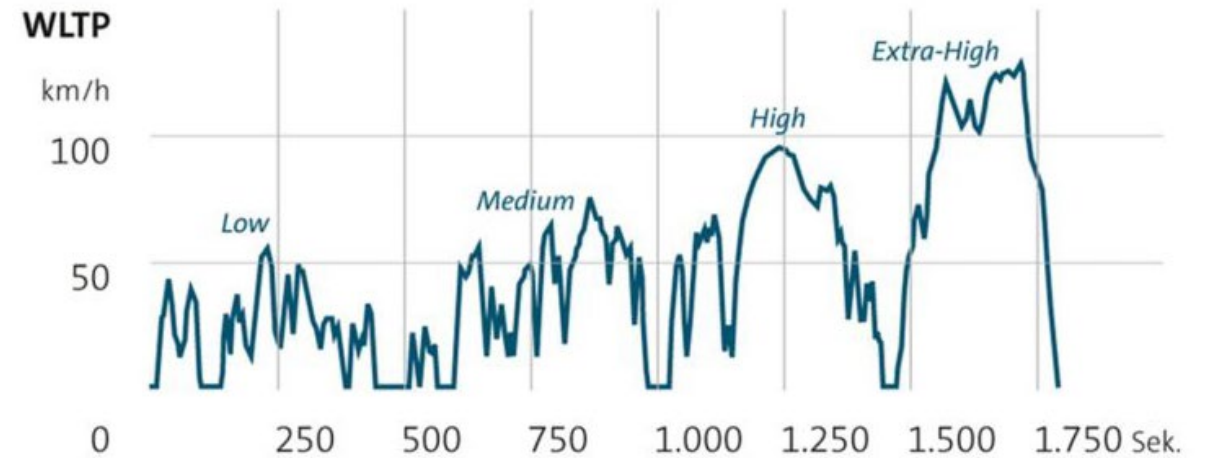
- ▶ 98,8 kWh batteri
- ▶ 600 km officiel rækkevidde (WLTP)
- ▶ Praktisk rækkevidde: Ca. 450 km (mobilsiden.dk)



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Driving cycles

- ▶ Veldefineret tid/hastighed-profil
- ▶ Måde at sammenligne bilers brændstofforbrug eller rækkevidde
- ▶ Mange forskellige slags. Indeholder dog ofte flere slags kørsler:
 - ▶ By
 - ▶ Landevej
 - ▶ Motorvej
- ▶ World harmonized Light-duty vehicles Test Procedure (WLTP)

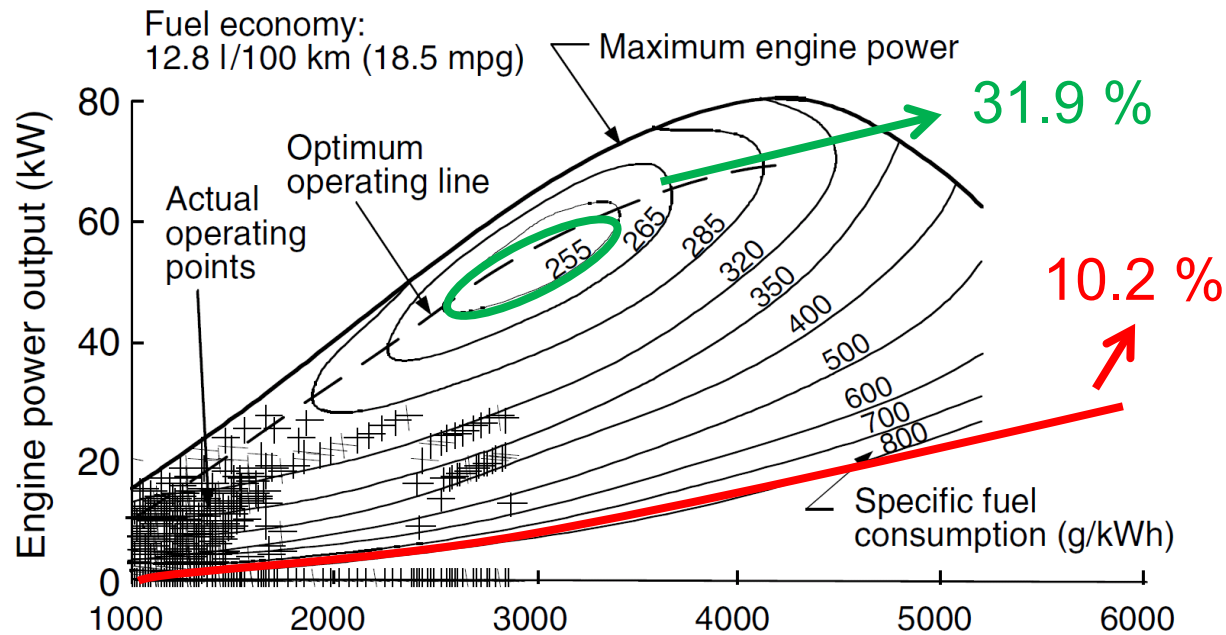


www.volkswagen.com

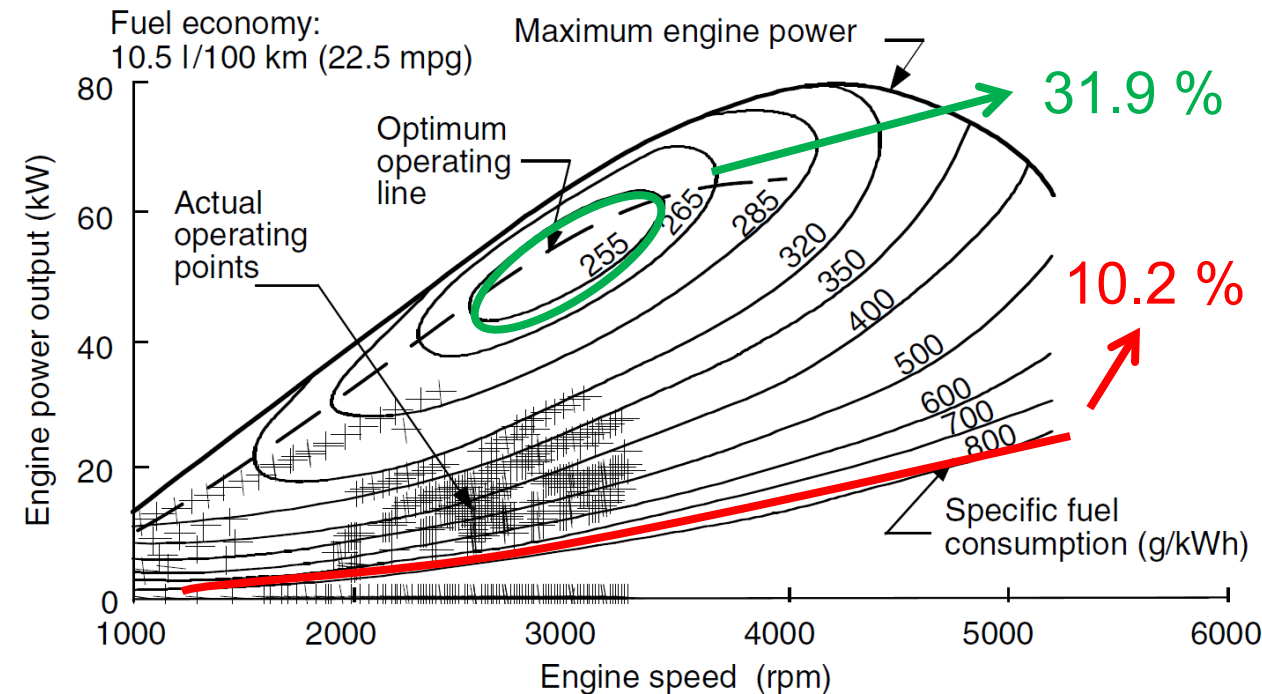


Arbejdspunkter forbrændingsmotor

EPA FTP75 Urban Driving Cycle



EPA FTP75 Highway Driving Cycle

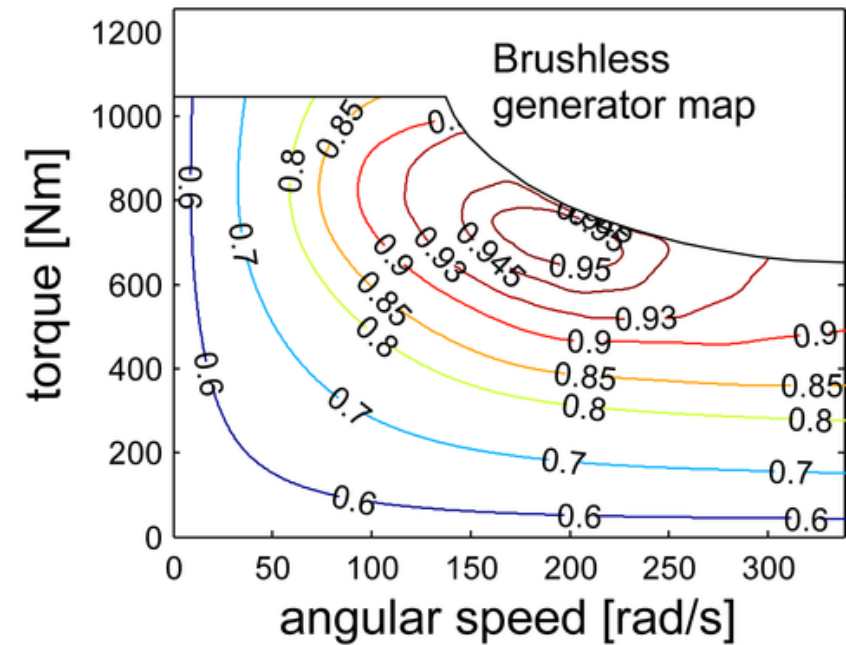
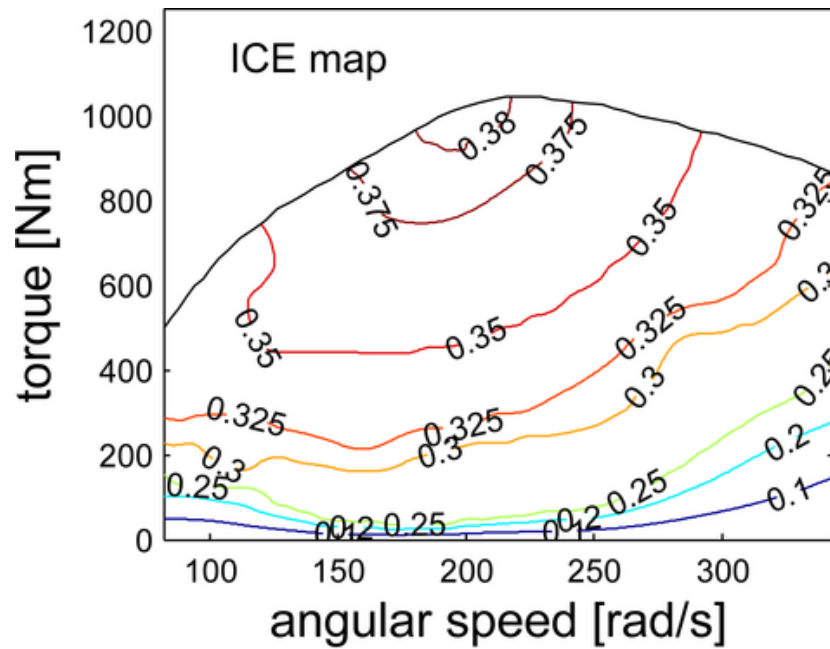


- ▶ ICE: Lav effektivitet
- ▶ Opererer sjældent på det mest optimale arbejds punkt



ICE vs elmotorer

- ▶ Elmotorer har langt bedre effektivitet end forbrændingsmotoren (ICE)
- ▶ Høj moment i stor hastighedsområde -> Kun brug for ét udvekslingsforhold i stedet for 5-6 gear



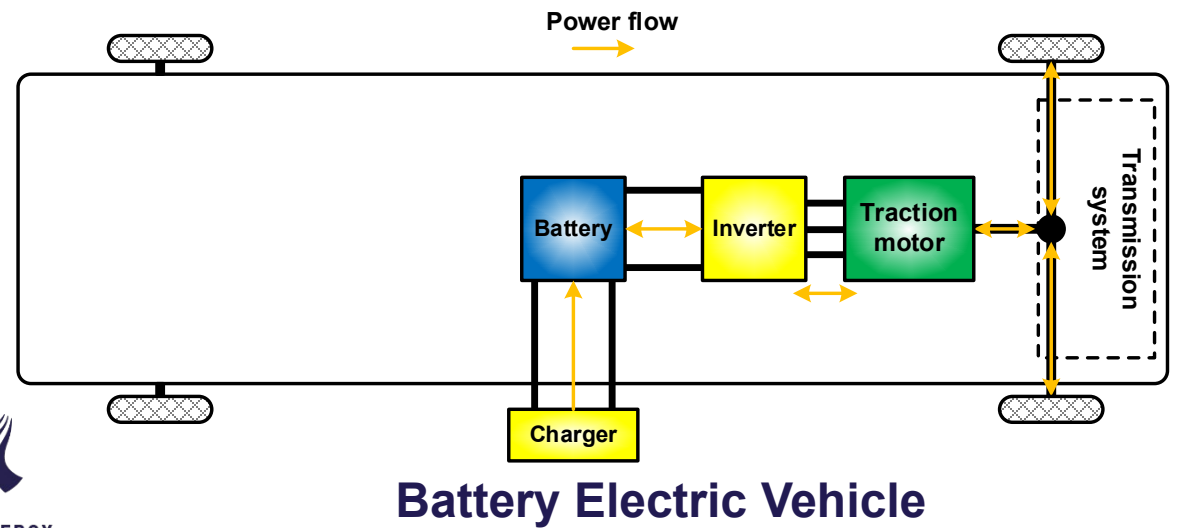
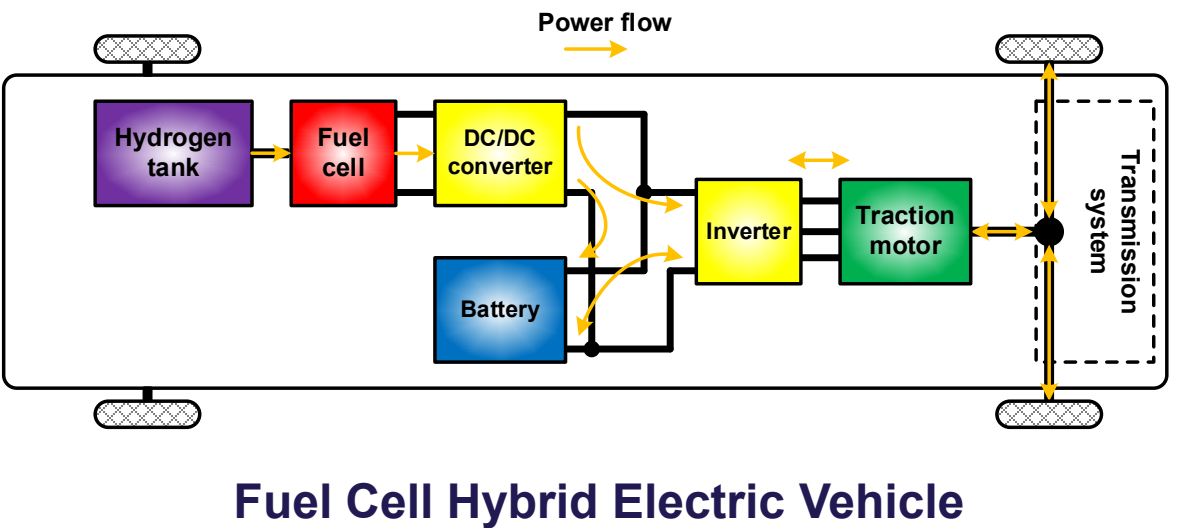
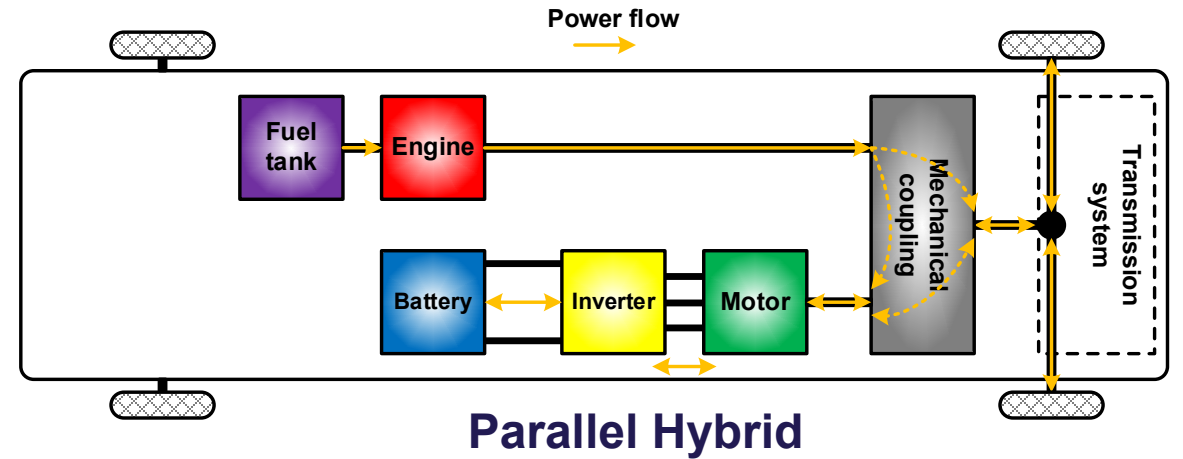
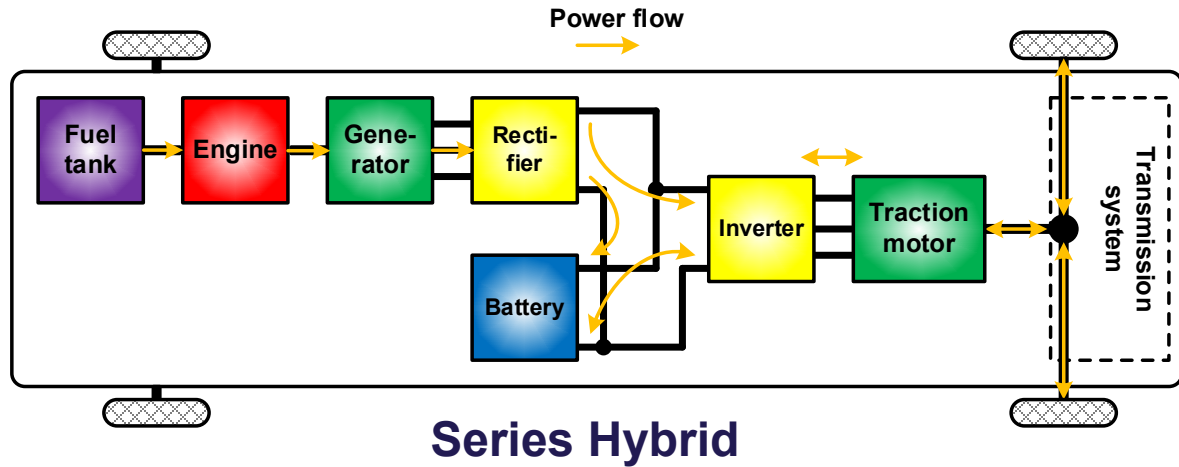
Bottiglione, F.; Contursi, T.; Gentile, A.; Mantriota, G. The Fuel Economy of Hybrid Buses: The Role of Ancillaries in Real Urban Driving. *Energies* **2014**, *7*, 4202-4220.

