# Zero-emission bus options: BEB vs FCB

## Paikallisliikennepäivät Hämeenlinna 23.9.2022

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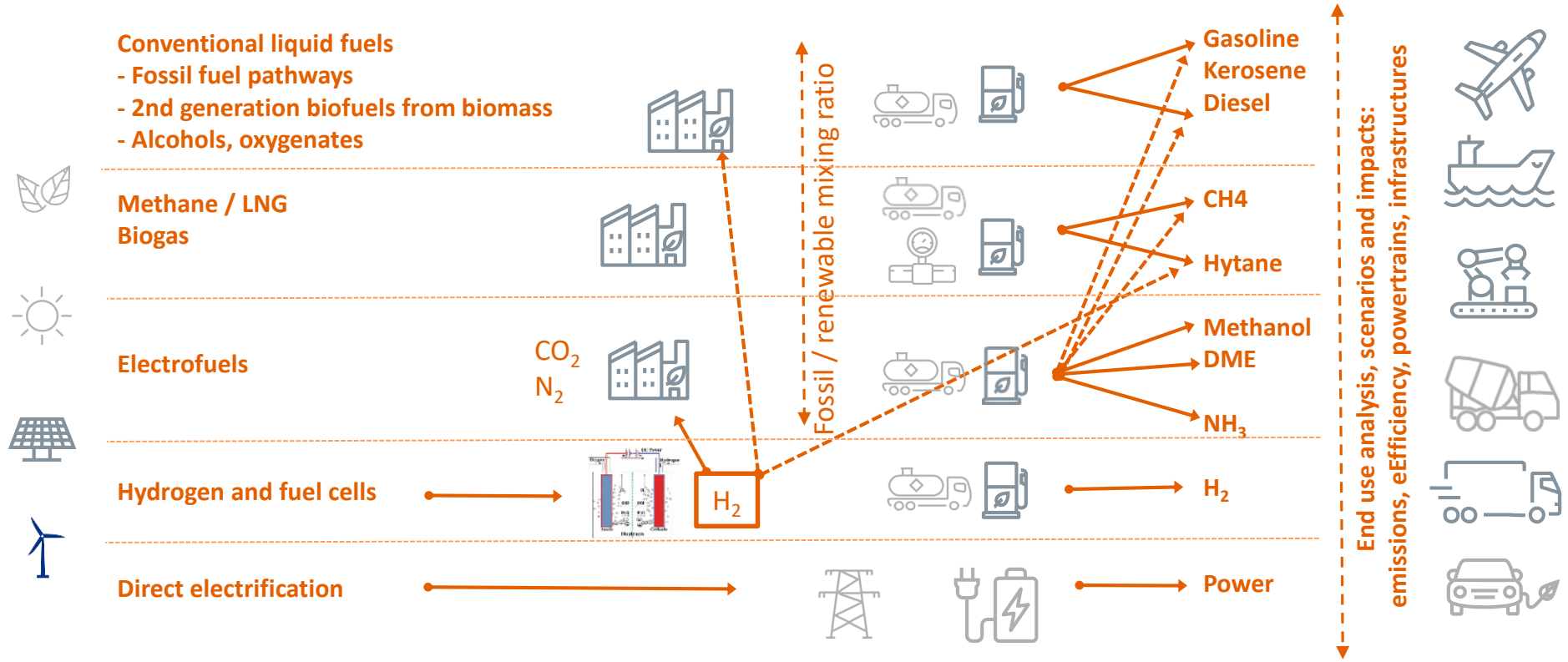
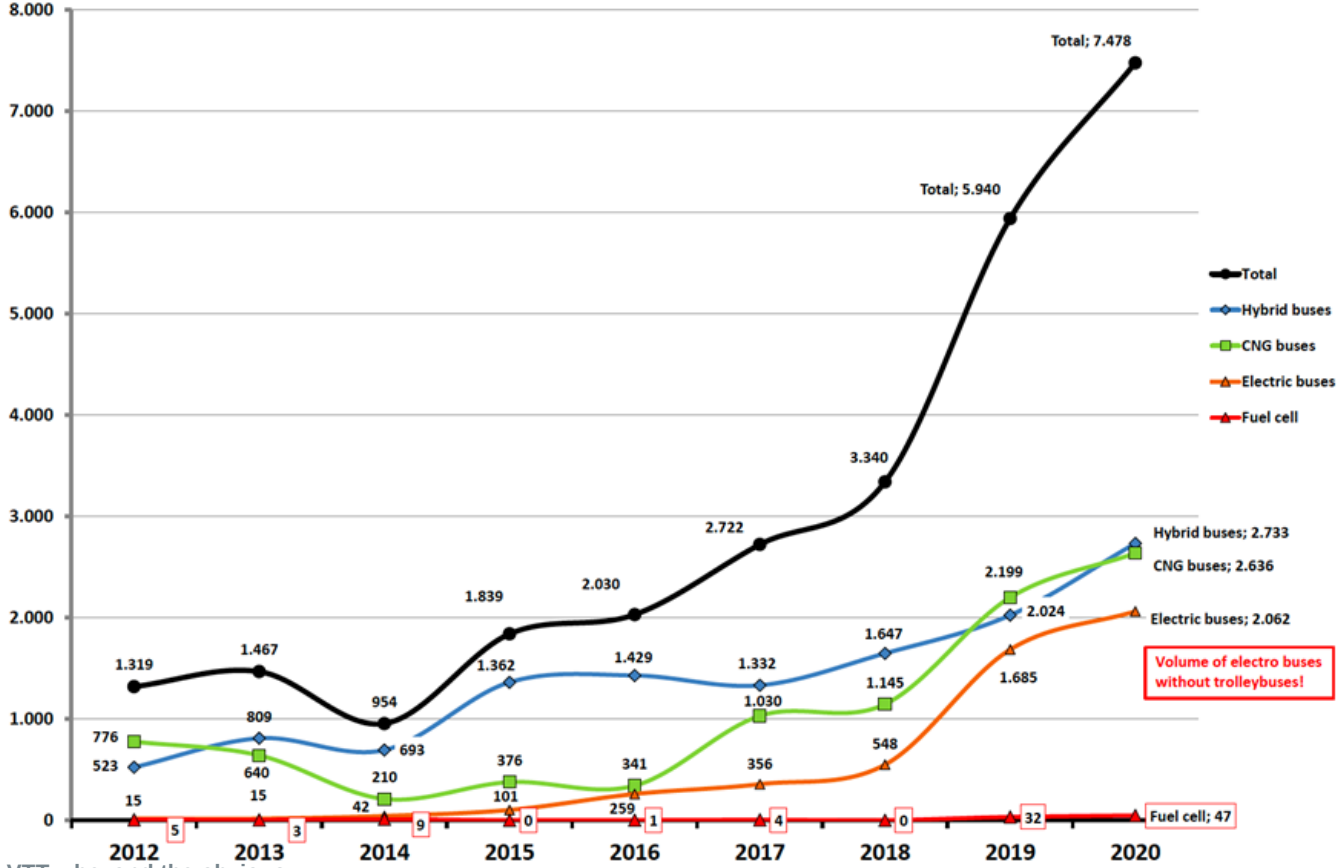
# Analysis of transport energy pathways



