Consideration of Clean Diesel and Alternative Energies for Underground Production Vehicles

M.C. Bétournay, M. Gangal, B. Rubeli, P. Laliberté, K. Zaghib and A. Tchouvelev

Mining Diesel Emissions Conference
October, 2011

Natural Resources Canada Ressources naturelles Canada

Canada

Drivers for Cleaner Energy Application

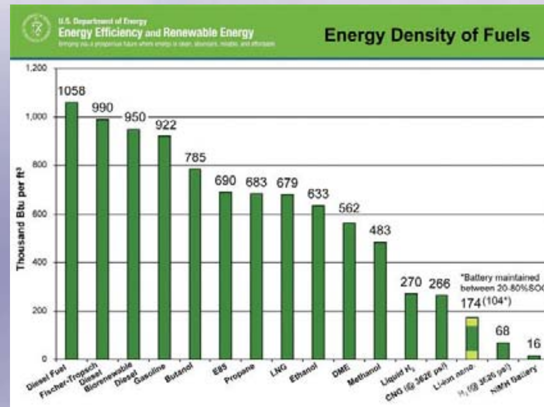
Important Considerations for the Mining Industry

- Workplace health
  - New generation of diesel engines to meet cleaner air requirements (EPA Tier 4 – in effect 2015)
  - Fuel cells offer a total solution, noise generation, vehicle heat load in deep mines, as well as eliminating all emissions
- Rising oil prices
  - Replacing diesel
- Economic opportunity for the industry through cost reductions
  - Reducing required ventilation
  - Ventilation costs (savings of 10% in site electrical and energy bill, ~0.3-1.0 $M/year)
  - Diesel equipment, maintenance, downtime, automation vs fuel cell lower maintenance costs, higher reliability
  - Automation, tele-remote operation improved
- Keeping pace with surface vehicle clean energy drive
- Clean Energy - Changing climatic conditions
  - Green House Gases (GHG): 1.0 MT/year of underground CO_2 eliminated from the 3.7 MT/year underground + open pit mining

Clean Solutions

Non-carbon emitting, maintaining freedom of vehicle movement

- Hydrogen fuel cells
- Hydrogen internal combustion engines
- Rechargeable batteries



Implementation

Power sources are at different stages of applicability

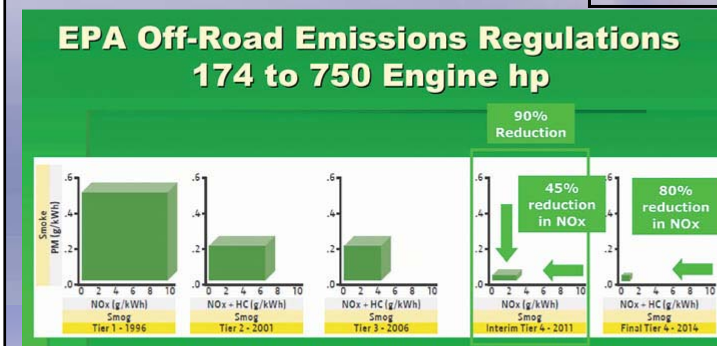
- Technological readiness
- Power plant design
- Operational testing
- Regulatory readiness
- Commercial availability

Natural Resources Canada Ressources naturelles Canada
Canada

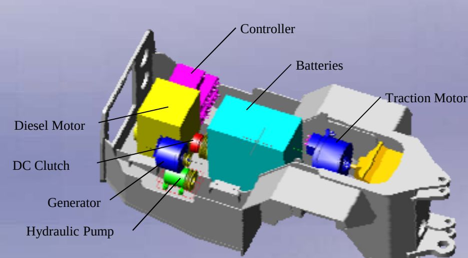
Diesel Technology

Diesel engine with and without Tier 4 after treatment.