DRIVSYSTEM OG KOMPONENTER I ELBILER



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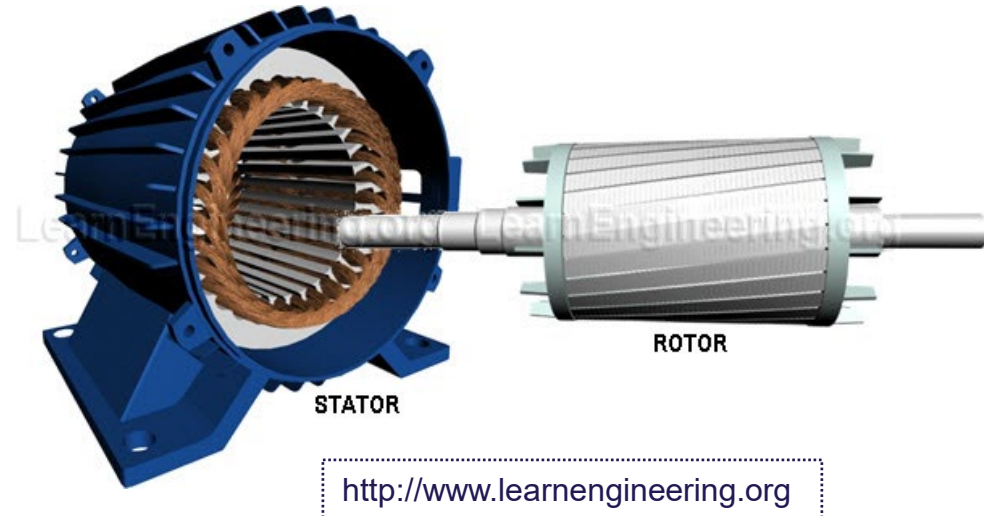
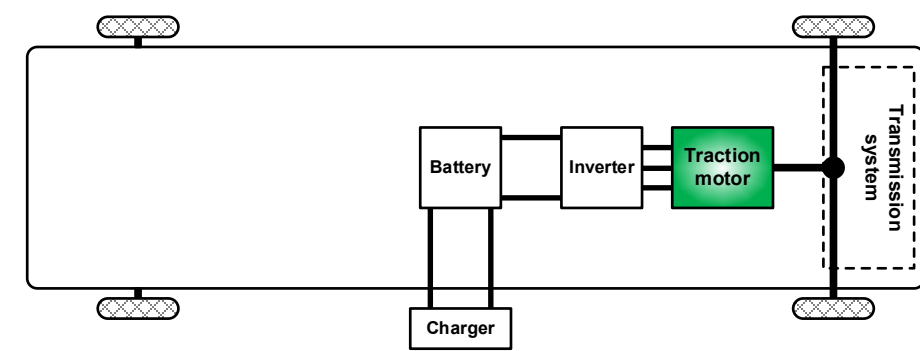
Forskellige typer elektriske drivsystemer



Elmotorer

Induktionsmaskine

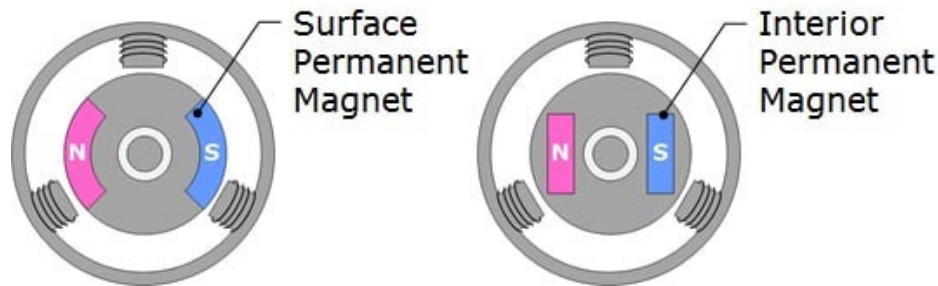
- ▶ Simpel and robust
- ▶ Lav emf (elektromotorisk kraft) ved høje hastigheder
 - ▶ Stort hastighedsområde
- ▶ Strømme i rotoren
 - ▶ Mindre virkningsgrad end permanent magnet (PM) motorer
 - ▶ Fylder og vejer mere for samme effekt end PM motorer



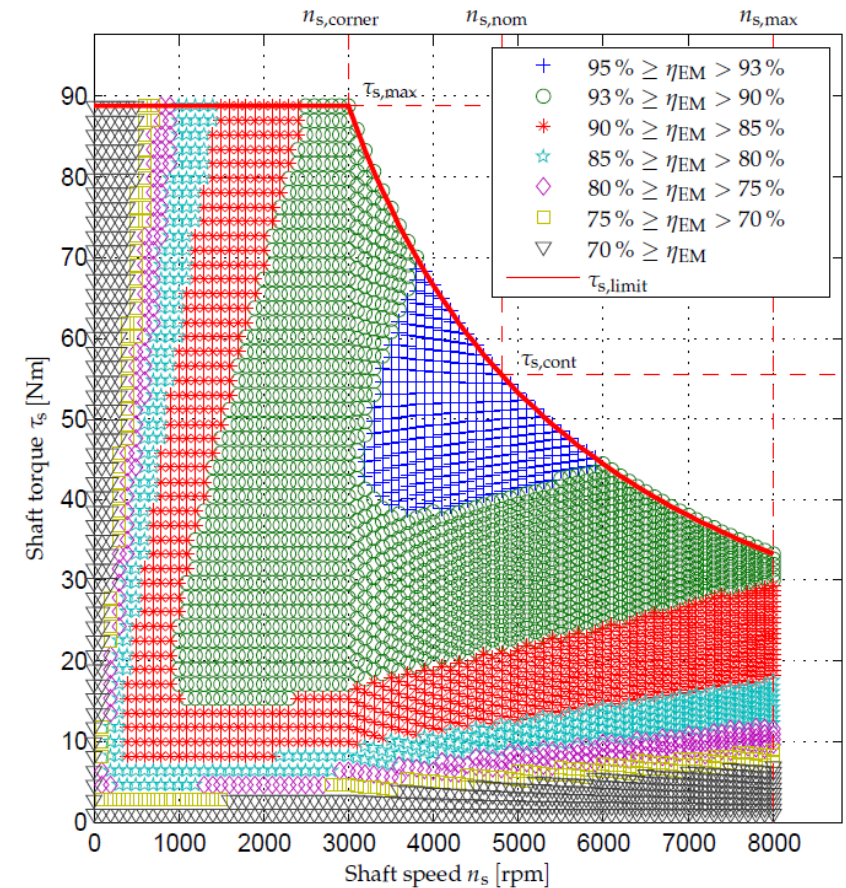
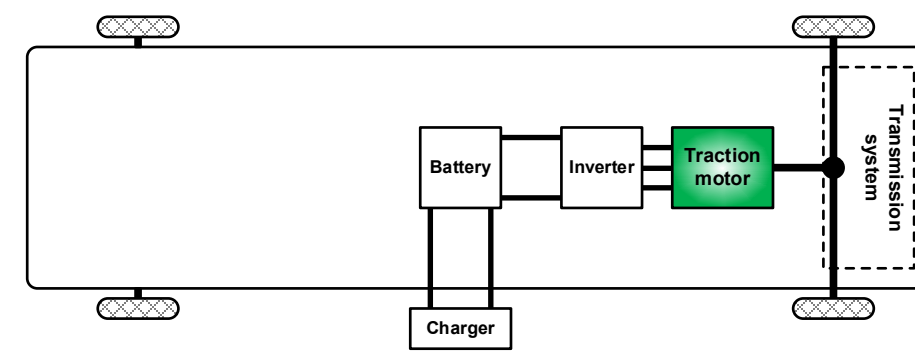
Elmotorer

Permanent Magnet Synkron Maskine (PMSM)

- ▶ "Gratis" magnetfelt fra PM i rotor
 - ▶ Høj effektivitet
 - ▶ Høj effekt og moment densitet
- ▶ Stor emf (elektromotorisk kraft) ved høje hastigheder
 - ▶ Feltsvækning måske nødvendig
 - ▶ Flere gear



www.renesas.com

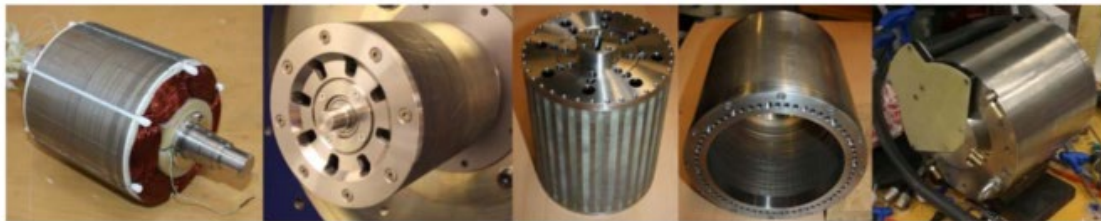
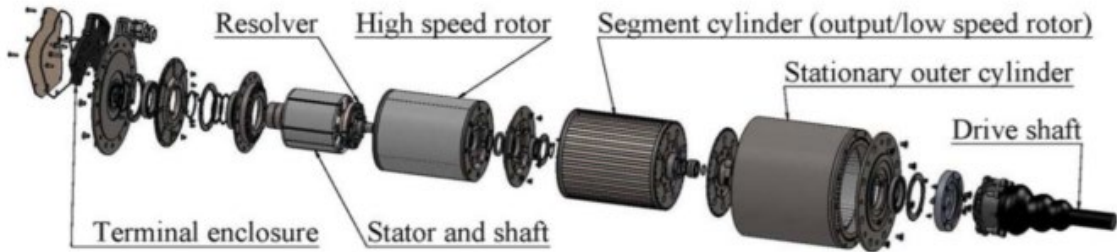


Erik Schaltz (2011). Electrical Vehicle Design and Modeling, Electric Vehicles - Modelling and Simulations, Dr. Seref Soylu (Ed.), InTech,

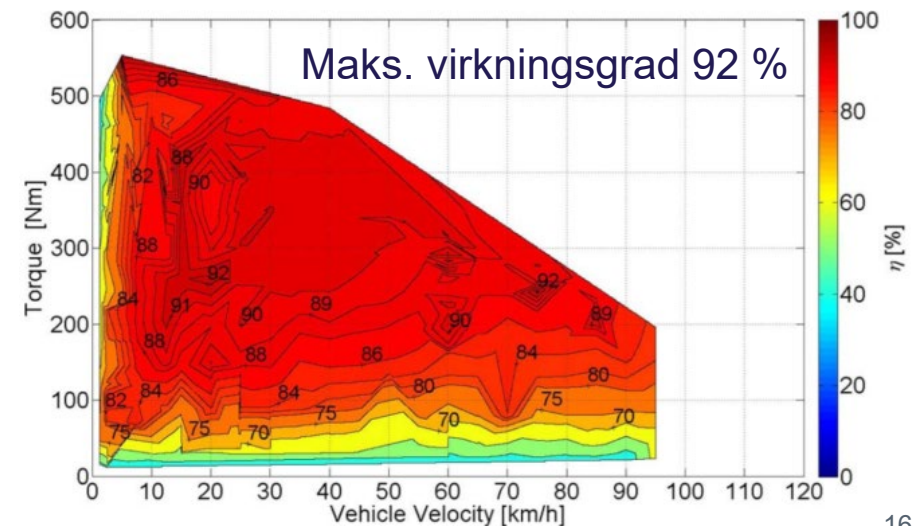
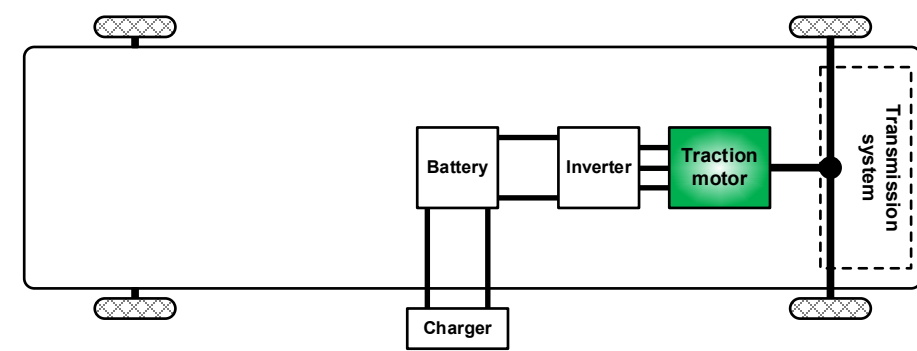
Elmotorer

Motor Integrated Permanent Magnetic Gear

- ▶ Motor og gear i én enhed
- ▶ Kompakt og høj-effektivt system



T. V. Frandsen *et al.*, "Motor Integrated Permanent Magnet Gear in a Battery Electrical Vehicle," in *IEEE Transactions on Industry Applications*, vol. 51, no. 2, pp. 1516-1525, March-April 2015.