# WTW energy efficiency of RFNBO in transport

| WTW energy efficiency of RFNBO in transport | Direct electrification | H2 (liquid) | H2 (pressurised) | e-diesel | e-CH4 (liquid) | e-CH4 (pressurised) | e-NH3 |
|---|---|---|---|---|---|---|---|
| Renewable electricity | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| AC-DC conversion | | 95 % | 95 % | 95 % | 95 % | 95 % | 95 % |
| Electrolysis | | 75 % | 75 % | 75 % | 75 % | 75 % | 75 % |
| CO2/N2 capture and fuel synthesis | | | | 63 % | 80 % | 80 % | 80 % |
| Compression / liquefying | | 80 % | 90 % | | 80 % | 90 % | 85 % |
| Transport, storage and distribution | 94 % | 90 % | 80 % | 95 % | 90 % | 85 % | 90 % |
| Fuel production efficiency (WTT) | 94 | 51 | 51 | 43 | 41 | 44 | 44 |
| Conversion AC/DC and charging | 93 % | | | | | | |
| Battery efficiency | 94 % | | | | | | |
| Conversion efficiency H2/NH3 to DC | | 45 % | 45 % | | | | 50 % |
| Conversion DC/AC | 95 % | 95 % | 95 % | | | | 95 % |
| Motor/engine efficiency | 90 % | 90 % | 90 % | 45 % | 38 % | 38 % | 90 % |
| Vehicle efficiency (TTW) | 75 % | 38 % | 38 % | 45 % | 38 % | 38 % | 43 % |
| **Overall WTW efficiency** | **70** | **20** | **20** | **19** | **16** | **17** | **19** |

# European bus market status (2020)



# Zero-emission buses are a system solution including charging & H2 refuel

- HSL is using roof-mounted ACD (pantograph)
  - Lighter infrastructure, easier to install to the city architecture, a pantograph failure will not render a charger out of service
- Initially chargers at both ends of the line, and vehicles were charged always at both ends
- Current trend is to concentrate fast opportunity charging in terminals/nodes, mostly trunk routes
- Many recent contracts have been won with large-battery depot charging
- $H_2$ buses will need refilling stations & infra (non-existent in Finland as of today)

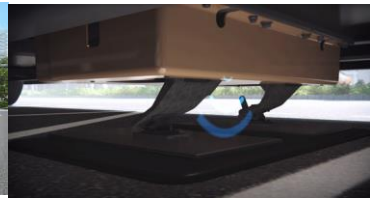
# Technical feasibility of fast charging

- Current capability up to 600 kW (developing towards MW)
- Several alternatives for contacting interface
- Standardised communication protocol CCS (-> MCS)
- Pantograph solutions identified as **most feasible** for e-buses
- Contacting also from the side or underneath
- Conductive or inductive
- Stable grid connection essential (battery buffer)


Pictures: Volvo, OppChargei

Pictures: PVI, Stäubli


Picture: Bombardier



Pictures: Alstom

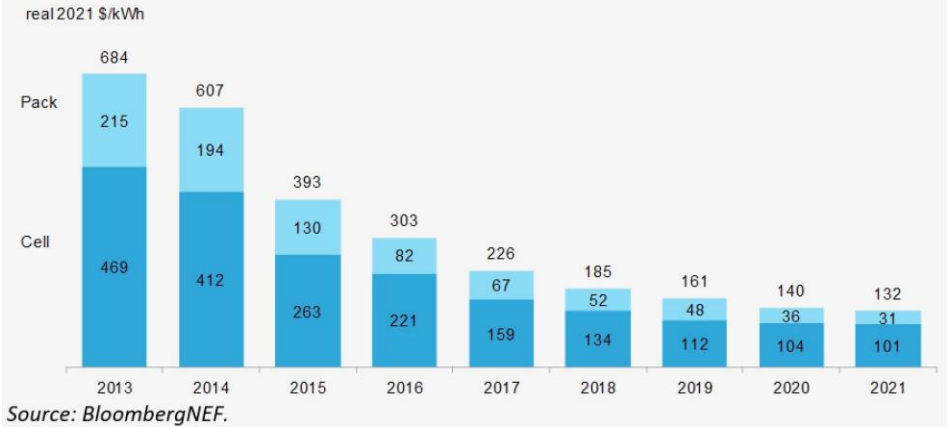
# But: current BEB solutions are mostly NOT zero-emission