Advantages	Disadvantages
Fuel cost	Noise
Durability	Heat release (deep mines)
Displacement flexibility	High NOx
Low hydrocarbons	High DPM
Low CO	GHG's
High torque	Low exhaust T° (after treatment)
Meets mine vehicles power demands	Power plant efficiency

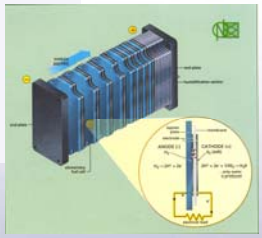


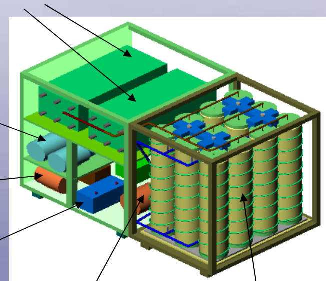
Diesel-Rechargeable Batteries Hybrid Operation



Advantages	Disadvantages
Reduced fuel consumption	GHG's
Durability	Lower heat release (deep mines)
Lower NOx	Power plant efficiency
Low DPM	Does not yet meet all mine vehicles power demands
Lower CO	Capital cost
Use of after treatment device	
High torque	

Hydrogen Fuel Cells





Power plant

(PLC controlled)

Advantages	Disadvantages
Low noise	Fuel Cost
Displacement flexibility	High diffusivity and flammability
No pollutants	Capital cost
Low heat release (deep mines)	
High torque	
Power plant efficiency	
Meets mine vehicles power demands	

Hydrogen Fuel Cell – Rechargeable Batteries

Advantages	Disadvantages
Low noise	Fuel Cost
Displacement flexibility	High diffusivity and flammability
No pollutants	Capital cost
Low heat release (deep mines)	
High torque	
Power plant efficiency	
Meets mine vehicles power demands	

Hydrogen Internal Combustion

Ford 6.8L Triton V10 HICE

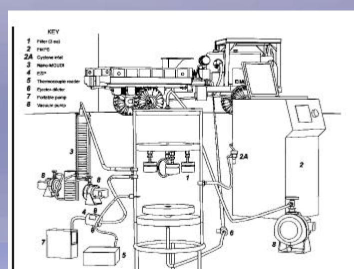
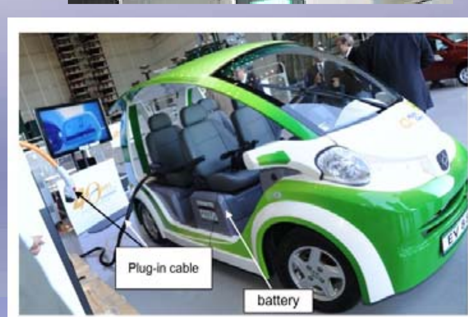


FIGURE 1. Hydrogen-powered vehicle and experimental setup.

Advantages	Disadvantages
Low noise	Fuel Cost
Displacement flexibility	High diffusivity and flammability
No pollutants	High capital cost
Low heat release (deep mines)	Does not yet meet all mine vehicles power demands
High torque	Not yet allowed underground
Power plant efficiency	

Lithium Ion Batteries



Advantages	Historical Disadvantages
High energy density	Heat caused cell rupture – well controlled now???
Ease of use for plug-in power	Distance limitations vs power requirement
High current application	Charge maintenance
Fast charge	Premature ageing (service life)
	Capital cost
	Does not yet meet all mine vehicles power demands

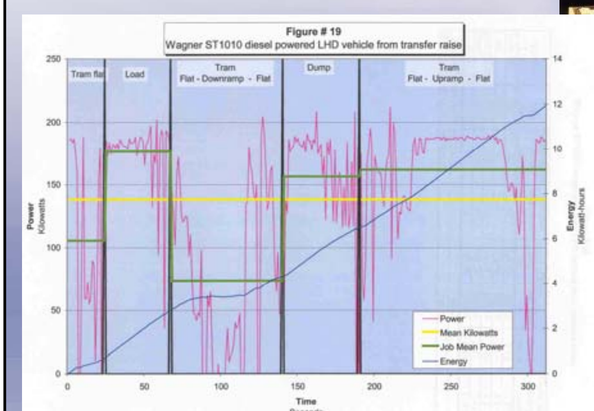
Purpose of the Article

Provide a first-ever base of comparison
for industry energy adoption decision-making

- Stages of clean diesel and alternate technology readiness, anticipated evolution
- Applicability to underground metal mine production vehicles
- Basic energy use issues: power storage, energy efficiency, operational functioning
- Large scale manufacturing
- Regulatory development required
- Cost aspects
- Adoption issues