Permanent magnet DC maskine

- Velegnet til gymnasie og lavere semestre

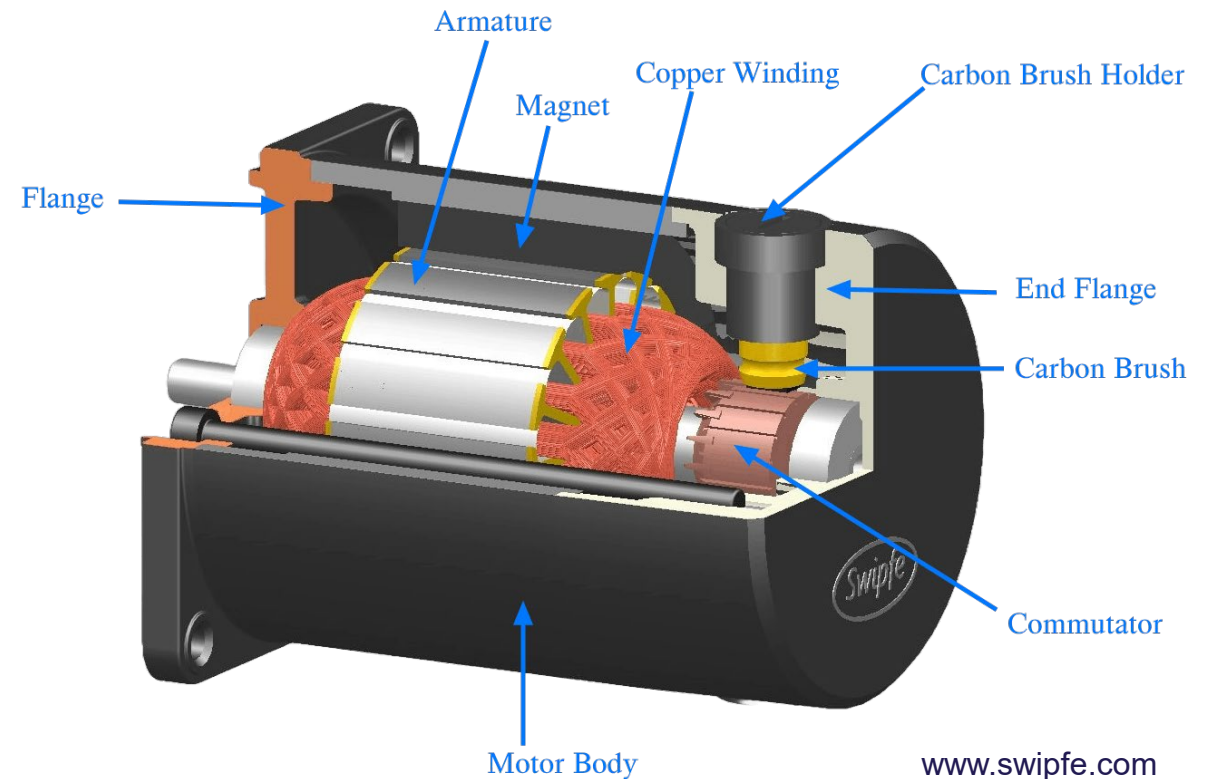
Modeldannelse

► Elektrisk del

- Spændingsfald
 - Resistans og induktans i viklinger
 - Børster
- Induceret spænding (back emf)

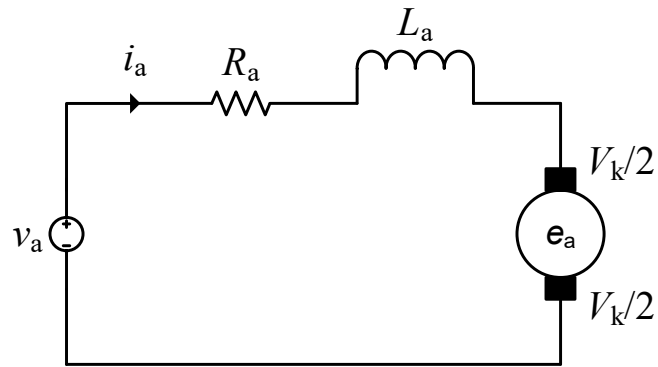
► Mekanisk del

- Statisk og dynamisk friktion
- Inerti i rotor aksel
- Last



Elektrisk maskine

- Elektrisk model



$$v_a = R_a i_a + L_a \frac{di_a}{dt} + V_k + e_a$$
$$e_a = K_\varphi \omega$$

- v_a [V], terminal spænding
- i_a [A], strømmen
- R_a [Ω], resistans i viklingerne
- L_a [H], motorens induktans
- V_k [V], spændingsfald over kullene
- e_a [V], induceret spænding
- K_φ [Vs], motor konstant
- ω [rad/s], Vinkelhastighed af rotor

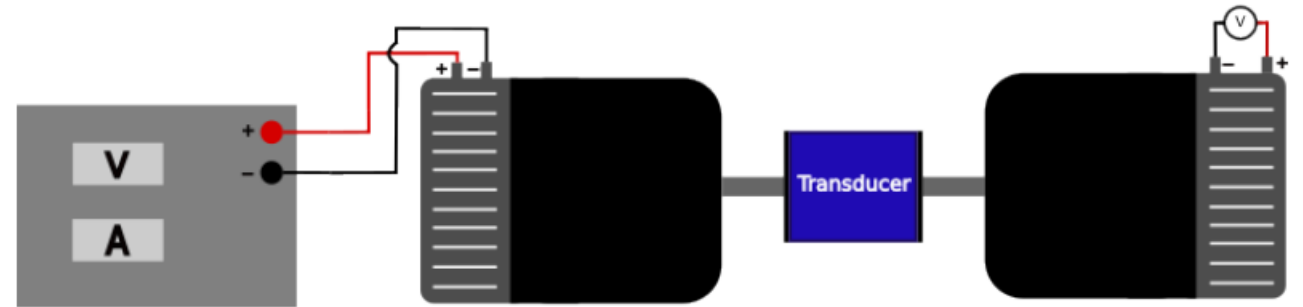


Elektrisk maskine

- Parameterbestemmelse: Motor konstant

Fremgangsmåde

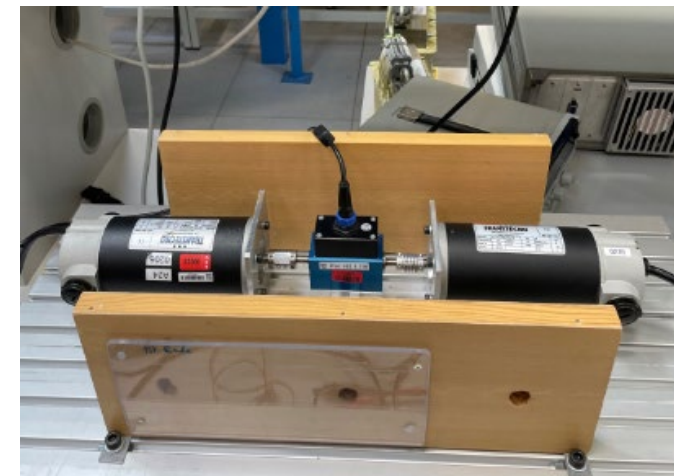
1. Motoren **drives** af en **anden motor**
2. Den **inducerede spænding** aflæses på terminalerne med et multimeter
3. Gentages for flere hastigheder



Fra studenterrapport

Reduceret ligning

$$\cancel{v_a = R_a i_a + L_a \frac{di_a}{dt} + V_k + e_a} \quad \Rightarrow V_a = e_a = K_\varphi \omega$$
$$e_a = K_\varphi \omega$$



Elektrisk maskine

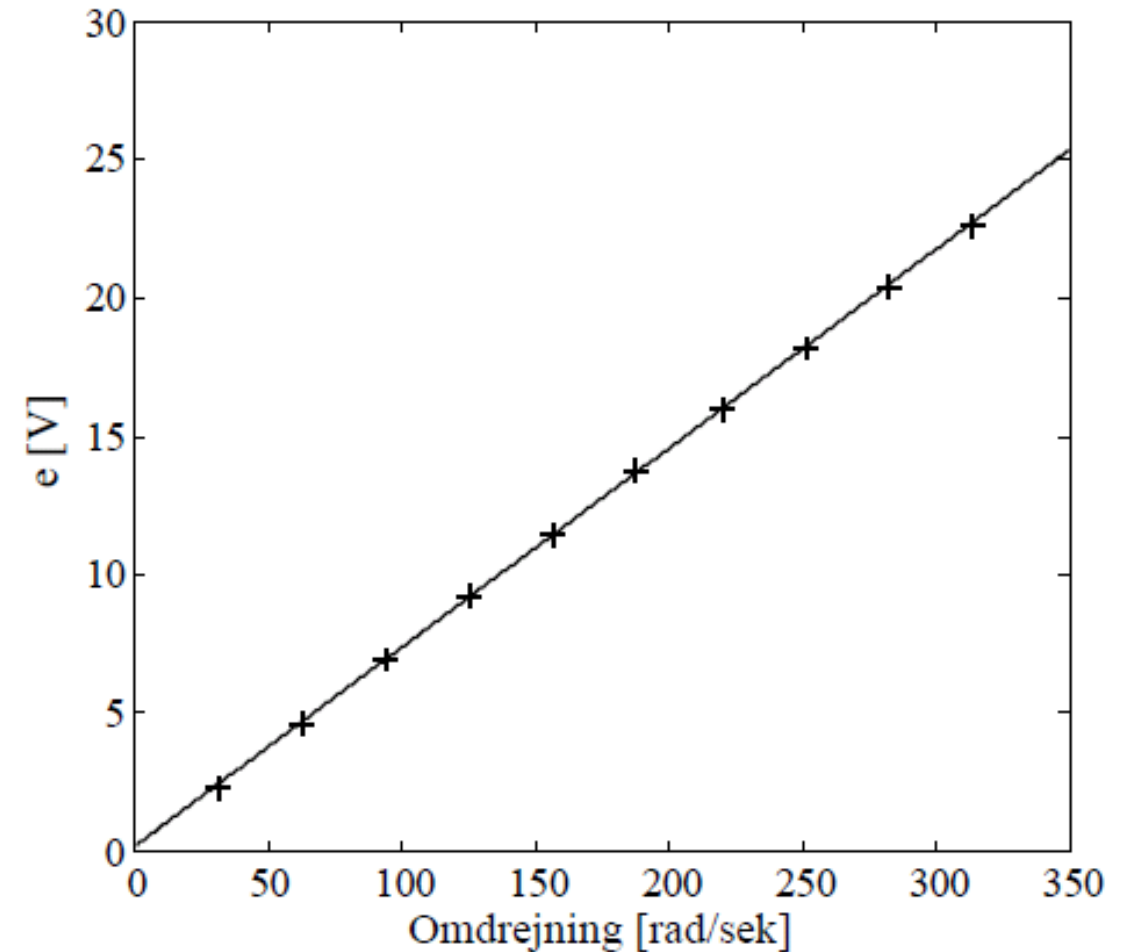
- Parameterbestemmelse: Motor konstant

Aflæsning

- $K_\varphi = 72 \text{ mVs}$, hældning på kurve

$$V_a = e_a = K_\varphi \omega$$

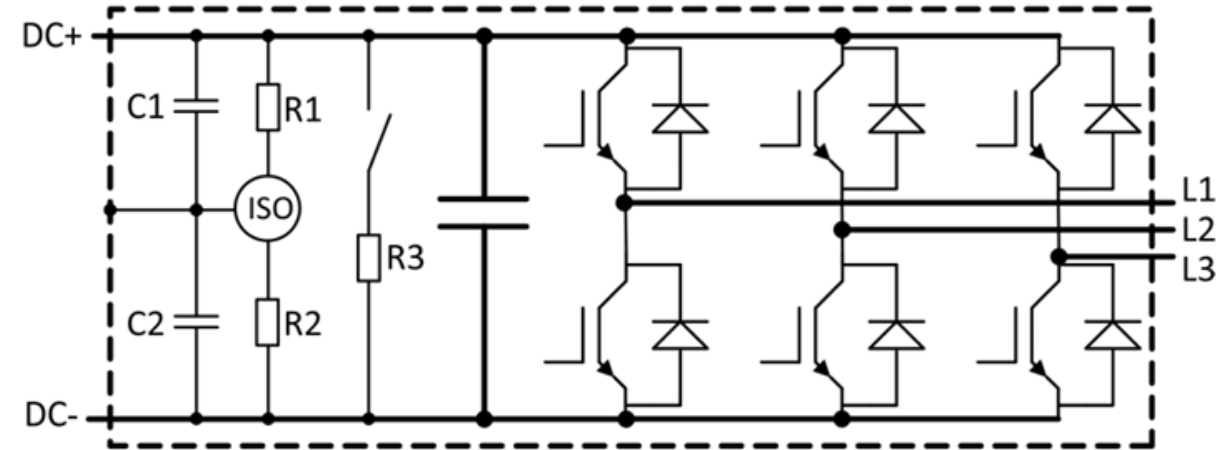
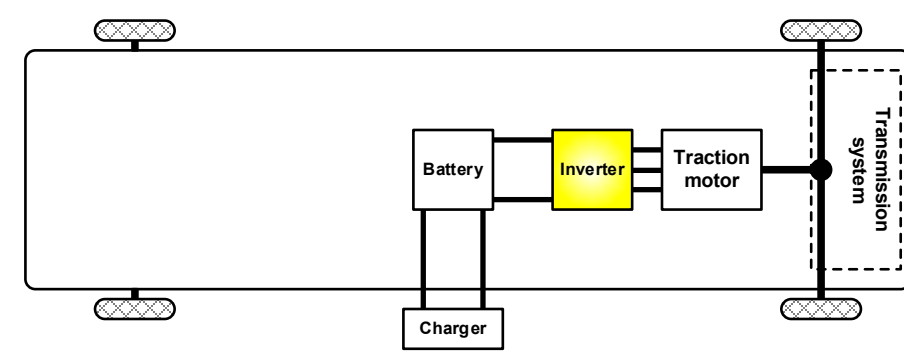
Fra studenterrapport



Inverter

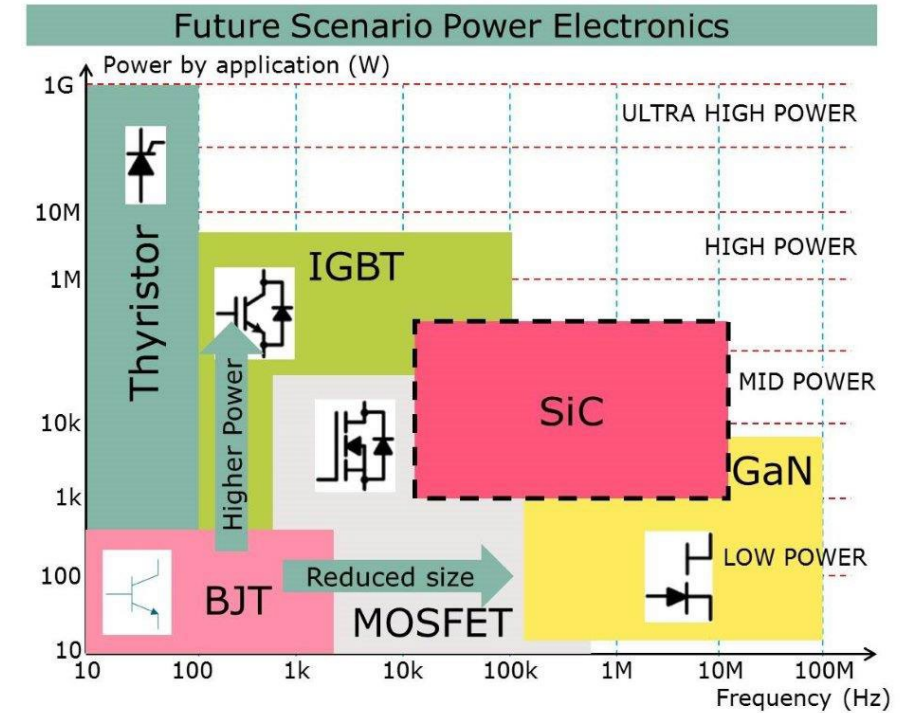
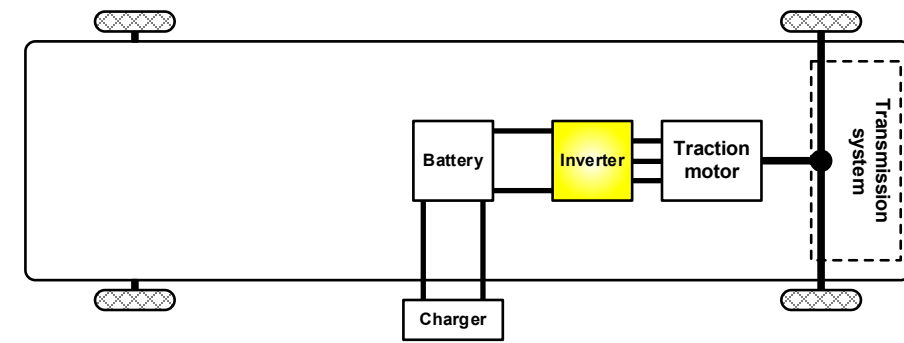
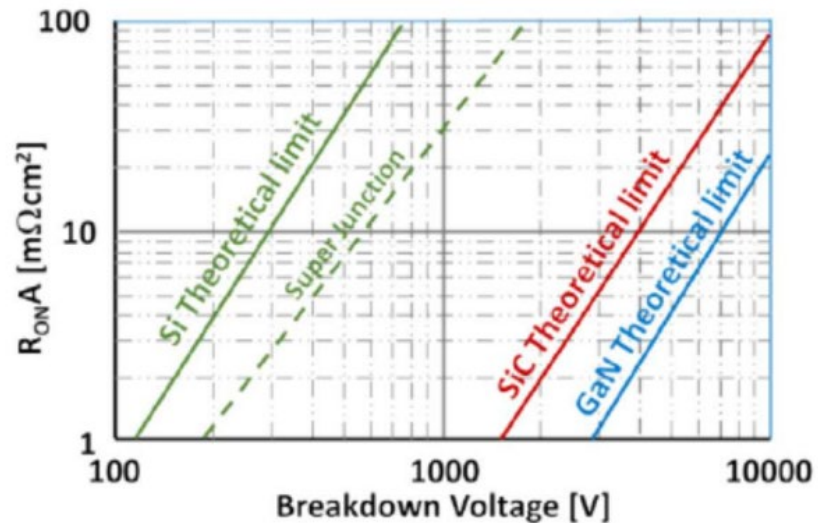
AC/DC konvertering