- Remaining open issues and challenges
  - Electric buses with auxiliary diesel heaters are not zero emission
  - Fully electric BEB operation in winter will increase electricity consumption by at least 50% (→ smaller range, more charging needed!)
  - Zero-emission range extenders and thermal management improvements needed
- Zero-emission energy options are fully electric and/or green hydrogen
- Paikallisliikenteen puhtaat käyttövoimat nyt ja tulevaisuudessa, https://cris.vtt.fi/en/publications/paikallisliikenteen-puhtaat-käyttövoimat-nyt-ja-tulevaisuudessa?utm_source=email

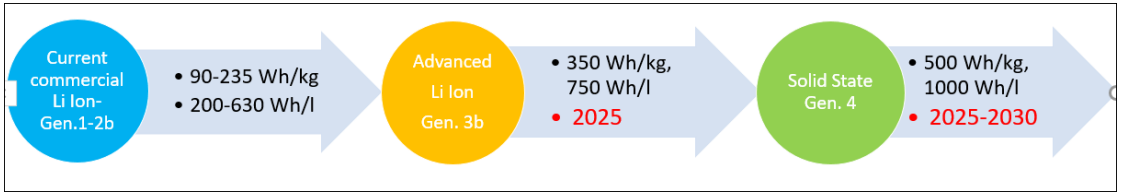
# Continuous development in battery technology and prices

- Li ion battery price continues to drop
- LFP currently slightly cheaper than NMC
- Battery capacity in fully electrical operation increasing
- Potential for a factor-of-two improvement in capacity (range)

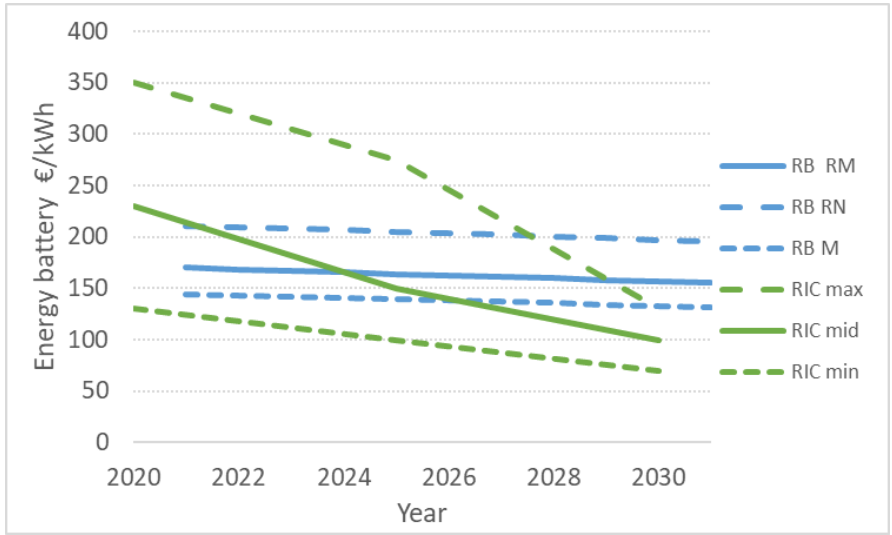
**Figure 1: Volume-weighted average pack and cell price split**

