Aalto University
School of Engineering

Recent research activities in Fuel Cells in Finland

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Antti Lajunen

Aalto University, Vehicle Engineering

antti.lajunen@aalto.fi

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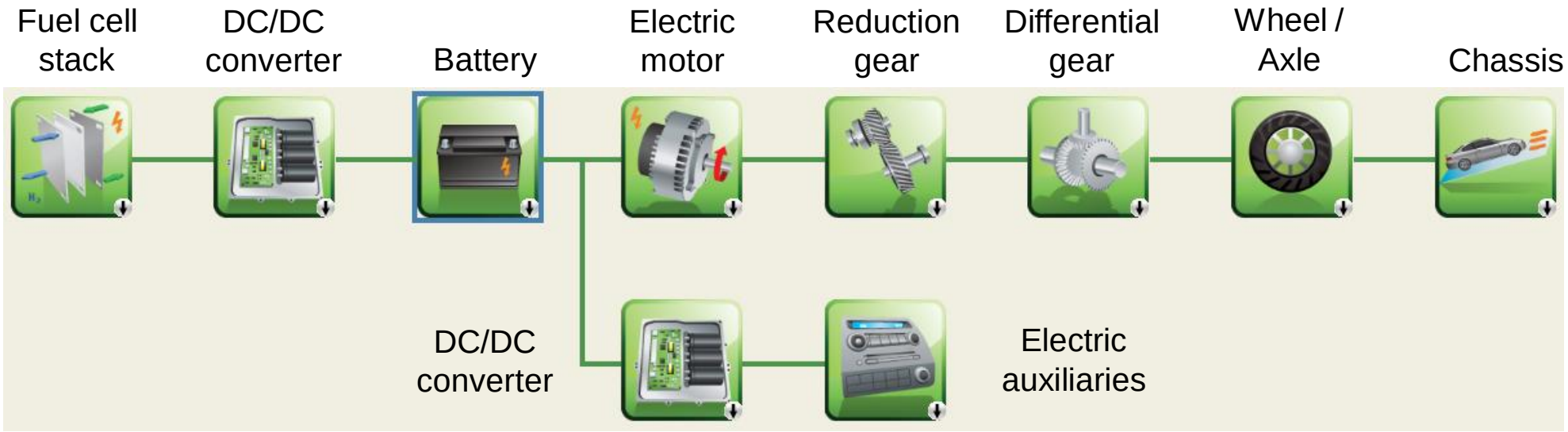
LCA and CO_2 emissions of city buses

- The objective is to compare different city bus technologies in terms of lifecycle costs and CO_2 emissions
  - Diesel, CNG, Hybrid-Electric, Fuel Cell Hybrid, and Electric
- Simulation models are developed in Autonomie
- CO_2 emission are taken into account from the energy production and bus operation
- Comparison and evaluation of CO_2 emissions
- The research is done in collaboration with UC Berkeley
  - There are 10 fuel cell buses operated by AC Transit in Berkeley

Simulation in Autonomie

- Autonomie is a vehicle simulation software developed by Argonne National Laboratory
- Software includes predefined vehicle topologies
  - Heavy vehicles need additional parameterization

Fuel Cell Hybrid powertrain



Vehicle parameters

General specifications	Value
Curb weight (kg)	10600
Vehicle frontal area (m^2)	7.24
Drag coefficient	0.79
Rolling resistance 1st coefficient	0.008
Rolling resistance 2nd coefficient (1/(m/s))	0.0012
Wheelbase (m)	6.85
Front weight fraction	0.4
Centre of gravity, height (m)	0.77
Differential gear ratio	4.72

- The total weight of the buses in the simulations was 14250 kg except EV2 which was 2000 kg heavier
- Ambient temperature was 20ºC
- Simulations were carried out in different types of driving cycles

	Fuel Cell Hybrid (FCH)	Electric 1 (EV1)	Electric 2 (EV2)
Fuel cell power (kW)	160	---	---
Transmission	Reduction gear	Reduction gear	Reduction gear
Transmission gear ratios	2.4	2.4	2.4
Electric motor power (kW)	170	170	200
Battery system voltage (V)	648	630	630
Battery capacity (kWh)	11.6	62.6	333.6

Lifecycle cost calculation

$$C_{LC} = (C_{CAP} + C_{OP} + C_{REP})(1 + d_{rate})^{-j}$$

- C_{LC} = lifecycle costs
- C_{CAP} = capital costs
- C_{OP} = operation costs
- C_{REP} = technology replacement costs
- d_{rate} = discount rate
- The capital costs include the purchase costs and the operation costs consist of the energy, maintenance and possible CO_2 costs
- The technology replacement costs refer to the necessary replacement of batteries and fuel cell stacks

Lifecycle cost parameters (preliminary)

- The default cost parameters are presented in the table
- The purchase cost of the fuel cell hybrid bus is assumed to be three times higher than diesel
- The electric bus purchase cost (EV1) is two times more expensive than diesel
- Useful life for batteries and fuel cell
  - High power battery: 10,000 cycles
  - High energy battery: 3000 cycles
  - Fuel cell stack: 15,000 operating hours