- ▶ Seks halvledere tændes og slukkes flere tusind gange i sekundet
 - ▶ Insulated-gate bipolar transistor (IGBT)
 - ▶ Metal-oxide-semiconductor field-effect transistor (MOSFET)
- ▶ Gør energien kontrollerbar
 - ▶ Roterende felt
 - ▶ Styre strøm og spænding
 - ▶ Styrer moment og hastighed af motor
 - ▶ Søger for rekuperering



Halvledere – Trends

- ▶ Wide band gap semiconductors
 - ▶ Silicon Carbide (SiC)
 - ▶ Gallium Nitride (GaN)
- ▶ Fordele
 - ▶ Højere spændingstolerance
 - ▶ Lav resistans
 - ▶ Højere temperaturtolerance

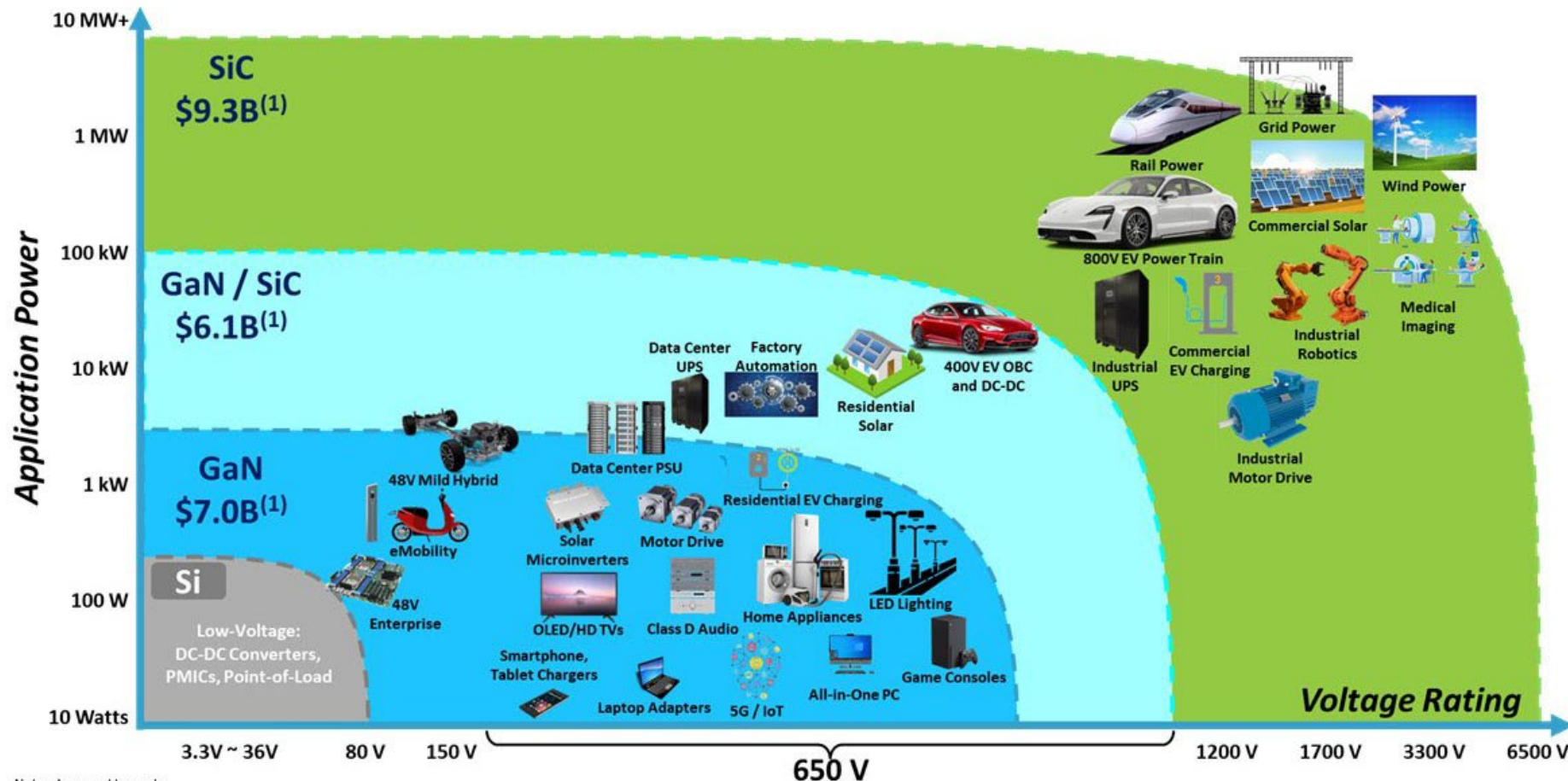
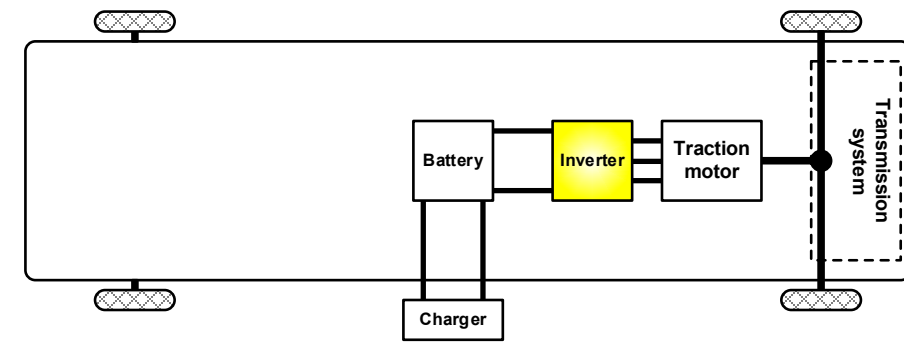


Bodo's Power System

A. Imbruglia, F. Gennaro and G. Di Marco, "Silicon and Wide Bandgap technologies in automotive power electronics and their applications," 2021 AEIT International Conference on Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), 2021, pp. 1-4, doi: 10.23919/AEITAUTOMOTIVE52815.2021.9662954.

Halvledere – Trends

► GaN og SiC anvendelsesområde

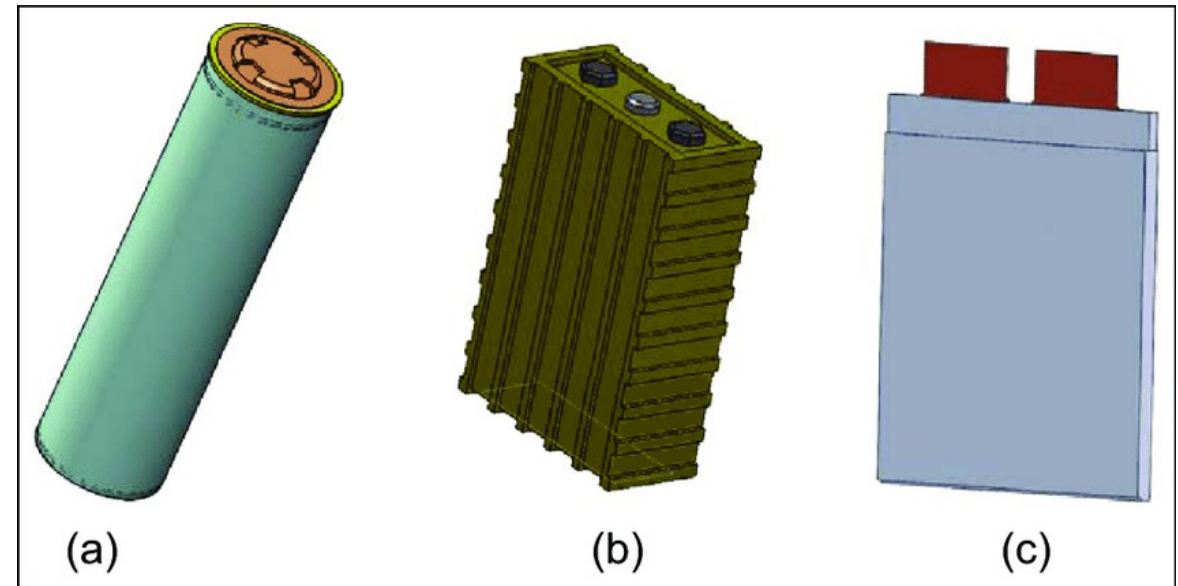
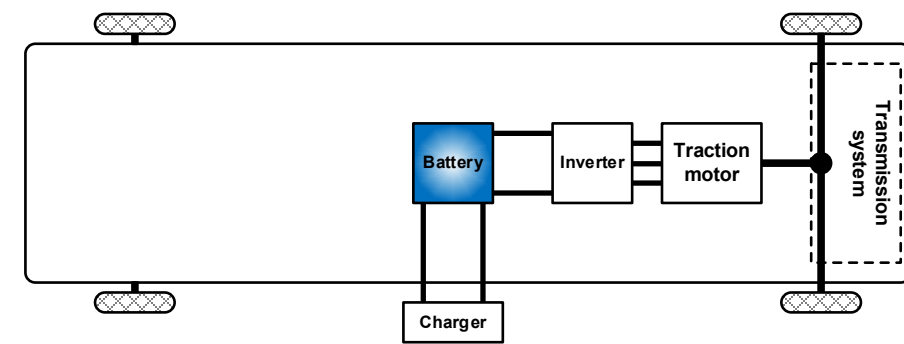


Note: Axes not to scale.
1) 2026E potential.

Batterier

Litium-Ion batterier

- ▶ Foretrukken batteri til hybrid- og batterielbiler
- ▶ Videreudvikling af teknologi fra mobiltelefoner og labtops
- ▶ Tre typer
 - ▶ Cylindriske celler (a)
 - ▶ Prismatiske celle (b)
 - ▶ Pose (pouch) celler (c)

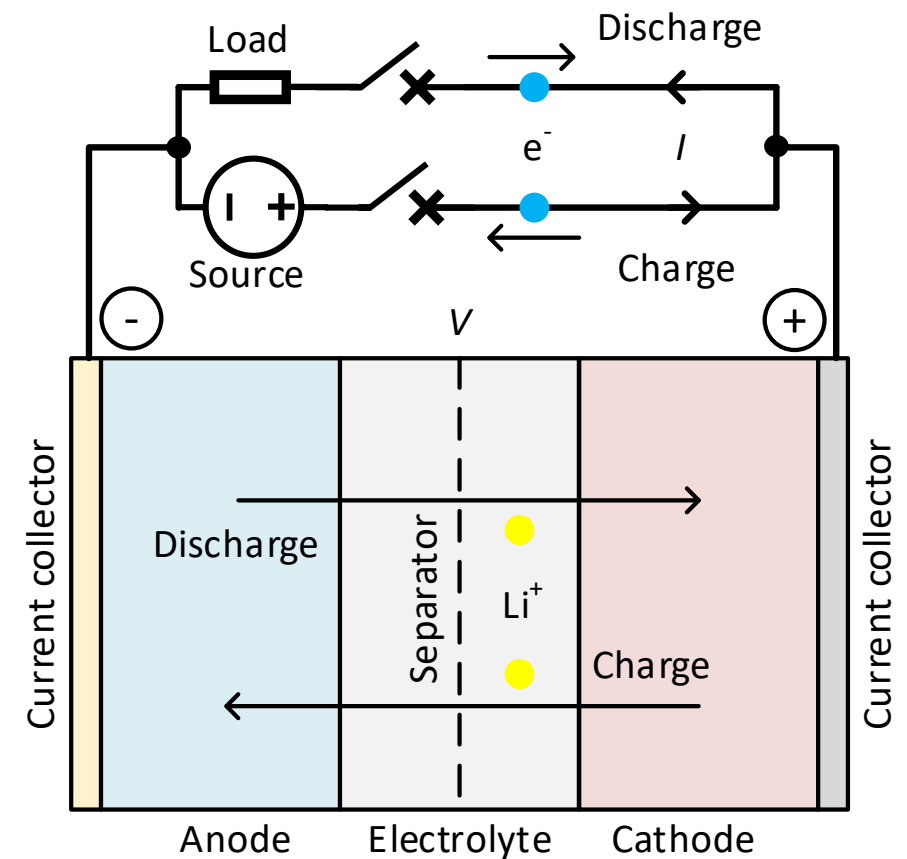
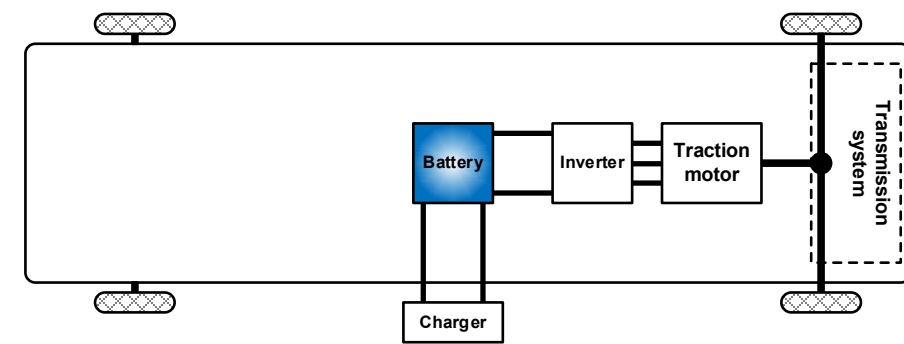


Budde-Meiwes, Heide & Drillkens, Julia & Lunz, Benedikt & Muennix, Jens & Lehner (maiden name Rothgang), Susanne & Kowal, Julia & Sauer, Dirk Uwe. (2013). A review of current automotive battery technology and future prospects. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 227. 761-776. 10.1177/0954407013485567.

Batterier

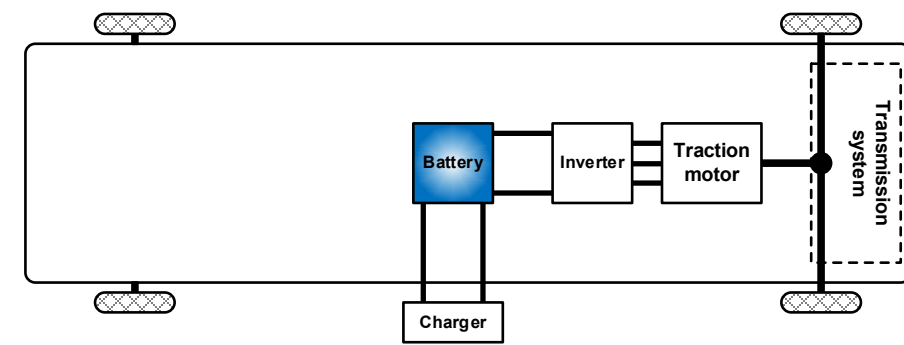
Litium-Ion batterier

- ▶ Lithium-ion og elektron bevæger sig hver sin vej fra/til anoden til/fra katoden
- ▶ Ofte benyttede materialer:
 - ▶ Seperator: Porøs polymer film
 - ▶ Elektrolyt: Lithium salt opløsning eller polymer
 - ▶ Current collectors
 - ▶ Anode: Kobber
 - ▶ Katode: Aluminium
 - ▶ Elektroder
 - ▶ Anode: Grafit (oftest), silicium eller titanium
 - ▶ Katode: Forskellige typer metaller afgør batteritypen og egenskaberne

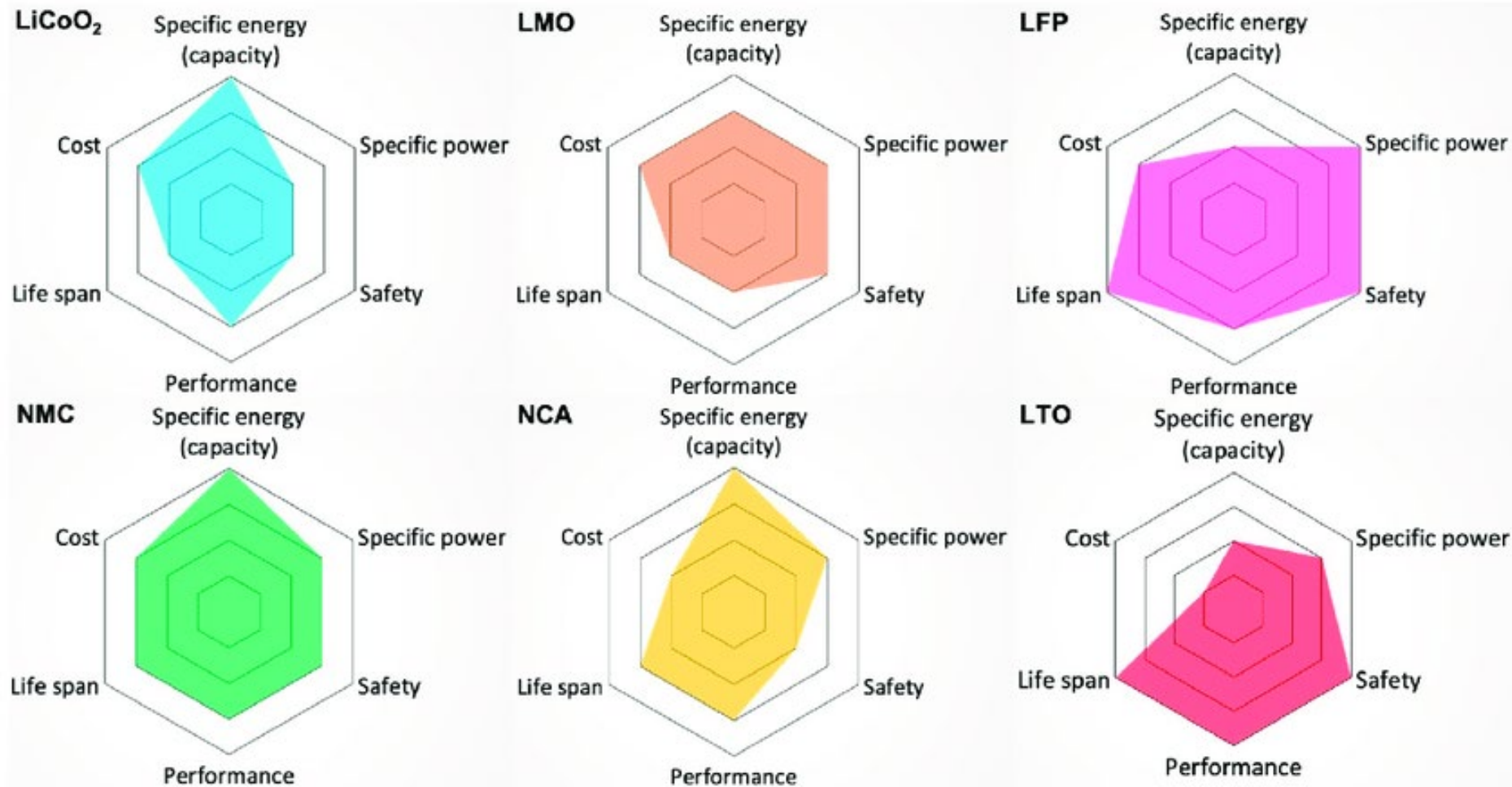


Batterier

Miao, Y.; Hynan, P.; von Jouanne, A.; Yokochi, A. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. *Energies* **2019**, *12*, 1074. <https://doi.org/10.3390/en12061074>