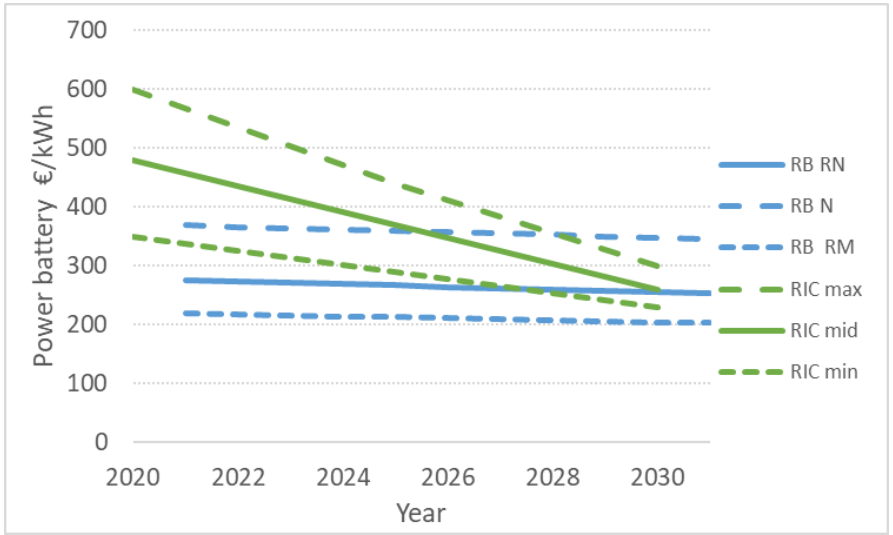



*Source: BloombergNEF.*



# Batteries for hybridisation and electrification

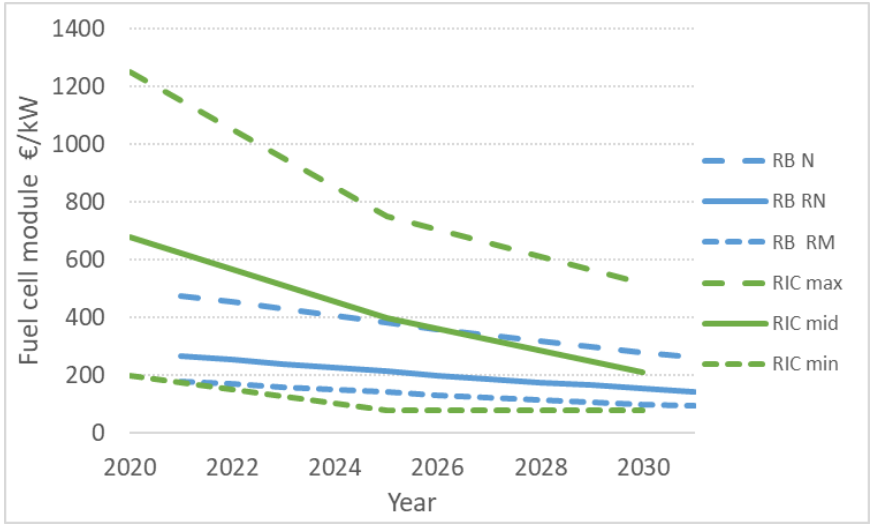


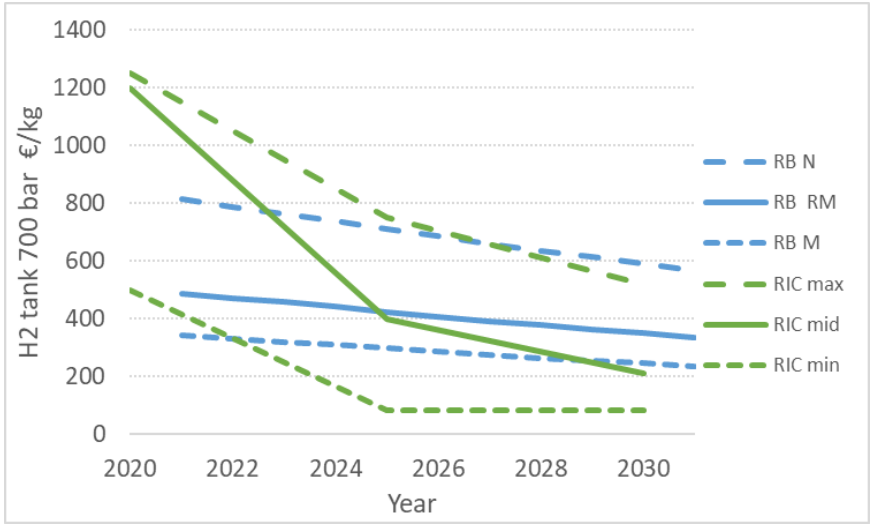




- Smaller high power batteries for hybrid topologies
- Larger high energy batteries when electrification degree increases

Sources: Ricardo/ICCT WORKING PAPER 2022-09 (**RIC**), Roland Berger/FCH JU report FCH Trucks Dec.2020 (**RB**)

# Fuel cells and hydrogen for hybridisation and electrification



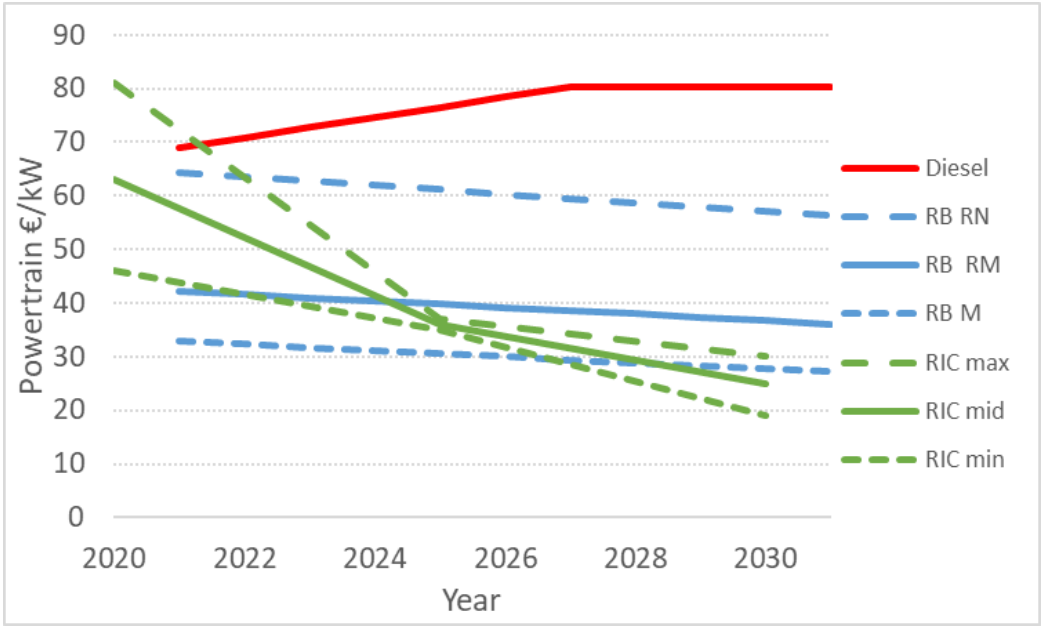

- FC (methanol or H2) as a zero-emission power source
- Smaller high power batteries for hybrid topologies



Sources: Ricardo/ICCT WORKING PAPER 2022-09 (**RIC**), Roland Berger/FCH JU report FCH Trucks Dec.2020 (**RB**)

# Powertrains for hybridisation and electrification

- Electric drives for traction, actuators and hydraulic pumps
- Powertrain topology development a related challenge
- ICE/diesel powertrains price increasing due to emission standards




Sources: Ricardo/ICCT WORKING PAPER 2022-09 (**RIC**), Roland Berger/FCH JU report FCH Trucks Dec.2020 (**RB**)

