Electrical mining and other non-road mobile machinery

International Conference
Electric Mobility and Public Transport

Santiago de Chile, 10-11 May 2017
Mikko Pihlatie, VTT
mikko.pihlatie@vtt.fi
Outline

- Vision
- Example: steps towards electrical bus transportation
- Benefits of electrification
- Technology enablers
- State of the art
- Challenges
- Lowering the barriers
- TCO – total cost of ownership
- Summary – Reflections from 2011 to the end of 2016
More electrical future

- Better fuel economy
- Less emissions
- Enhanced freedom of design
- Increased automation
- Better manoeuvrability and drivability
- Improved working process efficiency
- New operation concept

Top class products, business models and revenue
Vision on electrification

- Majority of **new** machines will be equipped with electrical powertrain by 2030
  - Advanced Heavy Machinery 1993-1998, Tekes, “…off-road heavy machinery manufacturers considered using electrical motors rather than internal combustion engines… …using electric power transmission in heavy machinery such as harbour straddle carriers, mine loaders, ice resurfacers, snow blowers and large electric vans…”

- Autonomous solutions without human operator on board promote diversity of operations and new energy logistics

- Diversity of energy carries will increase: diesel, petroleum, natural gas, hydrogen, batteries

- Successful electrification requires new earning models
Benefits of electrification

- Improved energy efficiency: energy consumption of an electrical machinery can be even 75% lower than that of its diesel engine powered counterpart
- Faster controllability
- Better manoeuvrability and drivability, compare, e.g., hydraulic and electrical boom
- Cancellation of idle
- Less gear reductions, elimination of clutch
- Drive by wire
- Reduced maintenance, both in cost and intensity
- Less noise
- Fully electrical machinery is locally emission free

Challenges

- Economic sustainability
- Fuel and energy prices
- Electricity generation, emitted CO₂ and production capacity vary
- Availability of charging, from grid to energy storages
- Lack of harmonisation, charging interface and charging communication
- Product lifecycle management, e.g. software updates
- Practical challenge: insufficient availability of suitable components
- In engineering, aim at good and good quality but not at perfect
Research background and questions

- Methods and knowledge from electric bus research are applied to NRMM environments (harbours, mines etc)
- Technological and economic feasibility analyses
  - Does current technologies enable the use of electrical machinery in harbour and mining operations?
  - What kind of factors and trade-offs are present?
  - What are the costs of using electrical machinery? How do the costs compare to the cost of using similar diesel machinery?
- Challenges and inaccuracies due to a lack of measurement and publically available data
  - Competitive nature of business
  - How do the costs change when design variables change?
Special features in non-road mobile machinery (as compared to electrical buses)

- What is the same?
  - Powertain dimensioning (average power typically ~150 – 250 kW)
  - High utilisation rate of the machines
  - Requirement for very high reliability, availability and productivity
  - Fast charging necessary

- What comes in addition?
  - Extreme and demanding conditions
    - Underground mining: heat, dust, dirt, salt, acidity, mechanical shocks
  - Robustness and sturdy designs
  - Very different work cycles
    - Lifting, cutting, loading, drilling, spraying, …
    - Use of hydraulics and hydraulic pumps
Hydraulics driven by electric motors

Displacement control (method: changing pump output flow)
  a) variable displacement pump + constant speed motor
  b) variable displacement pump + variable speed motor
  c) fixed displacement pump + variable speed motor

Electro-hydraulic actuators (EHA)
(compact pack of actuator, pump, electric motor)

Moving from mechanical and hydro-mechanical control systems to electronic solutions in following concepts

- **Fly-by-wire** and **Drive-by-wire** concepts
- **More Electric Aircrafts** (MEA) concept
- **Steer-by-wire**, power steering
Special factors in underground mining

- Ventilation is a major cost in mines
- Exhaust emissions from conventional machinery increase the need for ventilation
- Electrification of the underground mining machinery can offer two benefits
  - More efficient machinery operation
  - Savings in ventilation costs
- Charging is more challenging to arrange
  - As the mining process progresses, charging points need to be moved
- Very different power grids available in the mine systems
State of the art: examples

Volvo L220F Hybrid wheel loader

Powertrain configuration and main components
- Diesel-electrical parallel hybrid
- Volvo D12D LB E3 engine, 261 kW (SAE J1995 gross)
- Energy storage: battery

Enables
- Boosting during start-up and at breakout
- Regenerating power during normal operations
- Minimising idling which accounts for up to 40% of a wheel loader’s running time