Litium-Ion batterityper



Materialefordeling

Eksempel: Materiale mix 60 kWh 185 kg* NMC batteri

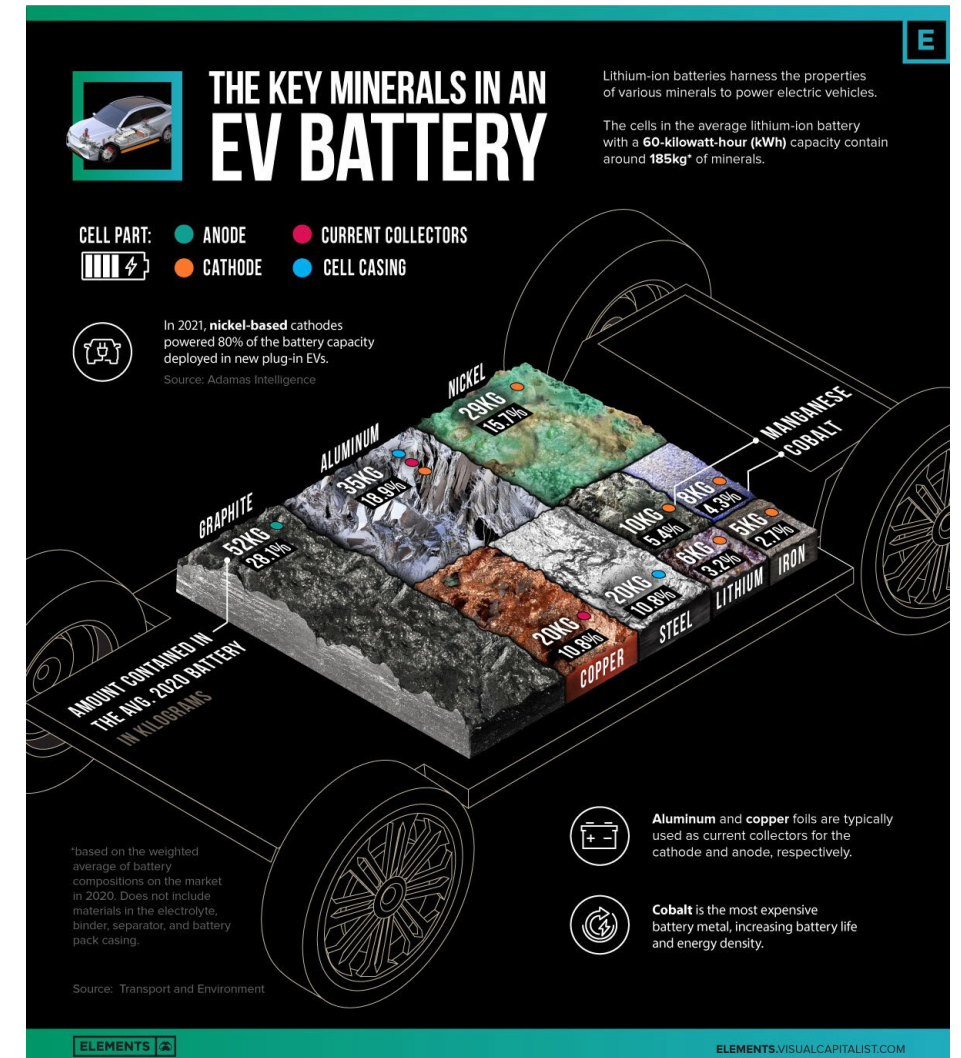
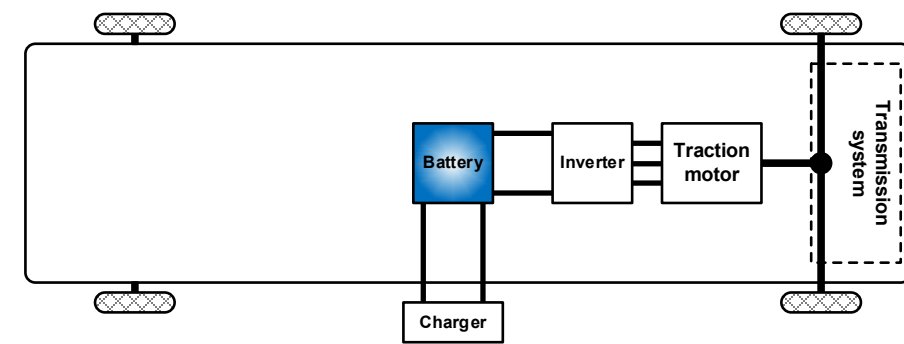
Mineral	Cell Part	Amount Contained in the Avg. 2020 Battery (kg)	% of Total
Graphite	Anode	52kg	28.1%
Aluminum	Cathode, Casing, Current collectors	35kg	18.9%
Nickel	Cathode	29kg	15.7%
Copper	Current collectors	20kg	10.8%
Steel	Casing	20kg	10.8%
Manganese	Cathode	10kg	5.4%
Cobalt	Cathode	8kg	4.3%
Lithium	Cathode	6kg	3.2%
Iron	Cathode	5kg	2.7%
Total	N/A	185kg	100%

<https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/>

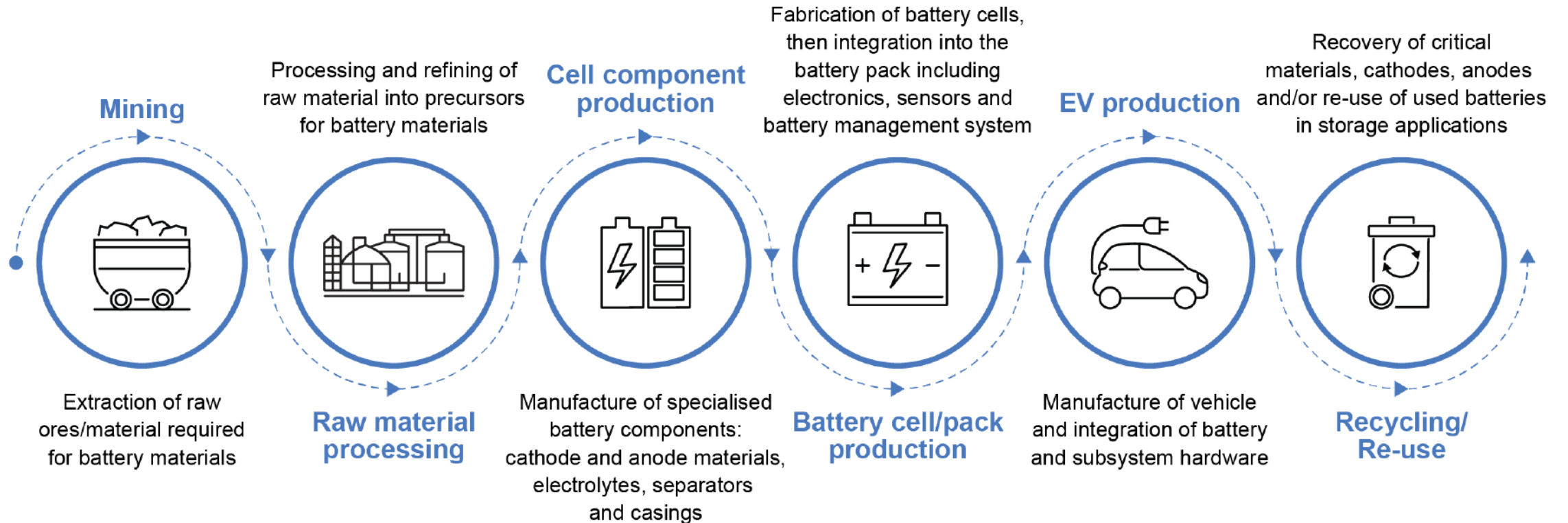
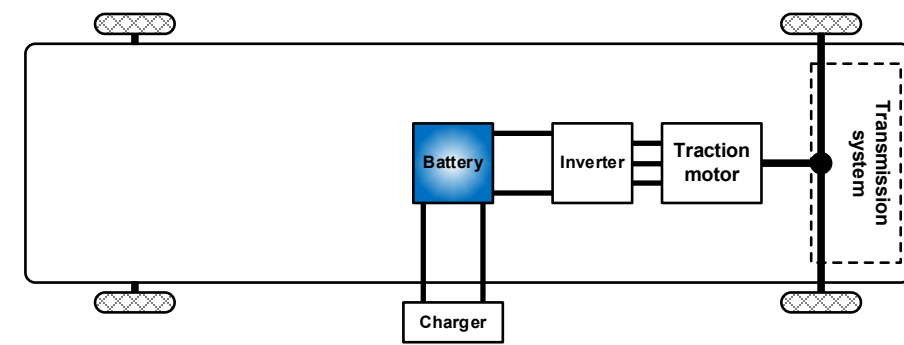
*Elektrolyt, separator, bindingsmaterialer og ramme ikke inkluderet



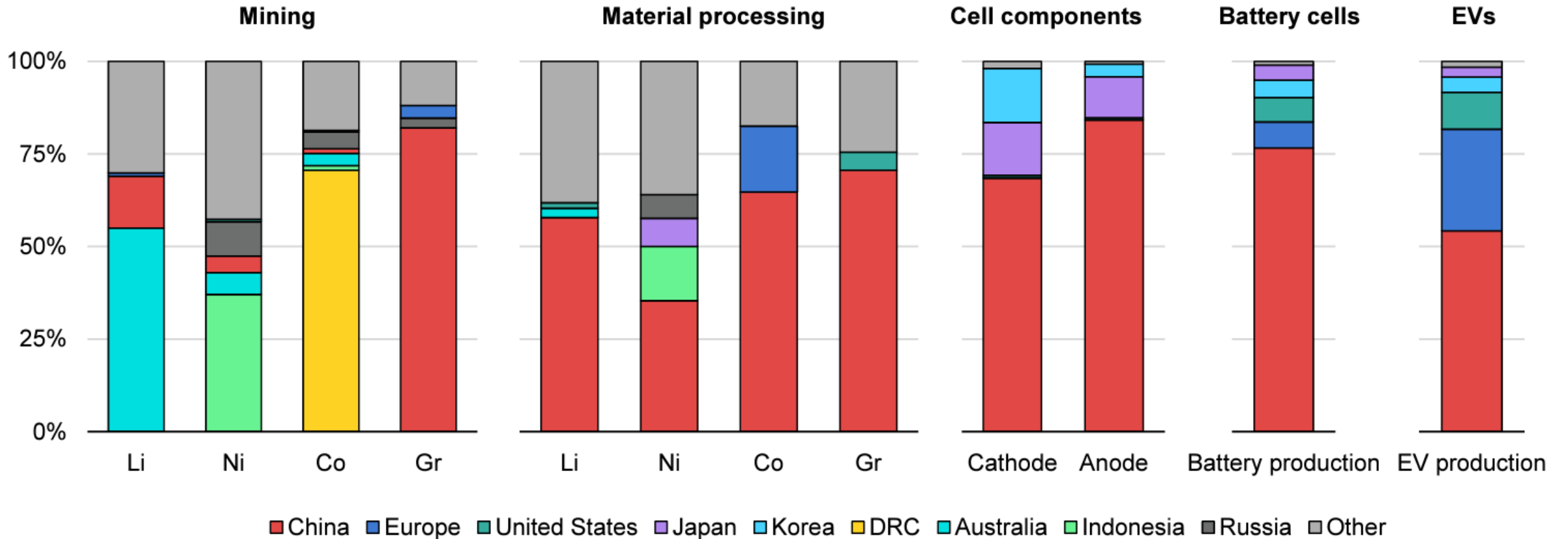
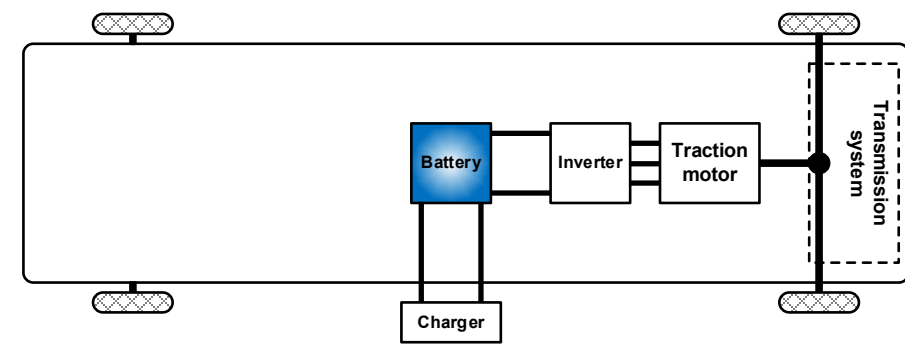
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Forsyningskæde for batterier



Udvinde og produktion af batterier

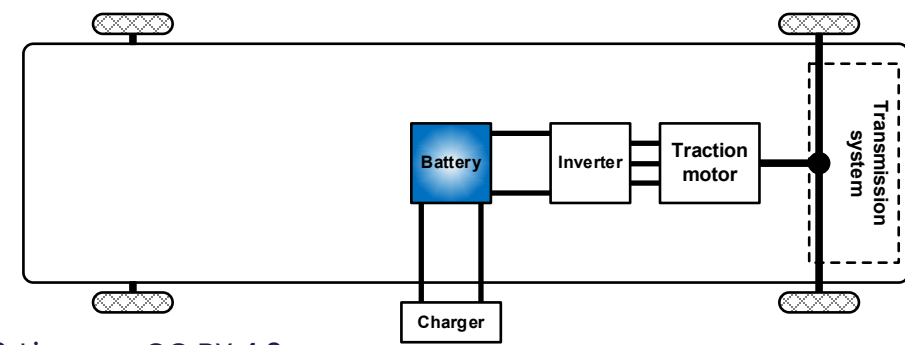


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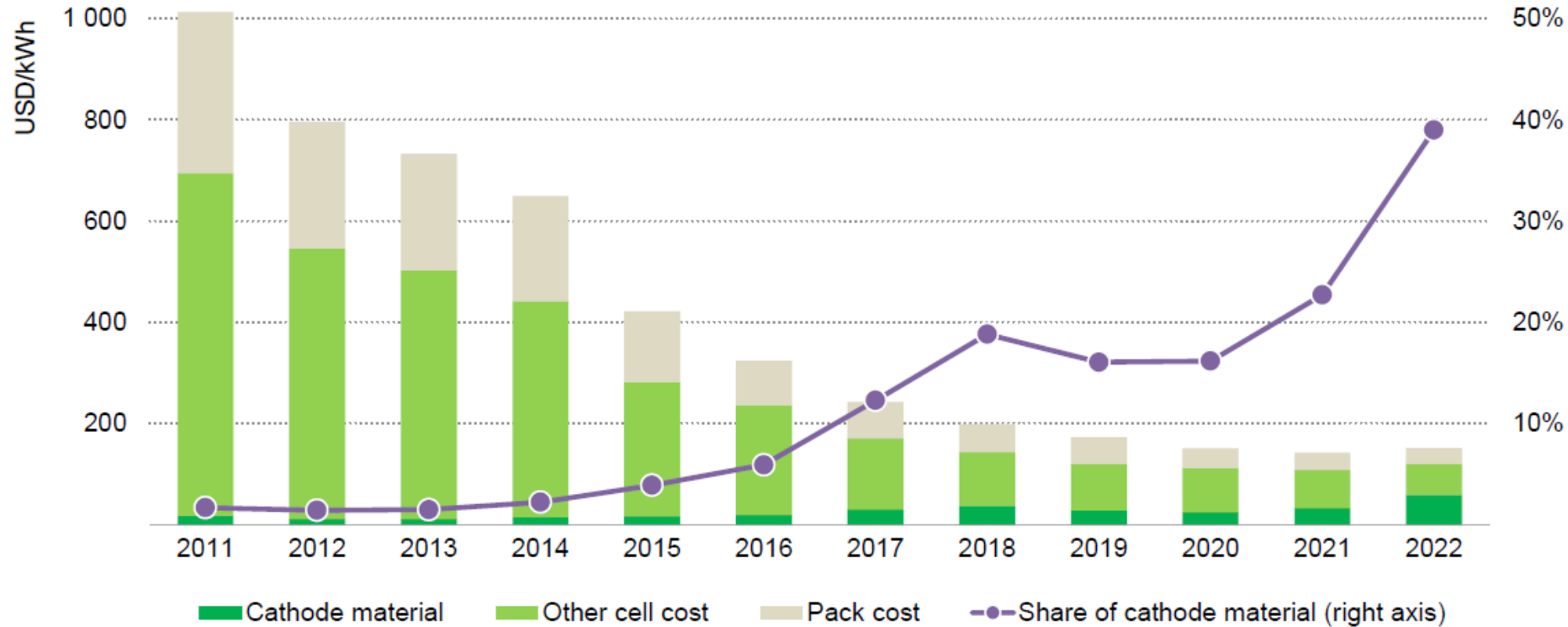
Batterier

Prisudvikling

IEA (2023), Critical Minerals Market Review 2023, IEA, Paris
<https://www.iea.org/reports/critical-minerals-market-review-2023>, Licence: CC BY 4.0



Average pack price of lithium-ion batteries and share of cathode material cost



IEA. CC BY 4.0.