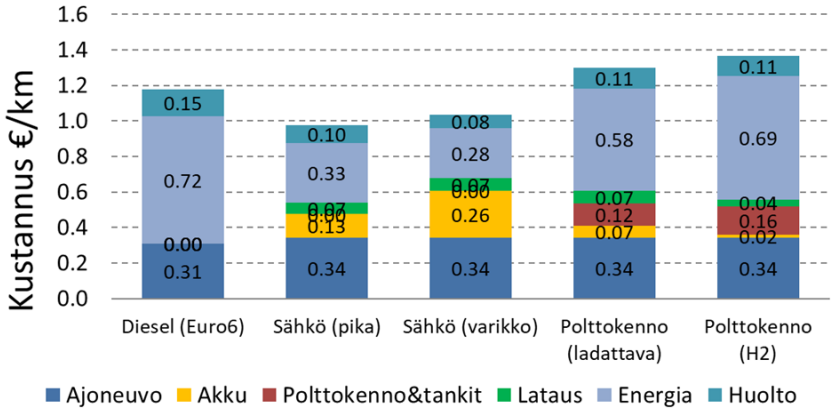
# Zero-emission options in TCO study

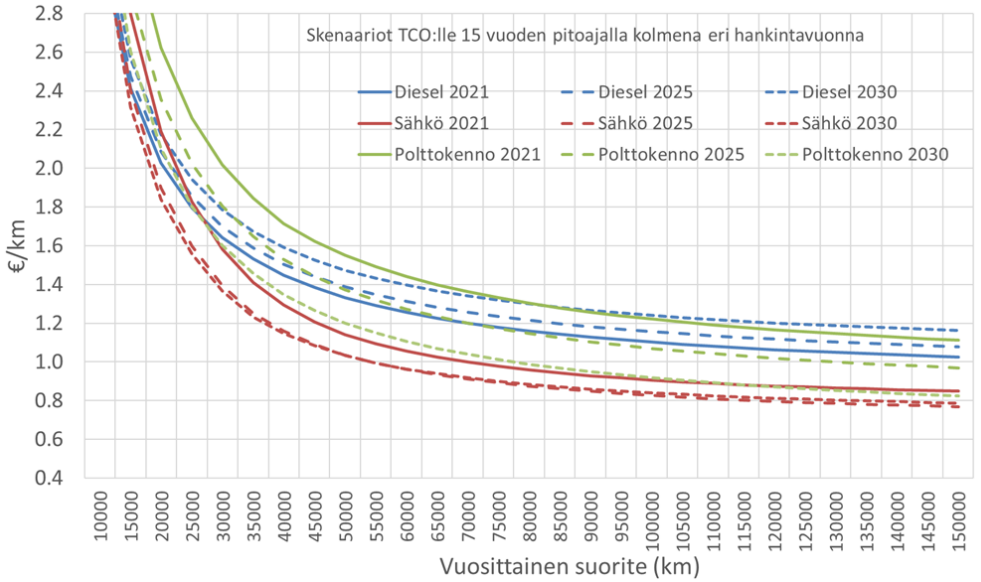
| Käyttötapaukset | Syöttölinja | Seutulinja | Runkolinja |
|---|---|---|---|
| Ajoneuvotyyppi | A | C | D |
| Ajosyklin tyyppi | Urban | Urban | Urban |
| Varikkoladattavan akun mitoituksen suunnitteluperusteena oleva keskeytyksetön ajomatka (km) | 225 | 300 | 420 |
| Akuston koko, varikkoladattava (kWh) | 363 | 572 | 916 |
| Akuston koko, pikaladattava (kWh)* | 182 | 286 | 458 |
| Akuston koko, polttokenno (kWh) ei ladattava; ladattava** | 182; 61 | 286; 95 | 458; 153 |
| Polttokennoteho (kW) | 100 | 120 | 120 |
| Pikalaturin (1,5 C) teho (kW) | 272 | 429 | 687 |
| Varikkolaturin (0,25 C) teho (kW) varikkoladattava; pikaladattava | 91; 45 | 143; 71 | 229; 114 |
| Pikaladattavan sähköbussin kulutus puolikuormalla (kWh/km)*** | 1,53 | 1,81 | 2,07 (C +10%) |
| Vetybussin kulutus puolikuormalla (kgH2/100 km)**** | 9,1 | 10,8 | 12,3 |
| Ladattavan vetybussin kulutus puolikuormalla (kgH2/100 km; kWh/km) | 4,7; 0,6 | 5,2; 0,7 | 3,6; 1,1 |
| Dieselbussin kulutus puolikuormalla (l/100 km) | 41,9 | 46,1 (A + 10%) | 50,7 (C + 10%) |
| Huolto ja ylläpito sähkö (€/km) | 0,10 (opp.) 0,08 (depot) | 0,10 (opp.) 0,08 (depot) | 0,20 (opp.) 0,15 (depot) |
| Huolto ja ylläpito vety (€/km) | 0,11 | 0,11 | 0,22 |
| Huolto ja ylläpito diesel (€/km) | 0,15 | 0,15 | 0,19 |