Natural Resources Canada | Ressources naturelles Canada | Canada

LHD - Basis of Comparison



Natural Resources Canada | Ressources naturelles Canada | Canada

Technology

	Engine Efficiency	Overall Power Plant Efficiency	Hybridization and Recharge	Mining Service	Shock, Impact, Mine Environment Resistance	Production enhancement
Clean Diesel	Max 35%	25%	None	Universal	No special requirements	Reliability
Diesel-battery	30%	22.5%	Traction motor: continuous recharge from onboard generator driven by diesel Hydraulic motor: driven by diesel	Prototype	Vehicle should avoid deep water: electrical wiring, connections	More torque from electric motor
Fuel cell-battery	94% (electric motor)	51%	Traction motor and hydraulic motor: 90 kW fuel cell, 60 kW NiMH batteries (regenerative breaking	Prototype	Power plant tested to 3 g (on average shock can go to 12 g) Little dust, exhaust emission impact	More torque from electric motor Independent traction, hydraulic motors help production
Fuel cell	94% (electric motor)	Max 55%	None	Not designed yet	As above	As above
Hydrogen IC	35%	25%	None	Not designed yet	Should be similar to diesel	None
Lithium plug-in batteries	94 % (electric motor)	Heavy duty plant not designed yet	None	Not designed yet	Water and wiring issues Shock and vibration to be determined	More torque from electric motor Independent traction, hydraulic motors help production

Application

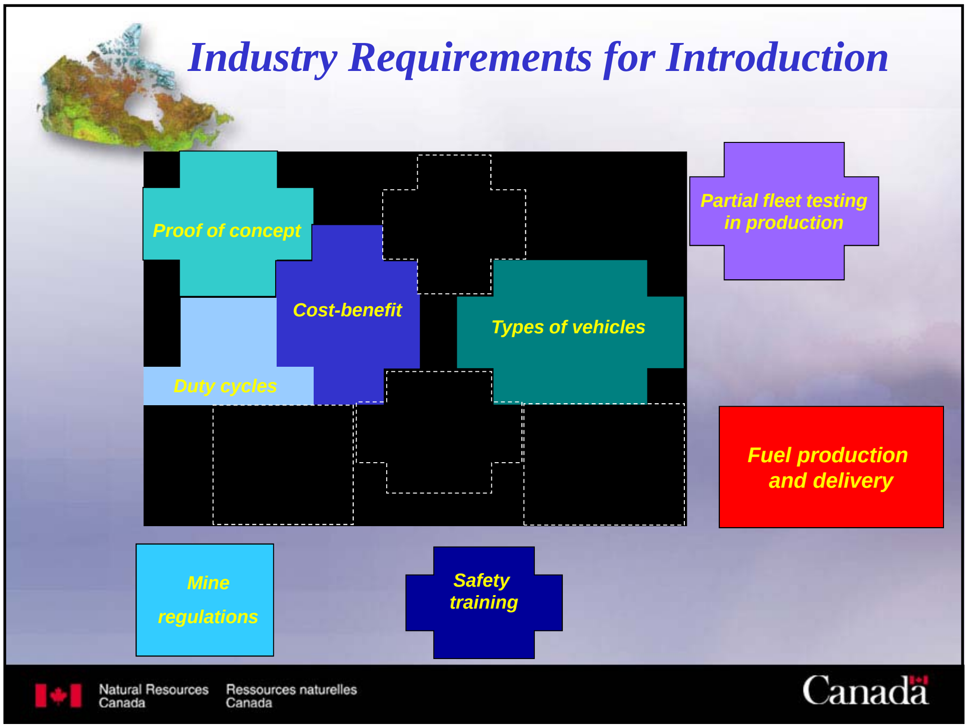
	Maximum time in continuous production (before refueling)	Loader Refueling Time	Refueling Infrastructure	Operation and Maintenance Complexity	Power Plant Maintenance Location	Maintenance Requirements
Clean Diesel	8-10 hrs	5 min	Established	No special requirements	Underground	No special requirements
Diesel-battery	8-10 hrs	5 min	Same as conventional	Complexity: on board generator	Underground and surface	Same as conventional, plus battery testing (u.g.)
Fuel cell-battery	10-12 hrs	15 min	At defined locations (e.g. near exhaust raise), further testing required	Less mobile parts than diesel engine and traction Rapid diagnostics Time consuming power plant repairs Hydrogen storage issues	Underground and surface	33% of diesel version requirements
Fuel cell	6-8 hrs	15 min	Same as above	As above	Underground and surface	33% of diesel version requirements
Hydrogen IC	4-8 hrs	15 min	Same as above	Typical ICE maintenance Hydrogen storage issues	Underground and surface	Similar to diesel
Lithium plug-in batteries	Not available	5 min	Dedicated recharger	Less mobile parts than diesel engine and traction Rapid diagnostics Time consuming power plant repairs	Underground and surface	Battery condition Recharging infrastructure