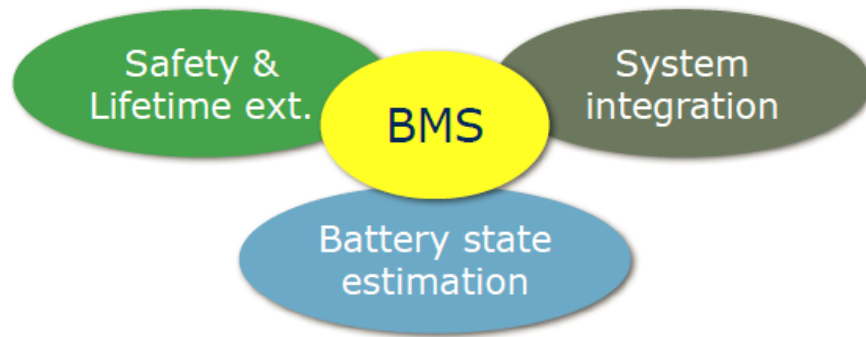
Notes: Cathode material costs include lithium, nickel, cobalt and manganese. Other cell costs include costs for anode, electrolytes, separator and other components as well as costs associated with labour, manufacturing and capital depreciation.

Source: IEA analysis based on [BNEF \(2022\)](#).

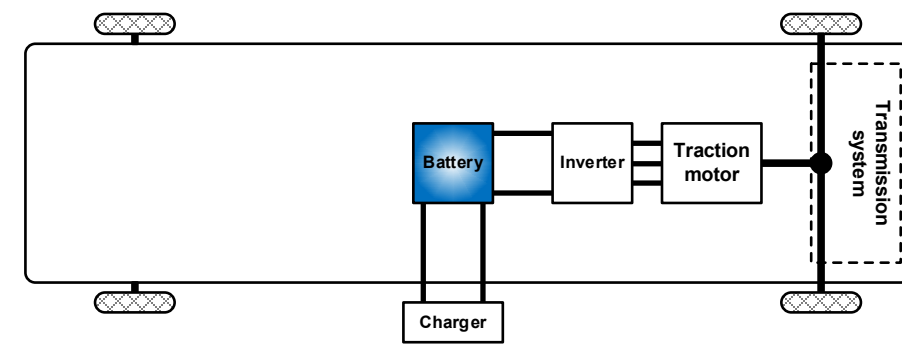
Batterier

Battery-Management-System

- Cell voltage, temperature and current measurement
- Main switch control
- Charge equalization
- Thermal management
- Data/Event logging
- Communication w/ other sub-systems
- Diagnostics & Prognostics



- State-of-Charge (SOC)
- State-of-Health (SOH)
- State-of-Power (SOP)



- Konsekvenser af dårlig batteri håndtering
 - Termisk run-away
 - Lavere batterilevetid
 - Mindre kapacitet (->rækkevidde)



Batterier

Kombineret SoC og SoH estimering

State-of-Charge (SoC): $SOC_t = SOC_{t_0} + \frac{q}{Q_{act}}$

Ladning er integralet af strømmen:

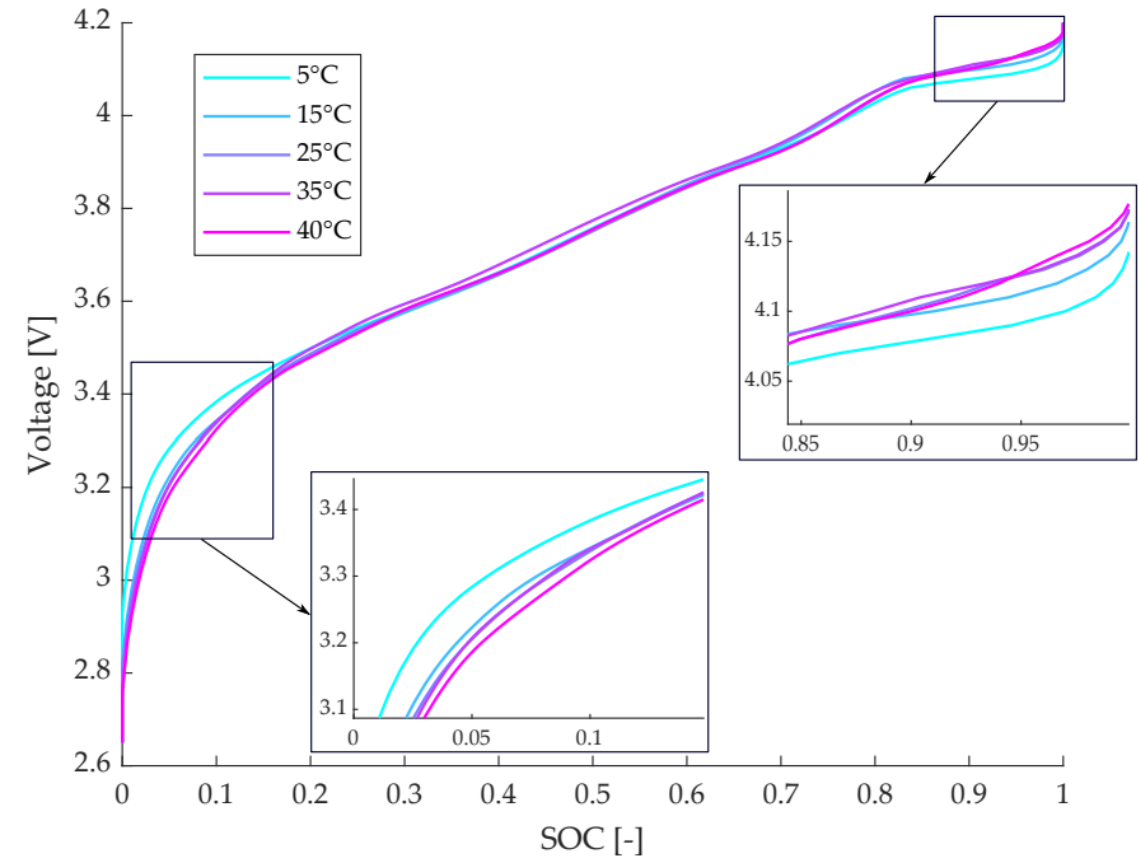
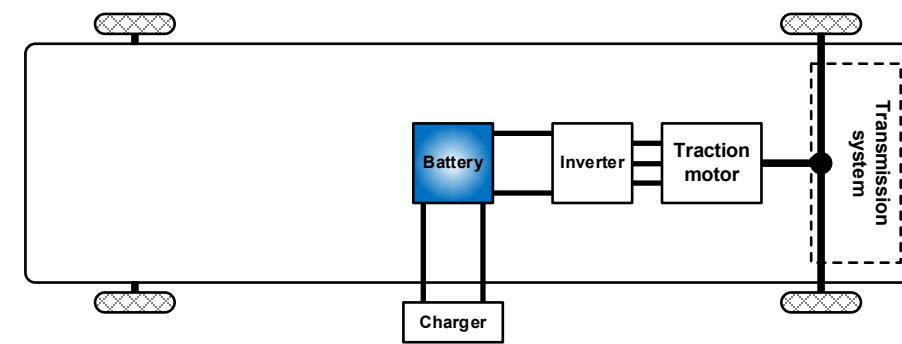
$$q = \int_{t_0}^t c f_{I,T} I_b dt$$

Forholdsvis veldefineret sammenhæng ml. SoC og åbenkredsspænding:

$$\Delta SOC = SOC_t^{OCVupdate} - SOC_{t_0}^{OCVupdate}$$

State-of-Health (SoH) kan estimeres:

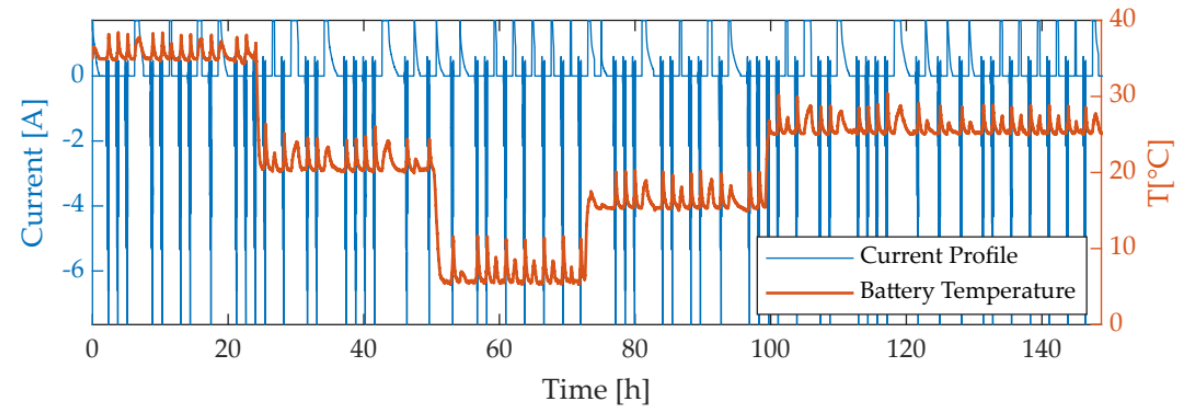
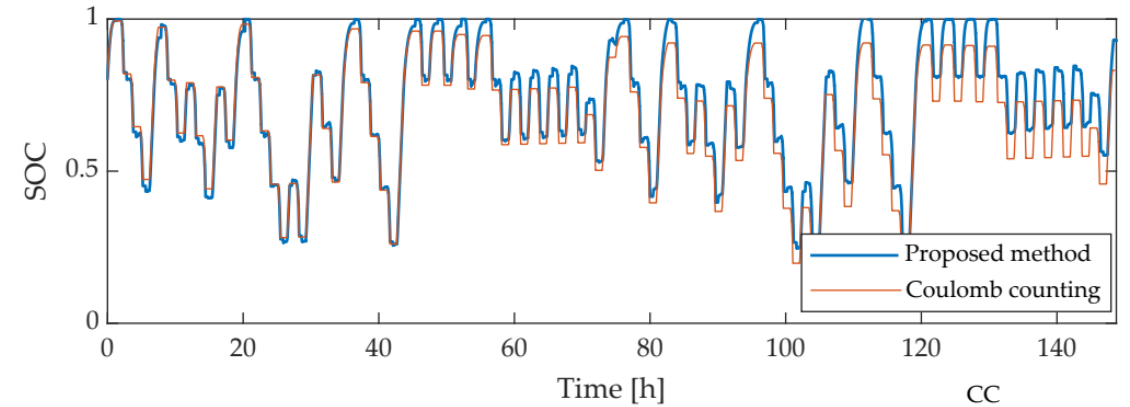
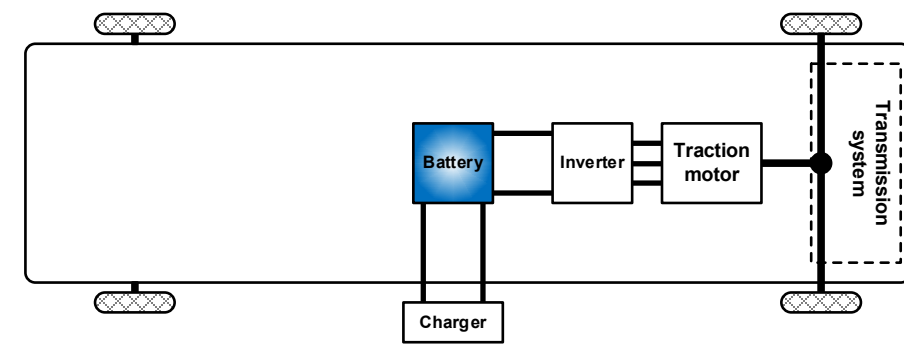
$$Q_{est} = \frac{q}{\Delta SOC}$$



Batterier

Resultater for SoC

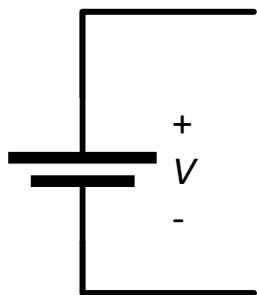
- ▶ Algoritme testet ved forskellige strømme og temperaturer
- ▶ Metoden sammenlignes med simpel strøm-integration (Coulomb counting)
- ▶ Coulomb counting giver fejl over tid, blot der er den mindste fejl i strømsensoren



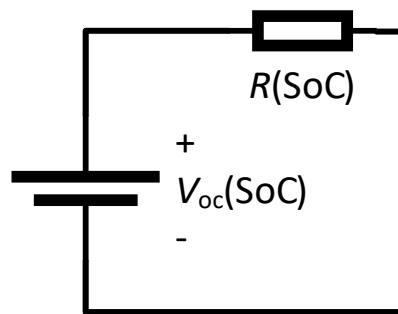
Batteri

- Kredsløbsmodeller

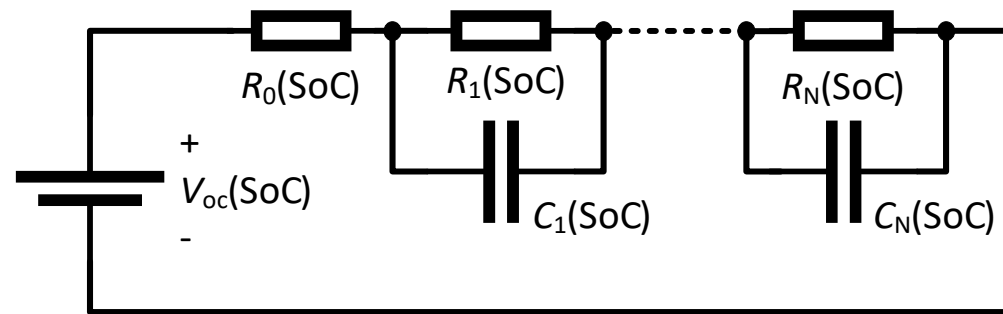
- ▶ Krævet kompleksitet afhænger af formålet med modellen
- ▶ Jo mere kompleks model, jo længere simuleringstid
- ▶ Statisk model godt kompromis mellem præcision og simplificering