# Scenario inputs to TCO study

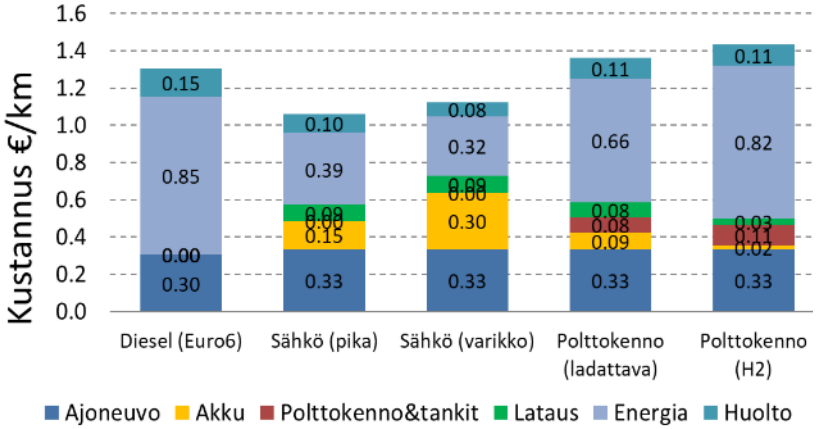
| Vuosi | Akusto €/kWh | Latauslaite €/kW | Polttokennо €/kW | Jakeluvelvoite | Foss. Diesel €/l | HVO €/l | Sähkö €/kWh | H2 €/kg | Akun syklielinikä | Polttokennon elinikä |
|---|---|---|---|---|---|---|---|---|---|---|
| 2021 | 330 | 600 | 500 | 0.2 | 1.61 | 2.03 | 0.17 | 7.63 | 2500 | 30000 |
| 2022 | 281 | 597 | 477 | 0.21 | 1.62 | 2.09 | 0.18 | 7.32 | 2550 | 30600 |
| 2023 | 232 | 594 | 453 | 0.22 | 1.64 | 2.15 | 0.18 | 7.03 | 2601 | 31212 |
| 2024 | 184 | 591 | 430 | 0.23 | 1.66 | 2.22 | 0.18 | 6.75 | 2653 | 31836 |
| 2025 | 182 | 588 | 407 | 0.24 | 1.67 | 2.28 | 0.19 | 6.48 | 2706 | 32473 |
| 2026 | 180 | 585 | 384 | 0.25 | 1.69 | 2.35 | 0.19 | 6.22 | 2760 | 33122 |
| 2027 | 179 | 582 | 360 | 0.26 | 1.71 | 2.42 | 0.19 | 5.97 | 2815 | 33785 |
| 2028 | 177 | 579 | 337 | 0.27 | 1.72 | 2.50 | 0.20 | 5.73 | 2872 | 34461 |
| 2029 | 176 | 576 | 318 | 0.28 | 1.74 | 2.57 | 0.20 | 5.50 | 2929 | 35150 |
| 2030 | 174 | 574 | 299 | 0.29 | 1.76 | 2.65 | 0.21 | 5.28 | 2988 | 35853 |
| 2031 | 173 | 571 | 280 | 0.3 | 1.78 | 2.73 | 0.21 | 5.07 | 3047 | 36570 |
| 2032 | 173 | 568 | 280 | 0.31 | 1.79 | 2.81 | 0.21 | 4.87 | 3108 | 37301 |
| 2033 | 173 | 565 | 280 | 0.32 | 1.81 | 2.89 | 0.22 | 4.67 | 3171 | 38047 |
| 2034 | 173 | 562 | 280 | 0.33 | 1.83 | 2.98 | 0.22 | 4.49 | 3234 | 38808 |
| 2035 | 173 | 559 | 280 | 0.34 | 1.85 | 3.07 | 0.23 | 4.31 | 3299 | 39584 |

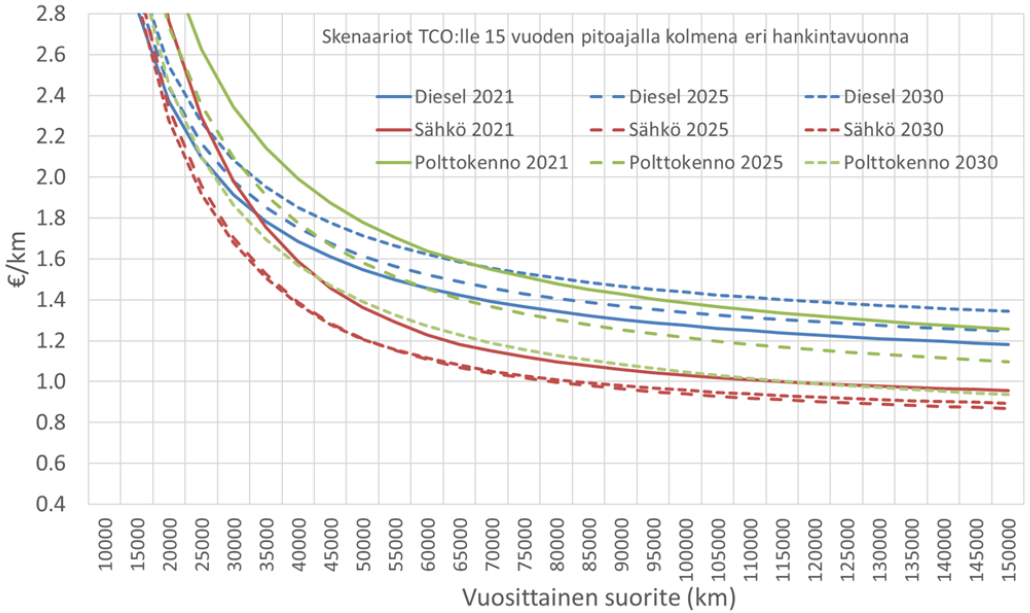
# TCO feeder line (75000 km/a nominal)