Benefits
- Fuel savings up to 10%

Caterpillar D7E Diesel-Electric Hybrid Tractor

Powertrain configuration and main components
- Diesel-electrical powertrain
- 175 kW diesel engine
- Energy storage: no energy storage

Enables
- Downsizing the diesel engine
- No gears to shift

Benefits
- 10-30% lower fuel consumption
- Better manoeuvrability → moving more cubic yards per fuel gallon
- Fewer moving parts → longer lifespan
State of the art: examples

ProSilva 910EH electric hybrid forest harvester
Powertrain configuration and main components
- Diesel-electrical parallel hybrid
- 60 kW diesel engine (in non-hybrid 155 kW)
- Energy storage: battery

Enables
- Downsizing the diesel engine
- Peak shaving: electrical drive and energy reservoirs for taking care of the high peak power demands

Benefits
- Reduction of exhaust emissions and fuel consumption

Hitachi Hybrid Excavator ZH200-5B
Powertrain configuration and main components
- Diesel-hydraulic powertrain with electrical assist and swing motors and drives
- Energy storage: capacitor

Enables
- Hybridisation of the swing motion*: 1) storing energy in the capacitor during the swing deceleration; 2) electrical assistance of the swing acceleration
- Boosting the hydraulic system with electrical assist motor

Benefits
- Reduction of fuel consumption and CO₂ by up to 20%

*primary target of hybridisation in the machine
State of the art: examples

John Deere 644K hybrid wheel loader
Powertrain configuration and main components
- Diesel-electrical powertrain
- 6.8-L IT4/Stage IIIB engine, 171 kW
- Energy storage: no energy storage. Equipped with brake resistor.
Enables
- Running diesel engine at constant speed
- Utilisation of the braking energy in assisting the engine in hydraulic processes
Benefits
- Up to 25% composite fuel consumption reduction

Kalmar hybrid straddle and shuttle carriers
Powertrain configuration and main components
- Diesel-electrical hybrid
- Energy storage: battery
- Automated start-stop system to balance between energy sources
Enables
- Utilisation of the electrical braking and spreader lowering energy
Benefits
- Fuel savings up to 40%
- Lower noise
- Less pollution

11/05/2017
State of the art: examples

**Konecranes SMV 4531 TB5 HLT hybrid reach stacker**

Powertrain configuration and main components
- Diesel-electrical series hybrid
- Energy storage: supercapacitor

Enables
- Electrical energy recovery
- Peak shaving: boosting the diesel-powered electrical generator during peak power demand

Benefits
- Estimated fuel consumption 30% lower than in conventional machines

**KESLA C860 Hybrid wood chipper**

Powertrain configuration and main components
- Diesel-electrical series hybrid
- Engine: Volvo Penta TAD572VE (160 kW / 910 Nm) EU Stage IV / EPA Tier 4 Final
- Energy storage: supercapacitor (by Visedo)

Enables
- Downsizing the diesel engine and its utilisation at optimal speed
- Elimination of traditional drivetrain

Benefits
- Reduced fuel consumption, 20-35% lower, and emissions

---

1. Konecranes
2. Kesla
State of the art: examples

Huddig Tigon construction machinery
Powertrain configuration and main components
- Diesel-electrical hybrid
- Energy storage: 25 kWh Lithium battery
- Both energy sources, diesel engine and battery, can be used for the operating the hydraulics or for propulsion
Enables
- Fully electrical operation possible
Benefits
- 30% higher output power than in diesel powered
- 25% reduction in fuel consumption

Logset 12H GTE HYBRID harvester
Powertrain configuration and main components
- Diesel-electrical hybrid
- Engine: Agco Power 74 AWF, Tier IV Final (4), 220 kW at 1900 rpm, 1200 Nm at 1500 rpm
- Electrical motor: 175 kW at 2100 rpm, 800 Nm at 0-2100 rpm
Enables
- Uplifted performance
- Peak shaving with the electrical drive
- Stable engine performance
Benefits
- Lower fuel consumption and running costs
- Less exhaust gases
State of the art: examples

**Kalmar FastCharge™ solution**

Powertrain configuration and main components
- Electrical powertrain
- Fast charging concept similar as in large capacity electrical buses

Enables
- Smaller number of vehicle components

Benefits
- Up to 50% increased efficiency in comparison with diesel/electrical drive
- Zero local emissions
- Reduced noise and maintenance