Ideal model



Static model



Dynamic model

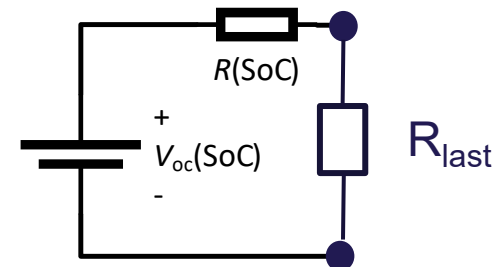


Batteri

- Parameterbestemmelse: OCV og Indre modstand

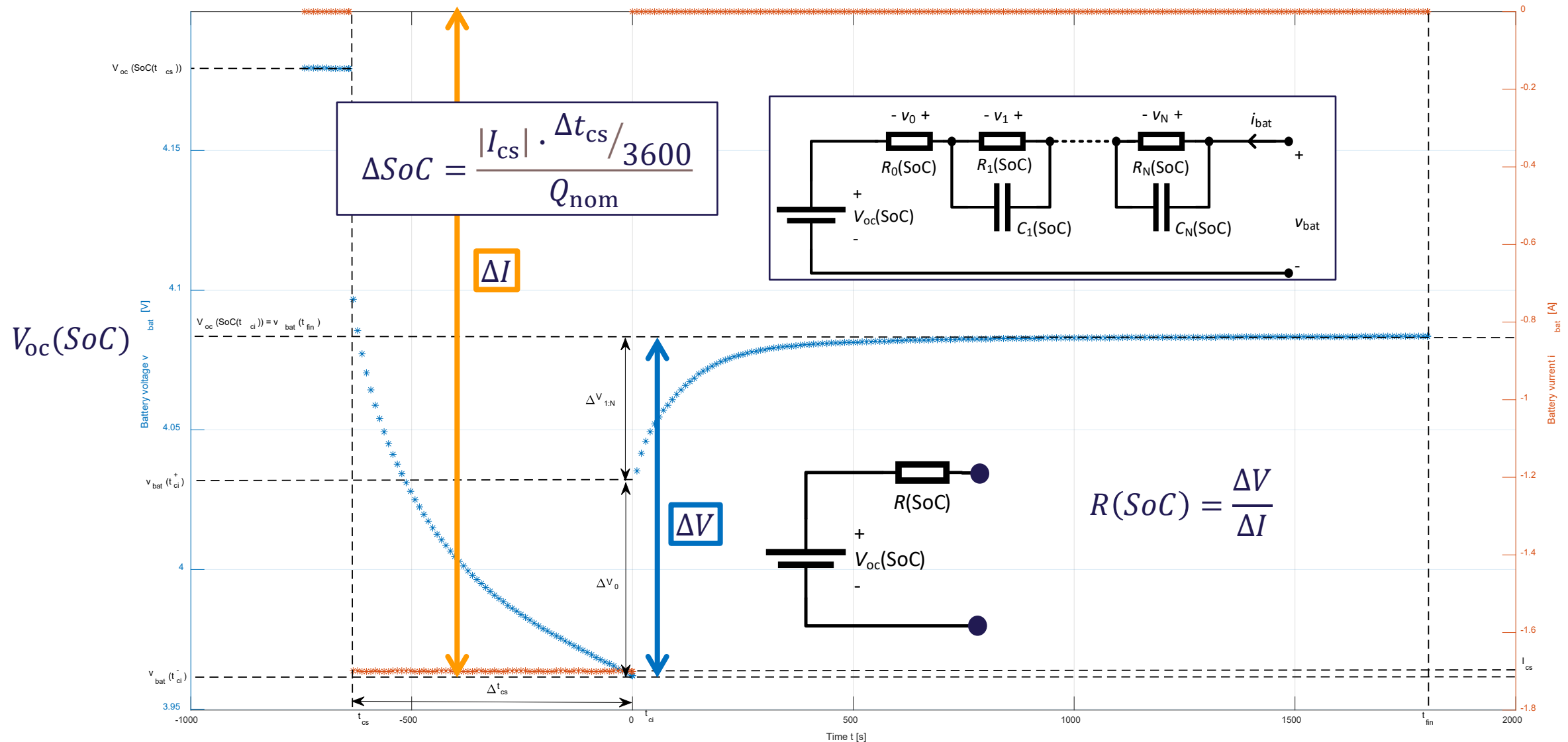
Fremgangsmåde

1. Oplad battericelle med alm. Laboriestrømforsyning
 - **Maks** strøm og **spænding** indstilles **inden opladning!**
2. Vent ca. en halv times tid til spændingen er faldet til ro
3. Aflad enten med en **konstant-strøm-last** eller **modstand** i et **begrænset tidsinterval**
 - F.eks. Step af 10 % SoC
4. Noter **strøm** og **spænding** lige før strømmen afbrydes
5. Vent ca. **en times** tid til spændingen er faldet til ro
6. Noter spændingen efter hvile periode
7. Gentag 3 til 6 indtil **minimum spændingen** nås!



Batteri

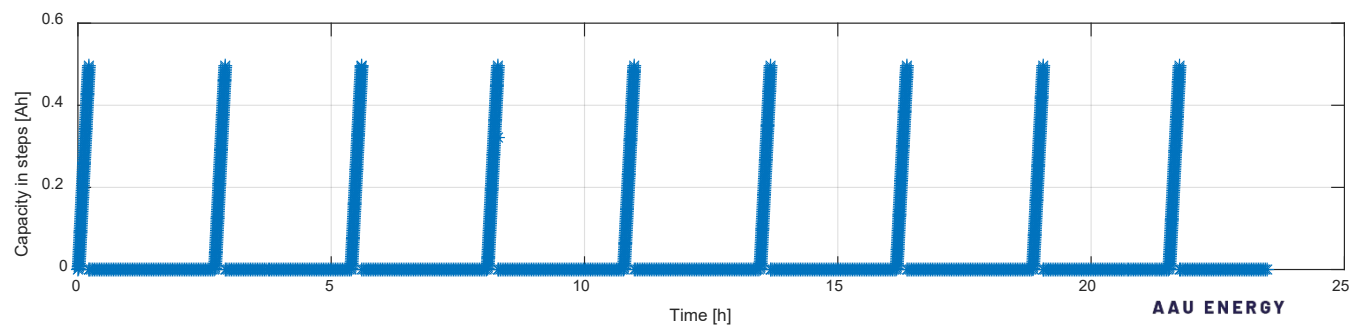
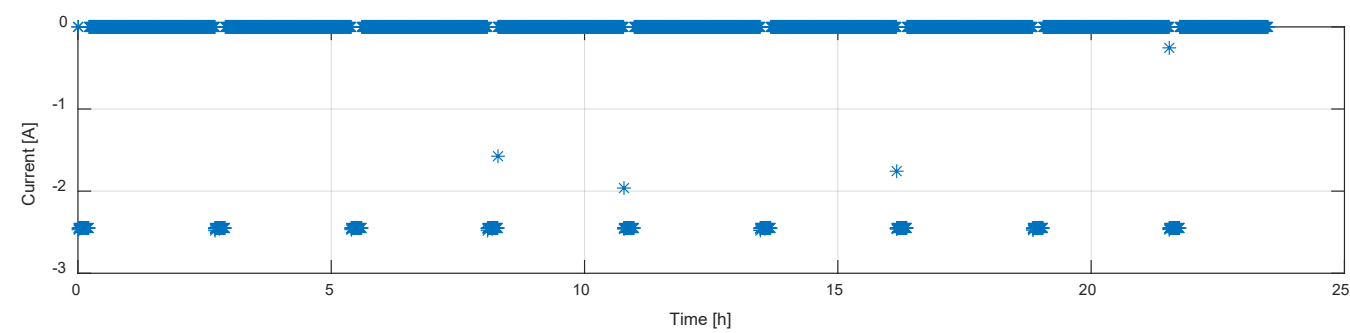
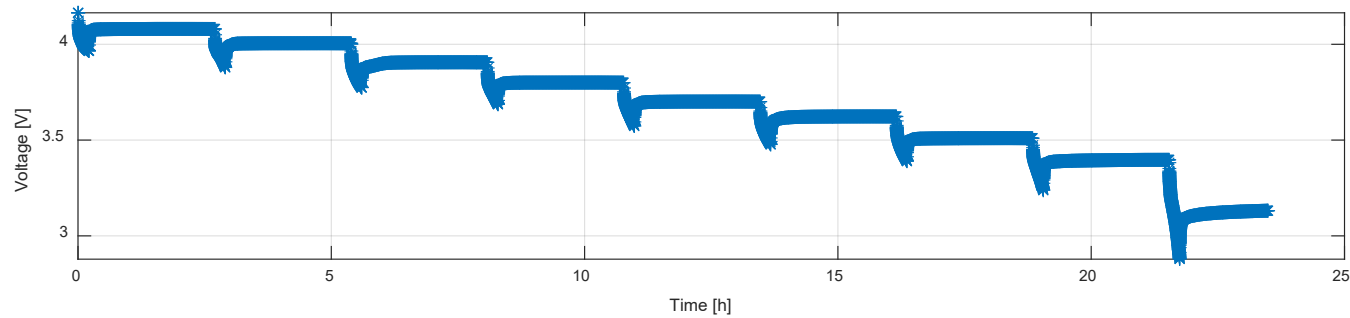
- Parameterbestemmelse: OCV og Indre modstand



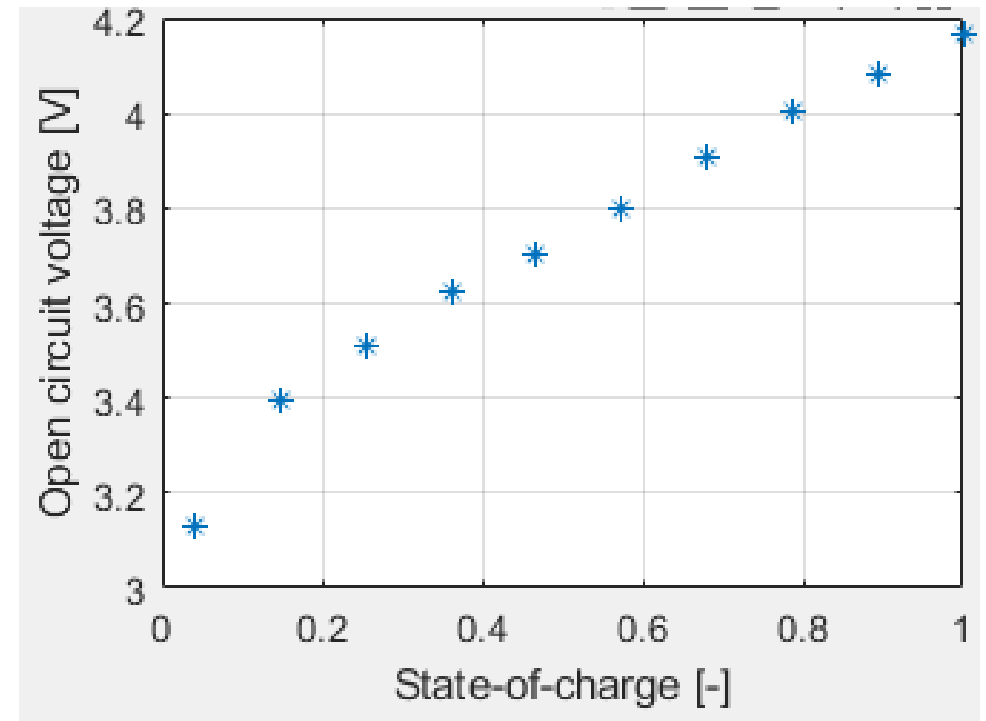
Batteri

- Parameterbestemmelse: OCV og Indre modstand

Eksempel - NMC batteri



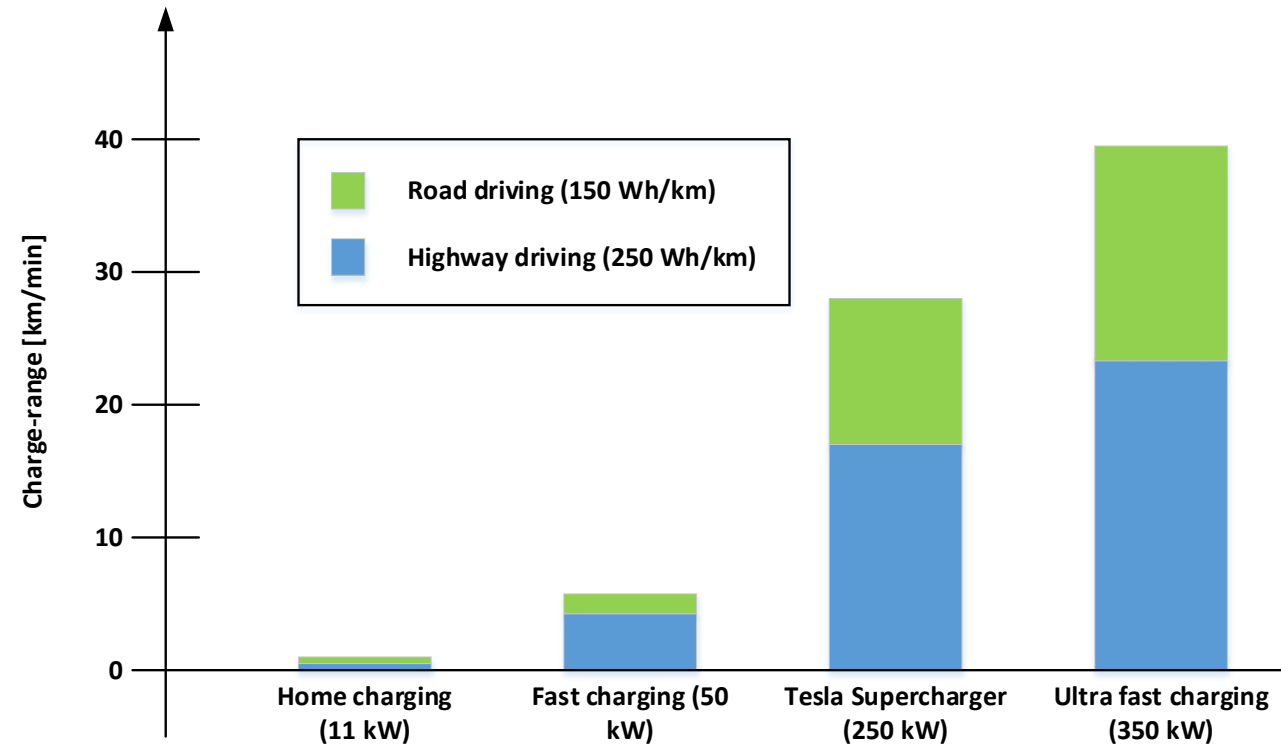
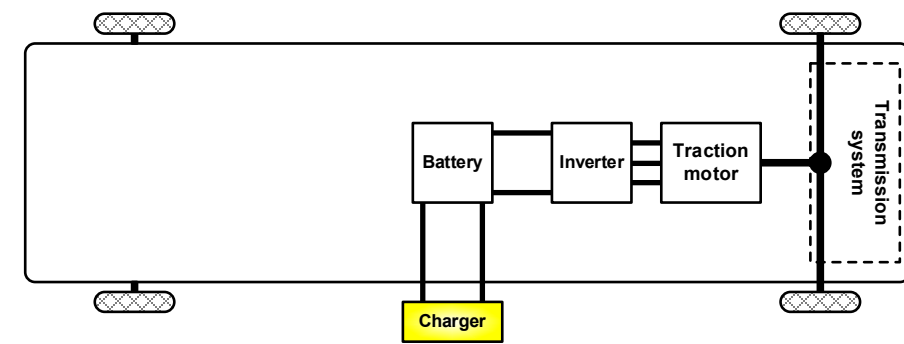
OCV fra hvilespændinger



Lader

Opladning

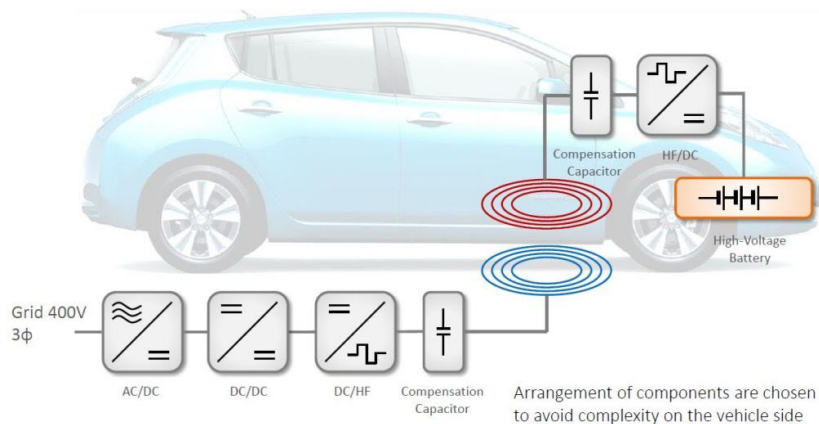
- ▶ Langsom AC opladning derhjemme
- ▶ Lynladning ved DC på farten
- ▶ 350 kW ladere under opførelse
- ▶ I øjeblikket er der dog ingen biler på markedet, som kan klare sådanne store effekter.