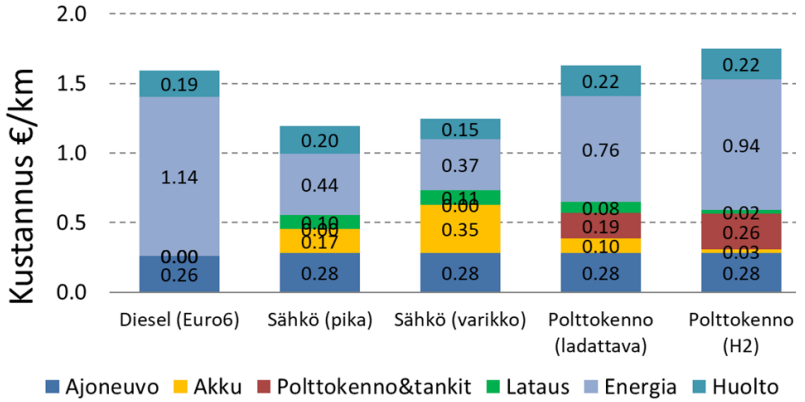



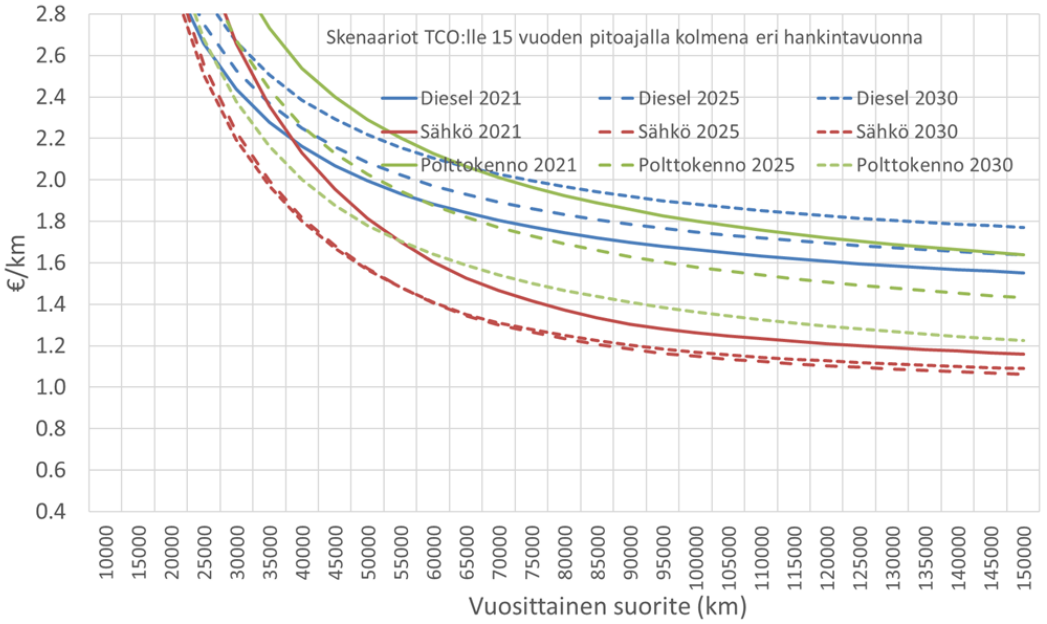
# TCO regional line (90000 km/a nominal)