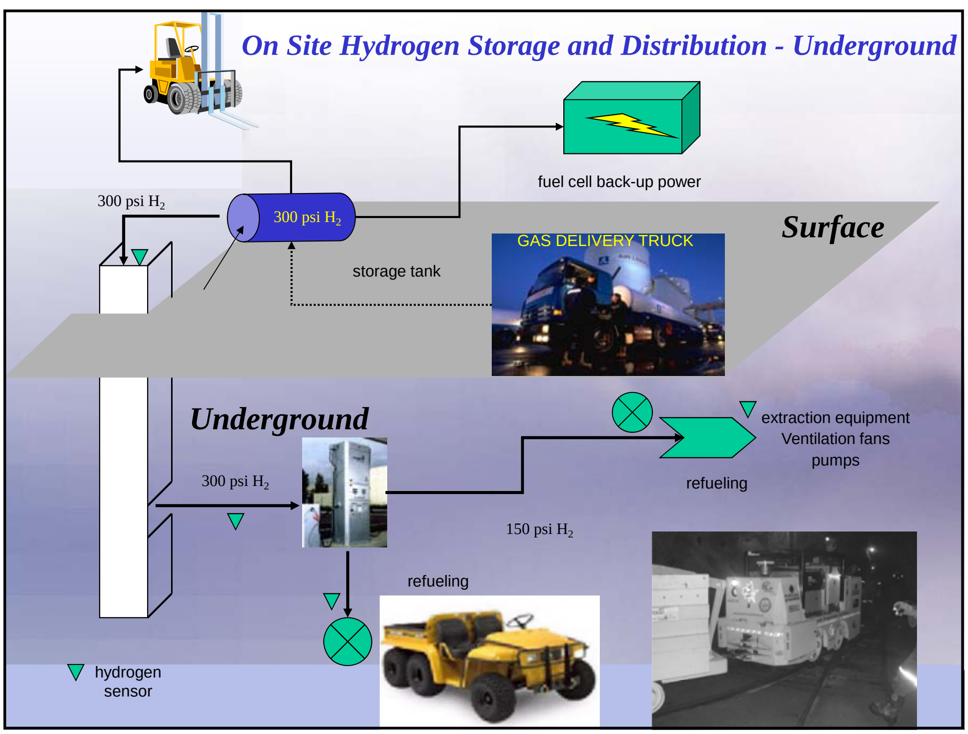
Loader Operation Regulatory Status

	Performance Data	Risk Characterizing	Risk Mitigation	Mine Application Norms and Standards	Specific Regulations	Meets EPA Tier 4 Emissions
Clean Diesel	Established	Established	Established	Established	Established	Established
Diesel-battery	Prototype loader tested 50% battery data level	80% data level	Lower vehicle performances if necessary	None	No	With dedicated Tier 4 engine
Fuel cell-battery	Prototype tested 50% fuel cell, 50% battery data level	80% fuel cell power, 80% rechargeable battery	Shut-offs, ventilation to control leaks (refueling, power plant) Personnal and vehicle sensors Power plant reinforcement (groundfall)	Initiated	No	Yes (Lower ventilation possible)
Fuel cell	50% fuel cell data level	80%	Shut-offs, ventilation to control leaks (refueling, power plant) Personnal and vehicle sensors Power plant reinforcement (groundfall)	Initiated	No	Yes (Lower ventilation possible)
Hydrogen IC	0%	0%	Engine fire suppression	None	Prohibited under current mine regulation	Yes (Lower ventilation possible)
Lithium plug-in batteries	100% Tested for surface applicaiton	100% for surface application	Lower vehicle performances if necessary	None	No	Yes (Lower ventilation possible)