**Atlas Copco Scooptram ST7**

Battery

Powertrain configuration and main components
- Electrical powertrain
- Artisan 1200 Series traction motor - 630 VAC / 108 kW, 149 kW peak, single power inverter
- Energy storage: Artisan battery, 165 kWh, LiFePO4, 630 VDC
- Charger system: Artisan 65 kW Master Service, input voltage 575 VAC

Enables
- Zero emission drive
- Fossil fuel free operation with renewable electricity

Benefits
- 80% lower energy consumption compared to diesel machines
NRMM case: Operating environment and equipment in ports

- Harbour layouts differ from each other
- Environment is salty, watery, dusty, sandy, etc.
- Operation must be fast due to high value of goods
- Ship-to-shore cranes (STS) and Automatic Stacking Cranes (ASC) already operate on electricity
- Study focuses on ship-to-yard machinery
  - Shuttle/straddle carriers, AGVs, and terminal tractors
Technical feasibility of charging

Charging equipment:
- Pantograph solutions identified as most feasible
  - Automatic connection
  - Fast connection
  - High charging powers

Batteries:
- Limitations and properties
  - Low charging power acceptance
  - High unit price
  - Uncertain lifetime duration
### Charging concepts

<table>
<thead>
<tr>
<th>Charging concept</th>
<th>Opportunity</th>
<th>Depot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging</td>
<td>Every break</td>
<td>Once per day</td>
</tr>
<tr>
<td>Battery size (type)</td>
<td>Small (LTO)</td>
<td>Large (LFP)</td>
</tr>
<tr>
<td>Charging power requirement</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Operating breaks</td>
<td>Short or none</td>
<td>Long</td>
</tr>
<tr>
<td>Operating range</td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td>Other</td>
<td>Charging duration depends on layout</td>
<td>Easy relocationing, battery swap</td>
</tr>
</tbody>
</table>

"The opportunity charging concept utilizes waiting periods between each work cycle to charge the battery."
TCO calculations and sensitivity analyses for opportunity charging concept

*Comparison of only costs of charger, battery, and electricity to the cost of using diesel machinery

- Assumes that a diesel-hybrid model is modified to a fully electric model

- Potential savings of around 50% compared to similar diesel machinery
- Investment payback time 1.6 years

### Assumptions*

<table>
<thead>
<tr>
<th></th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg power</td>
<td>40 kW</td>
</tr>
<tr>
<td>Usage per day</td>
<td>16 h</td>
</tr>
<tr>
<td>Battery</td>
<td>40 kWh</td>
</tr>
<tr>
<td>Fleet size</td>
<td>5</td>
</tr>
<tr>
<td>Battery unit price (LTO)</td>
<td>1000 €/kWh</td>
</tr>
<tr>
<td>Charger price</td>
<td>250 000 €</td>
</tr>
<tr>
<td>Battery and charger lifetime</td>
<td>10 years</td>
</tr>
<tr>
<td>Electricity price</td>
<td>0.10 €/kWh</td>
</tr>
<tr>
<td>System efficiency</td>
<td>75%</td>
</tr>
<tr>
<td>Residual value</td>
<td>0e</td>
</tr>
<tr>
<td>Discount rate</td>
<td>10%</td>
</tr>
</tbody>
</table>

### Diesel price (€/l)

<table>
<thead>
<tr>
<th></th>
<th>0.60 €</th>
<th>0.80 €</th>
<th>1.00 €</th>
<th>1.20 €</th>
<th>1.40 €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cost per hour</td>
<td>8.40 €</td>
<td>11.20 €</td>
<td>14.00 €</td>
<td>15.80 €</td>
<td>19.60 €</td>
</tr>
<tr>
<td>Consumption (l/h)</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Total cost per hour</td>
<td>10.00 €</td>
<td>12.00 €</td>
<td>14.00 €</td>
<td>16.00 €</td>
<td>18.00 €</td>
</tr>
</tbody>
</table>