# TCO trunk line (126000 km/a nominal)

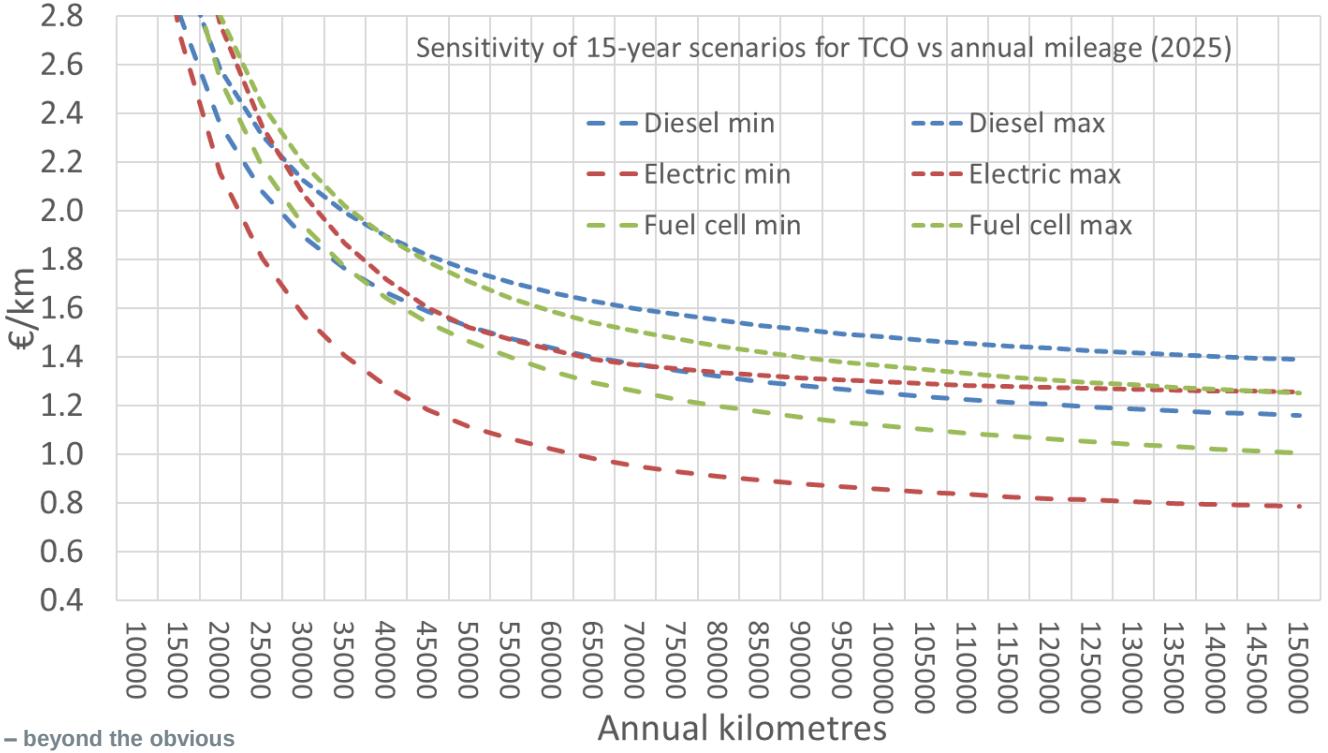


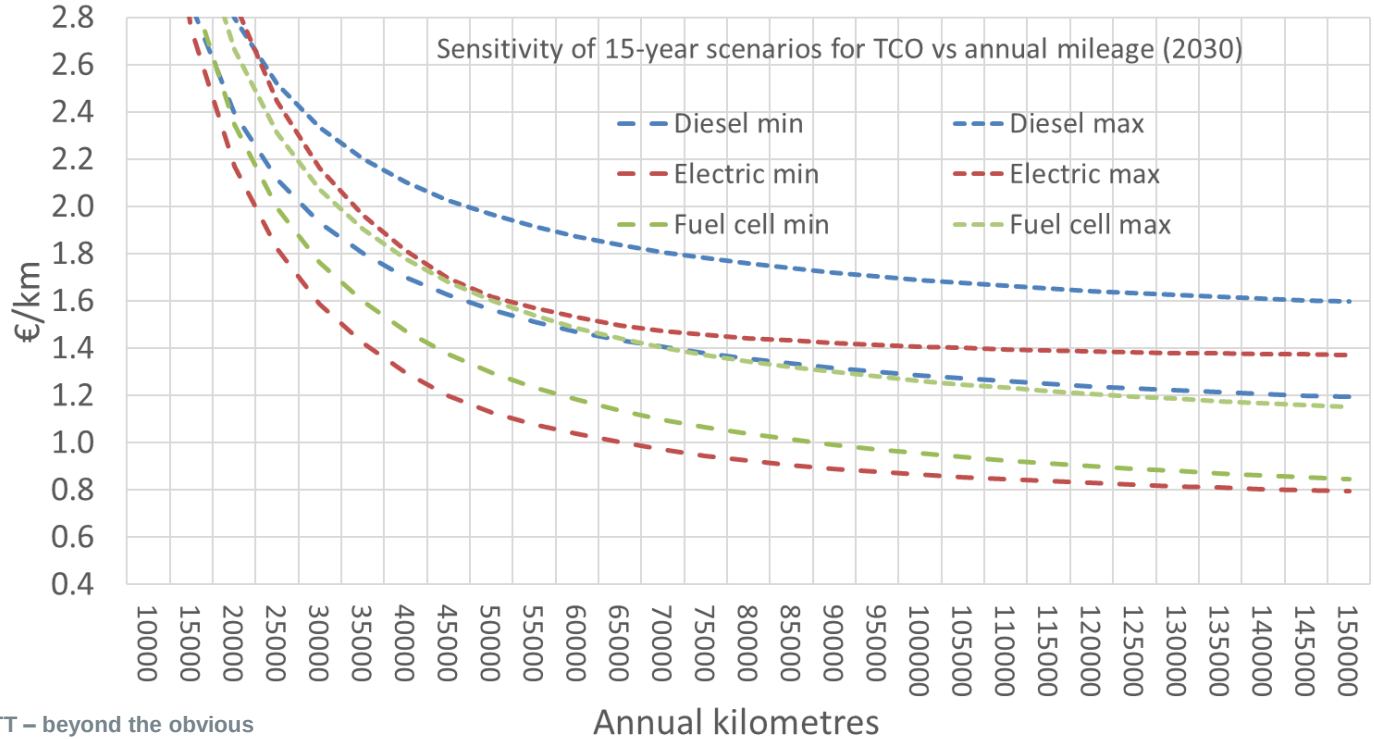
# Sensitivity analysis TCO vs km: diesel vs electric vs H2

| | min | mid | max |
|---|---|---|---|
| Akun hinta €/kWh 2030 | 147 | 173 | 217 |
| Dieselin hinnan nousu / v | 0.5 % | 1 % | 2 % |
| HVO:n hinnan nousu / v | 1 % | 3 % | 5 % |
| Sähkön hinnan nousu / v | 1 % | 2 % | 3 % |
| Vedyn hinnan lasku / v | -5 % | -4 % | -2 % |
| Akun syklielinikä | 4 % | 2 % | 1 % |
| Polttokennon elinikä | 3 % | 2 % | 1 % |
| Sähköbussin energiankulutuksen kasvu täyssähköisen lämmityksen kautta | **0%** | | 50% |

# Sensitivity analysis TCO vs km: year 2025 diesel vs electric vs H2



# Sensitivity analysis TCO vs km: year 2030 diesel vs electric vs H2



# Summary 1

- Electric buses are market-ready for large-scale deployment at a competetive cost: potential to be lowest TCO for all scenarios
- FCB competes with diesel and can in optimal conditions be a good alternative / addition to BEB
- We still have work to do: some remaining open issues and challenges
  - Electric buses with auxiliary diesel heaters are not zero emission
  - Increased consumption with zero-emission BEB in cold conditions lead to more charging needed (favours opportunity charging)
  - Zero-emission BEB range extenders not yet investigated
  - New developments in thermal management optimisation needed

# Summary 2

- Solutions are there: no need to delay green shift deployments
- Tendering specifications play an important role if we want real ZE
  - Allow big emissions from auxiliary diesel heaters?
  - Secure charging and $H_2$ refilling infrastructure for real zero emissions?
  - Technology-neutral criteria with progressive LCA, $CO_2$ and local emissions?
- Is FCB a real competitive option?
  - Not within the next 5 years: FCB is not a game changer
  - If FCH technology and market develops optimally, FCB or fuel cell hybrids can be a good complementing alternative in 5-10 years

# Thank you for your attention!