COST PARAMETERS	
Diesel bus purchase cost (€)	225,000
Natural gas bus purchase cost (€)	247,500
Parallel hybrid bus purchase cost (€)	292,500
Series hybrid bus purchase cost (€)	292,500
Fuel cell hybrid bus purchase cost (€)	675,000
Electric bus purchase cost (€)	450,000
Diesel fuel cost without VAT (€/l)	1.12
Natural gas cost without VAT (€/m^3)	0.78
Hydrogen cost without VAT (€/kg)	4.50
Electricity cost without VAT (€/kWh)	0.10
Maintenance cost for diesel bus (€/km)	0.14
High power battery cost (€/kWh)	750
High energy battery cost (€/kWh)	525
Fuel cell stack replacement cost (€/kW)	200
Operation time in a year (h)	4000
Service life in years	12
Discount rate (%)	6.0

CO_2 emission parameters

- CO_2 emissions will be analyzed based on different energy production models in different countries (Finland, US, …)

CO2 emission parameters for Finland

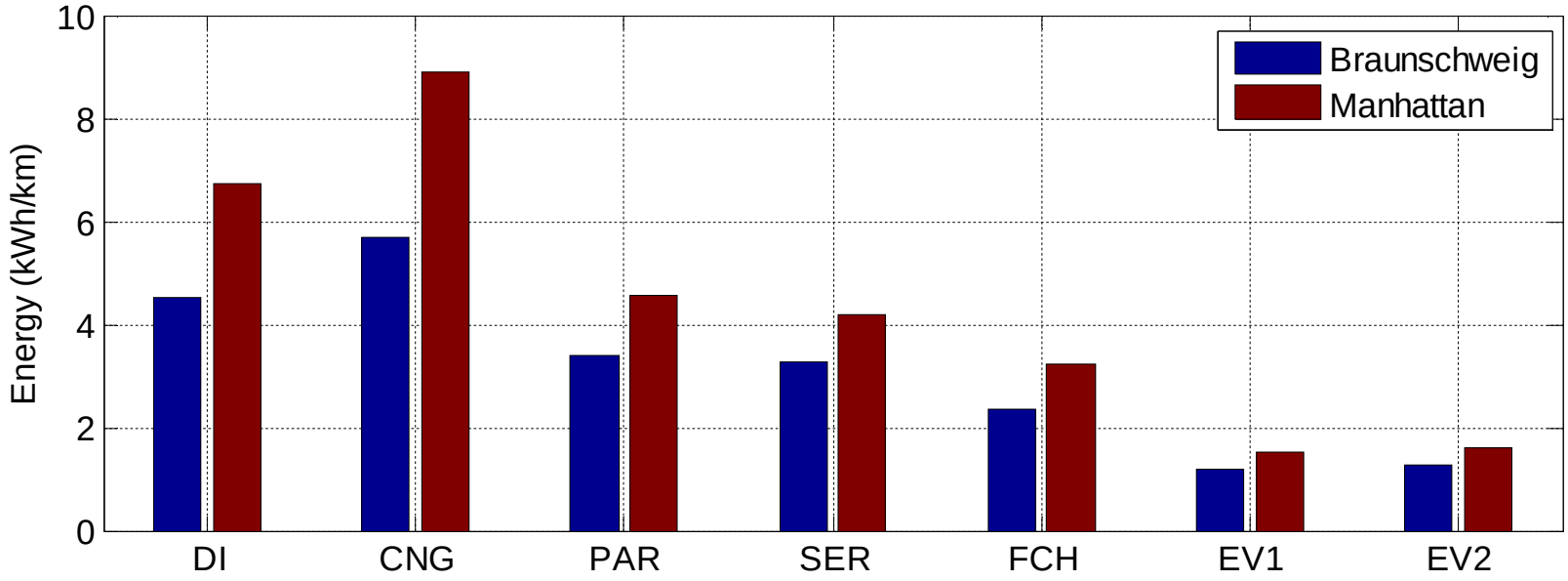
Energy	Model
Diesel	(Edwards et al., 2013)
Natural gas	CNG imported by pipeline
Hydrogen	Reforming on-site from CNG
Electricity	Finnish electric grid mix

	DI	CNG	PAR	SER	FC	EV1	EV2
CO_2 combustion (g/MJ)	73,0	56,1	73,0	73,0	--	--	--
CO_2 production (g/MJ)	15,5	22,5	15,5	22,5	125,0	42,0	42,0

Edwards, R., Larivé, J-F., Rickeard, D., Weindorf, W., 2013. Well-to-Tank Report Version 4.0, JRC Technical Reports.