### Yearly usage (h)

- 2920 h
- 4380 h
- 5840 h
- 7300 h
- 8760 h

### Battery size (kWh)

- 20 kWh
- 30 kWh
- 40 kWh
- 50 kWh
- 60 kWh

### Battery unit price (€/kWh)

- 200 €/kWh
- 400 €/kWh
- 800 €/kWh
- 1000 €/kWh
- 1200 €/kWh

### Battery cost (€)

- 150 000 €
- 200 000 €
- 250 000 €
- 300 000 €
- 350 000 €

### Battery and charger lifetime (years)

- 6 years
- 8 years
- 10 years
- 12 years
- 14 years

### Battery lifetime (years)

- 6 years
- 8 years
- 10 years
- 12 years
- 14 years

### Electricity price (€/kWh)

- 0.08 €/kWh
- 0.09 €/kWh
- 0.10 €/kWh
- 0.11 €/kWh
- 0.12 €/kWh

### Electricity cost (€)

- 5.20 €
- 5.56 €
- 5.98 €
- 6.11 €
- 6.25 €

### System efficiency (%)

- 69%
- 72%
- 75%
- 78%
- 81%

### Total cost per hour

- 6.51 €
- 6.30 €
- 6.11 €
- 5.94 €
- 5.77 €

- Sensitivity analysis suggests, that a change in usage hours, fleet size, and electricity price are most sensitive (affect total cost the most)

! High charger price together with small fleet size raises the cost significantly
Modelling and simulation as design tools

- Simulation based software development
  - Modelling and simulation will be increasingly important in the future
  - Virtual simulation enables faster and cheaper product development
- MATLAB/Simulink or similar are tomorrow’s engineers’ “office software” like Word and Excel are today. Wide educational use supports MATLAB.
- Open source development vs. safety & security
  - Development of automation systems requires a lot of work.
  - Possible errors increase with the increased complexity. Therefore it is not foreseen that the customer or operators could access the core of the automation system.
- Service – remote control as part of business model both to machine manufacturer and operators.
Simulation of electric vehicle systems

Simulation output
- Simulation enables fast and detailed analysis of energy consumption
- Influence of disturbances (broken charger, congestion, slippery roads) and different placements of chargers can be analysed
- Sensitivity to changes in time schedule and delays

Total cost of ownership (TCO)
- Economical impact of entire vehicle fleet
- Includes vehicle, charging infrastructure, energy and maintenance costs
Simulation of electric vehicle systems – future development

Bus fleet development

- The simulation will be extended to simulation of entire vehicle fleets
- Statistical analysis is being implemented by varying variables such as amount of passengers, stopping frequency, temperature, driving style
- Optimisation algorithms will be added to find the optimal solution for charger placement, driving schedule, battery capacity, battery lifetime …

Mining environment

- Vehicle profiles will be modified for mining vehicles
- Work cycle will be modified to include various working processes, for instance connection of vehicle to grid during stationary and tough processes
- Route description will be developed for mining environment
Finnish companies with public activity in electrification of NRMM

- Kalmar FastCharge™ solution and hybrids
- Konecranes hybrid reach stacker
- SANDVIK towards all-electric mine
- Linkker buses
- KESLA hybrid wood chipper
- Logset hybrid harvester
- Vilakone Wille hybrid
- Avant e5 as battery powered
- Normet
- Valmet Automotive active in NRMMs, too, GIM Oy in robotics, Hybria, Visedo…

Now we can see clear movement from theory to practice and from lab to industry.

Please note that the listing may be incomplete. It is based on our observations from news, articles, press releases etc.
Summary – Reflections from 2011 to the end of 2016

- Stage IV in production, stage V is a year closer
- Price of oil was 120$/b in the end of 2011, last year at this time, it was 27$/b. Now like 55 $/b. What it will be early 2018?
- Battery powered city bus turned out to be a feasible solution over the hybrids – intermediate phase of hybrids might be shorter than believed.
- Role of charging also in terms of mechanical and software connection, is a critical matter still – for cars you see charging stations more and more.
- Tesla Gigafactory?
- New voltage levels, like 48 V in passenger cars i.e. small steps are taken continuously now – noticing these steps demands observation.
Further research

- More *precise* analysis of harbour and mine operations
  - Real *usage* hours
  - Avg. *consumptions* of current diesel machinery
  - Avg. available charging *times*
- More accurate analysis of cost factors
  - €/kW cost of charging equipment
  - Lifetime of battery and charging equipment in harbour and mine conditions
- Other factors
  - Effect of *regenerative braking*
  - Ventilation in mines underground and its impact on total economy
  - External factors, power grid
- VTT continues to research harbour and mining machinery electrification
- Electrification will enable an increased level of automation
Summary and discussion

- Opportunity charging concept identified as more feasible than depot charging concept
- The identified key factors that affect total cost the most:
  - Large fleet size
  - High usage hours
  - Electricity price
- TCO of electrical machinery is about half of similar diesel machinery
  - Sensitivity analysis shows lower costs for electrical machinery in every scenario
- Uncertainty is related to real operating environment and costs
  - Research is continued

Sources: [1-6] found in published thesis
TECHNOLOGY FOR BUSINESS