Lader

Trådløs opladning

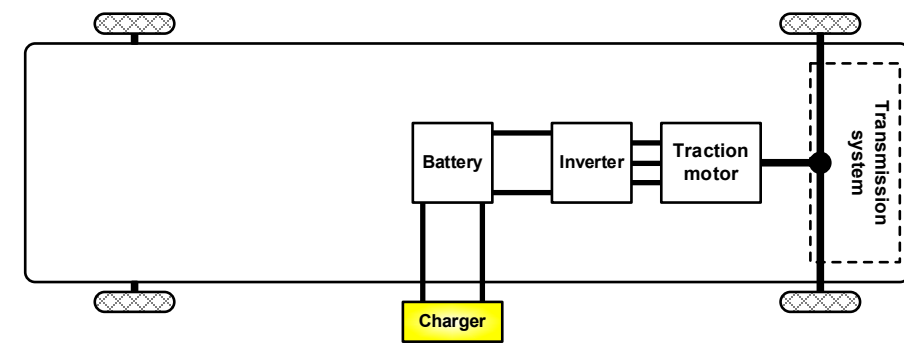
- ▶ Øget komfort
- ▶ Manglende standard for interoperabel opladning
- ▶ Jo større afstand, jo større tab
- ▶ Detektering af fremmedlegemer



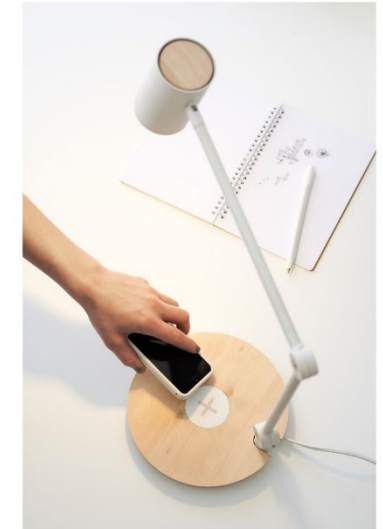
<https://www.chademo.com/>



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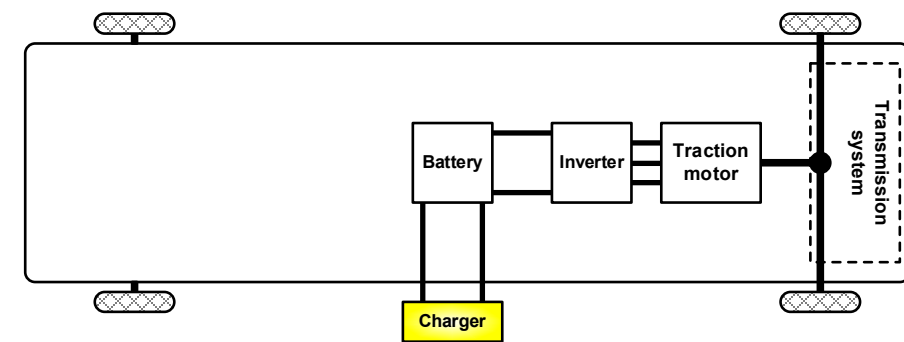


www.newchic.com

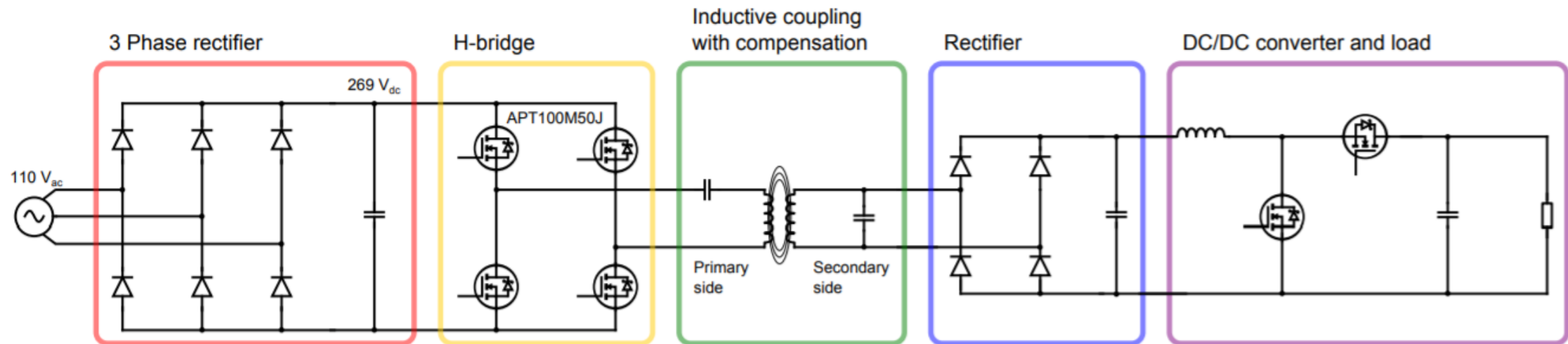


www.mobilefun.co.uk

Lader: Trådløs opladning



- ▶ Der indgår flere konverteringstrin fra primær til sekundær siden
- ▶ Kendte og velafprøvede konverter topologier benyttes ofte

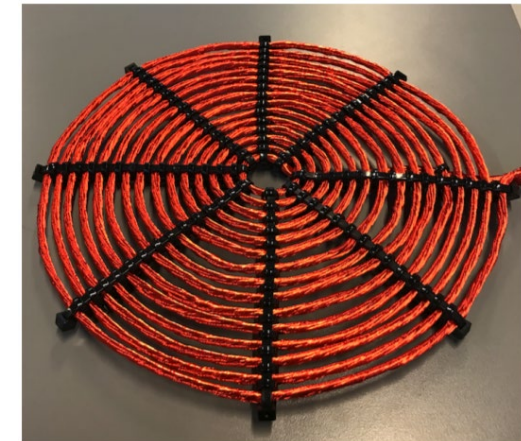
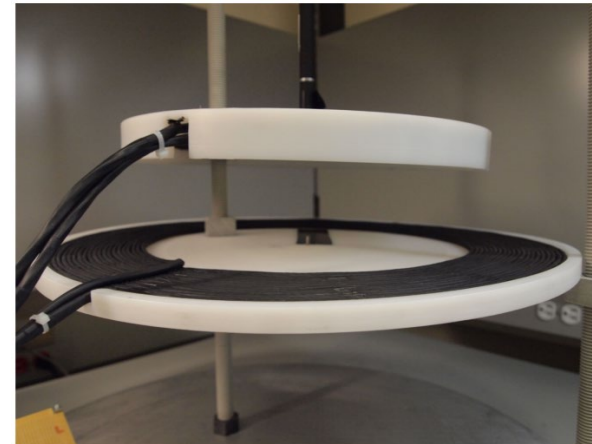
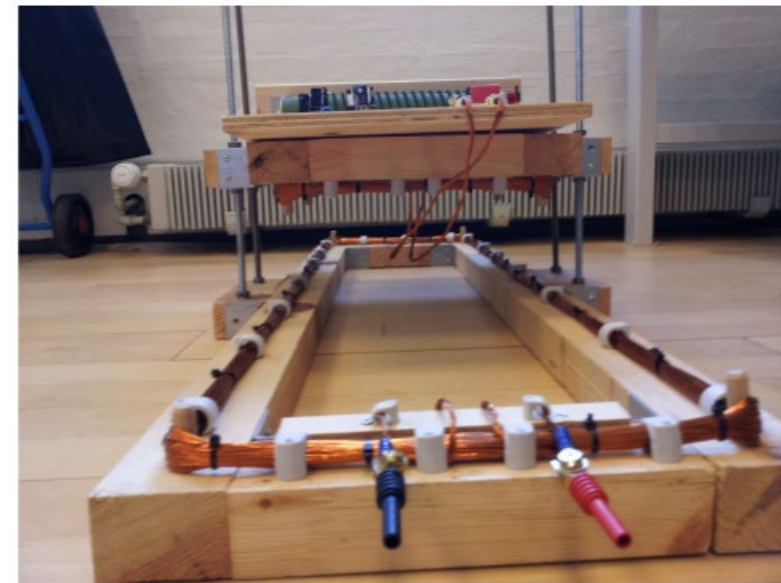


9. semester 2012: Design and Control of Inductive Coupled Power Transfer System

Lader: Trådløs opladning

Studenter projekter

- ▶ 6. semester 2012: Wireless Charging of Electric Vehicles
- ▶ 9. semester 2012: Design and Control of Inductive Coupled Power Transfer System
- ▶ 7. semester 2017: Wireless Charging of Electric Vehicles
- ▶ 7. semester 2017: Wireless Power Transfer for Electric Vehicles



Lader: Trådløs opladning

Ph.d. projekt med fokus på spoledesign

- Undersøge **spoledesignets** indflydelse på de **magnetiske felter**
- Undersøge **designets** indflydelse på diverse **performance parametre**, f.eks. effektoverførsel, tab, vægt, pris, osv.
- **Minimering af magnetfelterne til omgivelserne**



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DENMARK

**Design of Static Wireless Charging System for Electric Vehicles with
Focus on Magnetic Coupling and Emissions**

**Design af statisk trådløs opladningssystem til elbiler med fokus på
magnetisk kobling og emissioner**

PhD Thesis
by
Tushar Batra

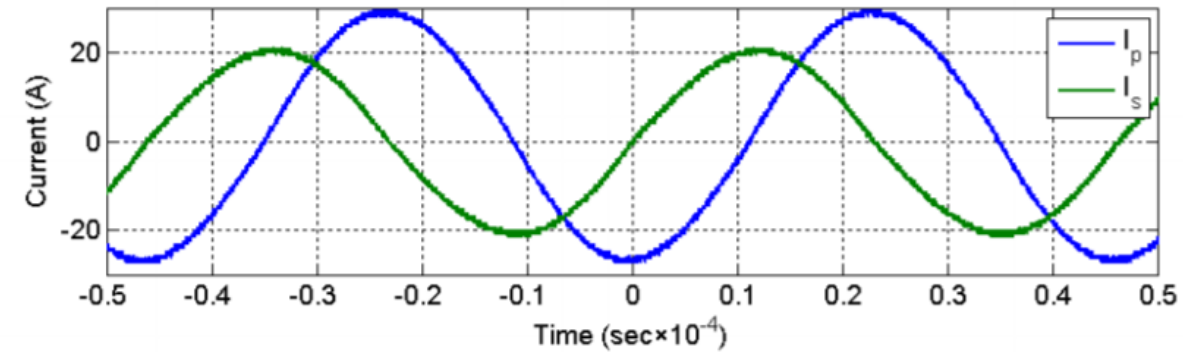
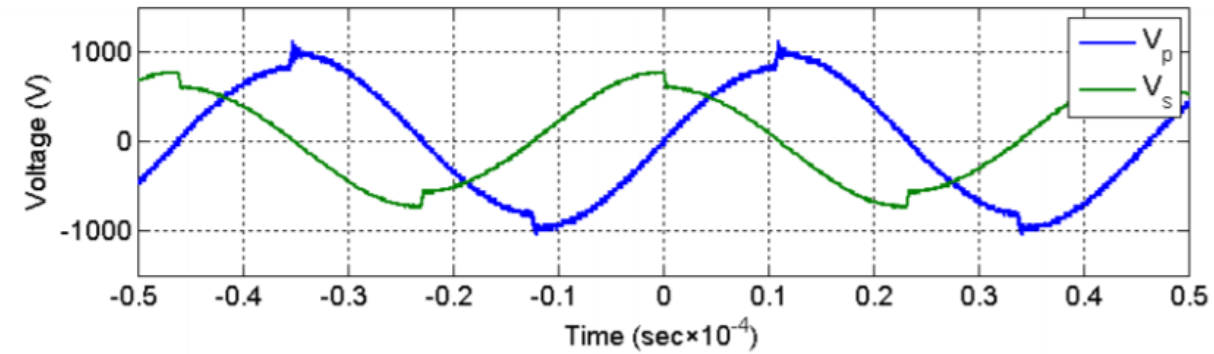
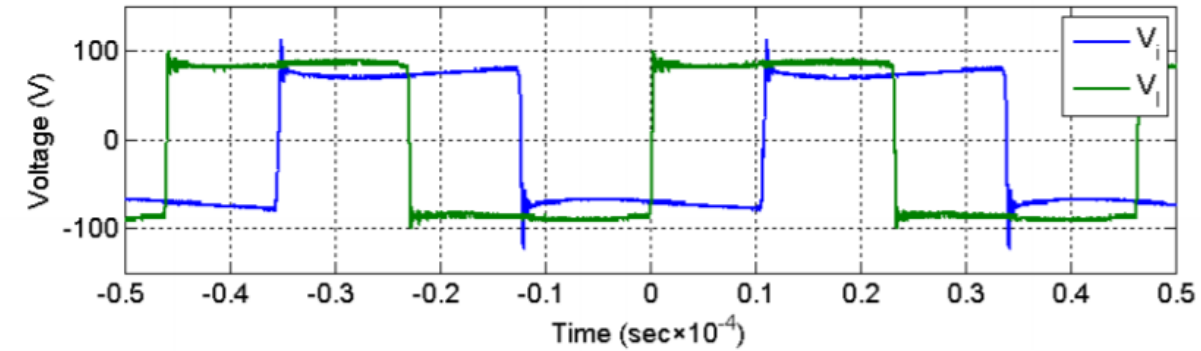
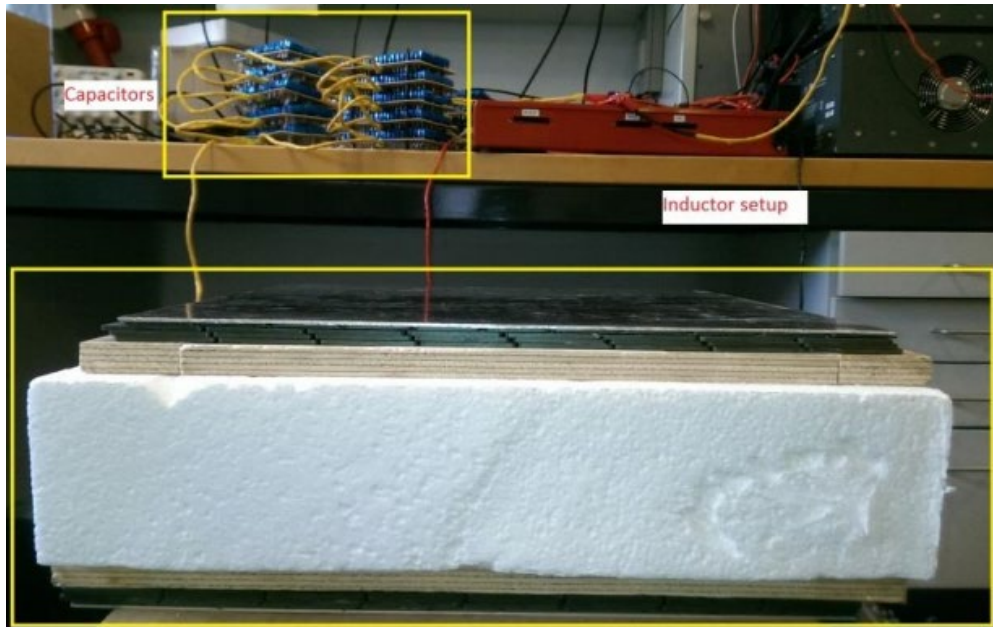
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Resultater

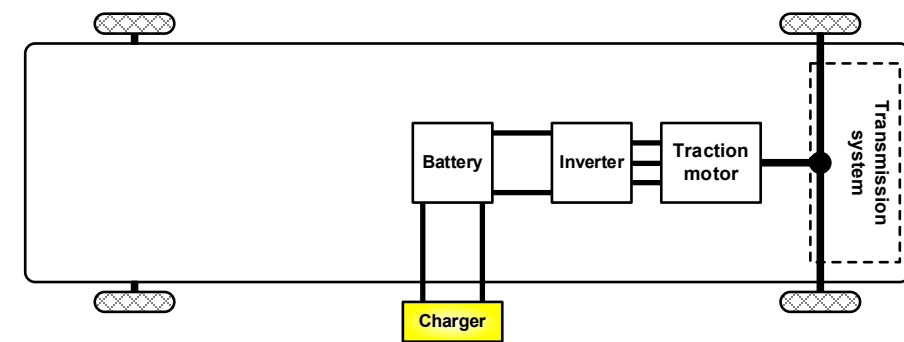
- ▶ Virkningsgrad (magnetisk kobling og kompenseringskondensatorer)
 - 89 % at 10 cm, 2.0 kW
 - 82 % at 20 cm, 1.2 kW



Lader

Vehicle-to-X

- ▶ Vehicle-to-load (V2L)
 - ▶ Bilen kan forsyne diverse stand-alone laste



Vehicle-to-X

- ▶ Vehicle-to-grid (V2G)
 - ▶ Elbiler kan understøtte nettet med forskellige ydelser, f.eks. frekvensregulering
 - ▶ Usikker forretningsmodel
- ▶ Vehicle-to-home (V2G)
 - ▶ Bilen sender strøm tilbage til huset i de dyreste timer
 - ▶ Off-grid løsning i svage net
- ▶ Manglende standarder og variation fra land til land



EFTERUDDANNELSE



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Masteruddannelse i Power-to-X

- ▶ Fleksibel masteruddannelse
- ▶ To til seks år
- ▶ Flere relevante eltekniske kurser
- ▶ <https://www.aau.dk/uddannelser/efteruddannelsen/master>
- ▶ Mulighed for at tage enkelte kurser

Kurser

	AC and DC Microgrids	+
	Avanceret computerbaseret fluiddynamik	+
	Gridtilpassede invertere – Principper og praksis	+
	Solcellebaserede elsystemer i teori og praksis	+
	Advanced Power-2-X Systems	+
	Avancerede Kulstoffangstsystemer	+
	Litium-ion batterier – Fundamentale egenskaber, modellering og tilstandsestimering	+
	Introduktion til vindkraft (generation og integration)	+
	Effektelektronik – fra det grundlæggende til avancerede emner	+
	Vurdering af pålidelighed i elektriske forsyningsystemer	+



EVALUERING



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Evaluering af Gymnasielærerdagen 2024



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