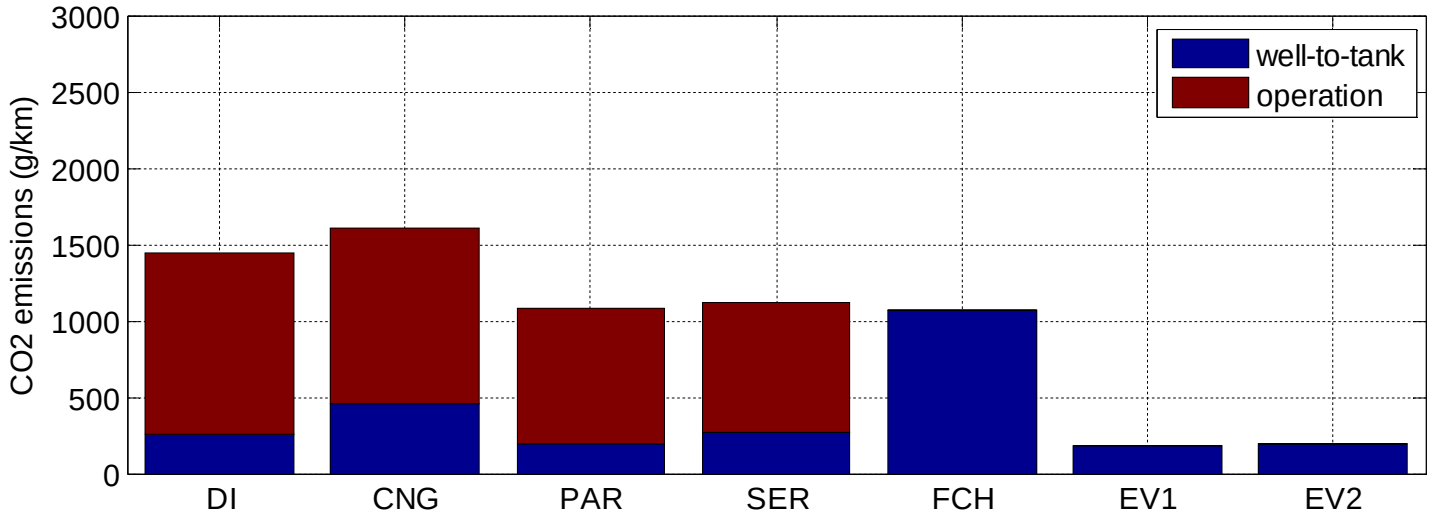
Simulation results – energy consumption

- CNG bus consumes 25-30% more energy than diesel
- Hybrid-Electric buses consume 25-35% less energy than diesel
- FCH bus consumes 45-50% less energy than diesel
- Electric buses consume 70-75% less energy than diesel

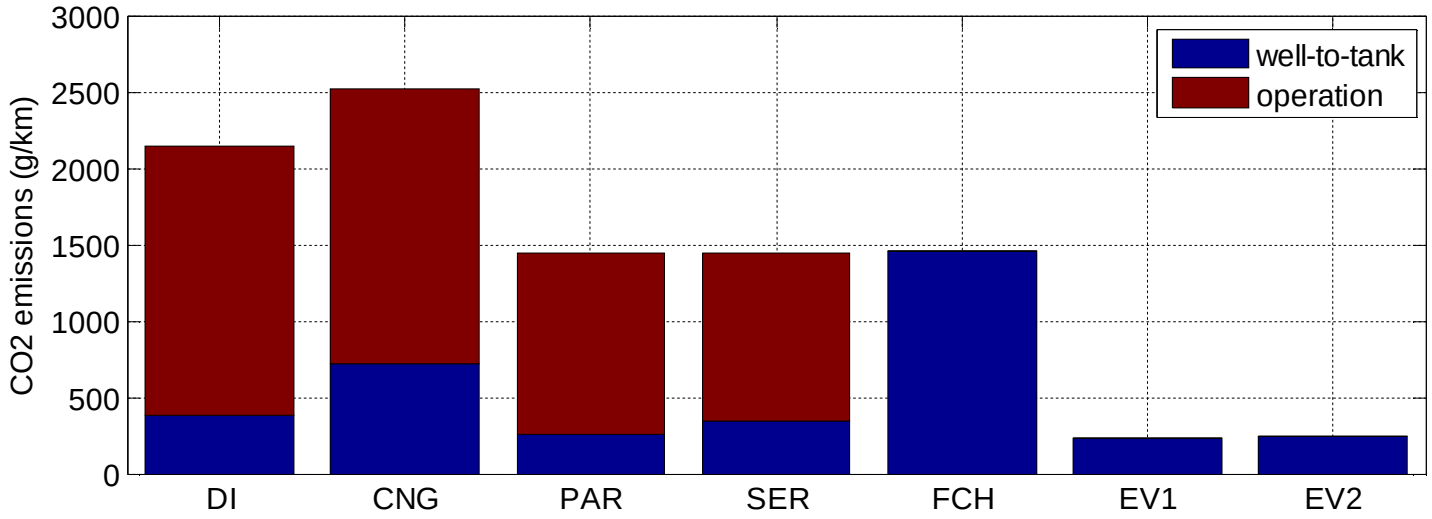


CO_2 emissions: case Finland

Braunschweig cycle



Manhattan cycle



Lifecycle costs (Braunschweig)

- CNG and Hybrid-electric buses have about the same lifecycle costs than diesel buses
- Fuel Cell hybrid buses have much higher lifecycle costs
- The lifecycle costs of electric buses depends strongly on the bus configuration (charging method and batteries)