Loader Power Costs

	Present Day Power Plant 3 year Trend	Fuel Storage and Refuelling Station (surface, underground)	Fuel Delivery Infrastructure	On Board Storage Medium	Fuel, Average Loader 8 hr Shift
Clean Diesel	$100/kW; $135/kW Tier 4	$460K	$90K	None	Current fuel pricing 200-350 litres required
Diesel-battery	Diesel as above; Battery $810/kW	As conventional	As conventional	None	As conventional
Fuel cell-battery	Fuel cell $1,500/kW; $250/kW Battery $810/kW	Surface storage and underground dispenser: $30K/month lease	Surface to underground piping: $70K	Metal hydride $10,000/kg stored	$8/kg hydrogen ~$120 per loader per shift
Fuel cell	$1,500/kW; $250/kW Battery $250/kW	Surface storage and underground dispenser: $30K/month lease	Surface to underground piping: $70K	Metal hydride $10,000/kg stored	$8/kg hydrogen ~$120 per loader per shift
Hydrogen IC	Not established 50% higher than conventional diesel	Surface storage and underground dispenser: $30K/month lease	Surface to underground piping: $70K	Metal hydride $10,000/kg stored	$8/kg hydrogen ~$120 per loader per shift
Lithium plug-in batteries	$810/kW	Not yet available	Surface to underground piping: $70K	None	Not established


Industry Requirements for Introduction
Proof of concept
Cost-benefit
Types of vehicles
Duty cycles
Partial fleet testing in production
Fuel production and delivery
Mine regulations
Safety training
Natural Resources Canada
Ressources naturelles Canada
Canada


On Site Hydrogen Storage and Distribution - Underground
fuel cell back-up power
300 psi H_2
300 psi H_2
storage tank
GAS DELIVERY TRUCK
Surface
Underground
300 psi H_2
extraction equipment
Ventilation fans
pumps
refueling
150 psi H_2
refueling
hydrogen sensor

Conclusions

All technologies have or can theoretically be configured to power existing mine production vehicles for current production needs

All technologies will meet or exceed EPA Tier 4 regulations, but significant ventilation savings are possible for the alternative energies

There is a limit as to the toxic emissions reductions possible from carbon-based fuels

There is insufficient testing to define the lifespan and performance of alternate energy power plants but less maintenance is anticipated

All alternate technologies, except for hydrogen IC, will be allowed underground

The regulatory approval process for alternate energy application will be longer than the configuration and testing of pre-commercial power plant design

Current material research is producing more efficient and cheaper alternate energy systems which will match clean diesel engine cost in the timeframe required for alternate energy application regulatory development

There is currently insufficient alternate energy power plant manufacturing capacity to meet mine production vehicle requirements

Studies are required to the best power application for various types of mining methods, depths and mine types, to optimise the mix energy options

Hydrogen Mine Initiative, Underground

Proof of Concept Projects

- Impact of underground environment on fuel cells (C)
- Mine vehicle duty cycles (C)
- Risk evaluation methodology (C)
- Cost-benefit analysis (C)
- Mine production locomotive $2.4M (C)
- Locomotive automation design, long-term testing (C)
- Mine production loader $13M (C)
- Light duty mine vehicle

Introduction Projects

- Hydrogen production and delivery (S)
- Commercial hydrogen production
- Mining regulation development (S)
- Partial fleet testing at a mine site
- Maintenance training program

C=completed S=started

POWER RANGE

Underground Vehicles

- Mine loco 15-75 kW
- Light duty 50-100 kW
- LHD 150-300 kW
- Truck 300-500 kW

Comparative Operating and Capital Costs for Underground Mine Loaders

Annual operating cost comparison 8 LHD's, Louvicourt.

	Diesel	Fuel cell-hybrid	Difference between diesel and fuel cell-hybrid
Operation			
maintenance, fuel, hydride bed cooling	$ 2,722,390	$ 3,016,500	$ (513,760)
ventilation	$ 2,194,800	$ 1,6401,000	$ 553,800
TOTAL	$ 4,917,190	$ 4,657,500	$ 259,690

Diesel loader capital costs 8 LHD's, Louvicourt.

Tanks, delivery system, pumps, stations, excavations, extinguishing systems, ventilation systems	$ 666,100
8 LHD's, 8yd^3	$ 5,842,000
TOTAL	$ 6, 508,100

Fuel cell hybrid loader capital costs, 8 LHD's Louvicourt

Surface storage tanks, delivery system, monitoring equipment, filling stations, excavations, extinguishing systems, ventilation systems	$ 338,280
8 LHD's, 8yd^3	$ 9,521,788
TOTAL	$ 9,860,068

Natural Resources Canada Ressources naturelles Canada Canada