Energy Saving Fluid Power Technology for Off-Road Vehicles

Professor Kim A. Stelson
University of Minnesota

Global Fluid Power Society Webinar

April 8, 2025

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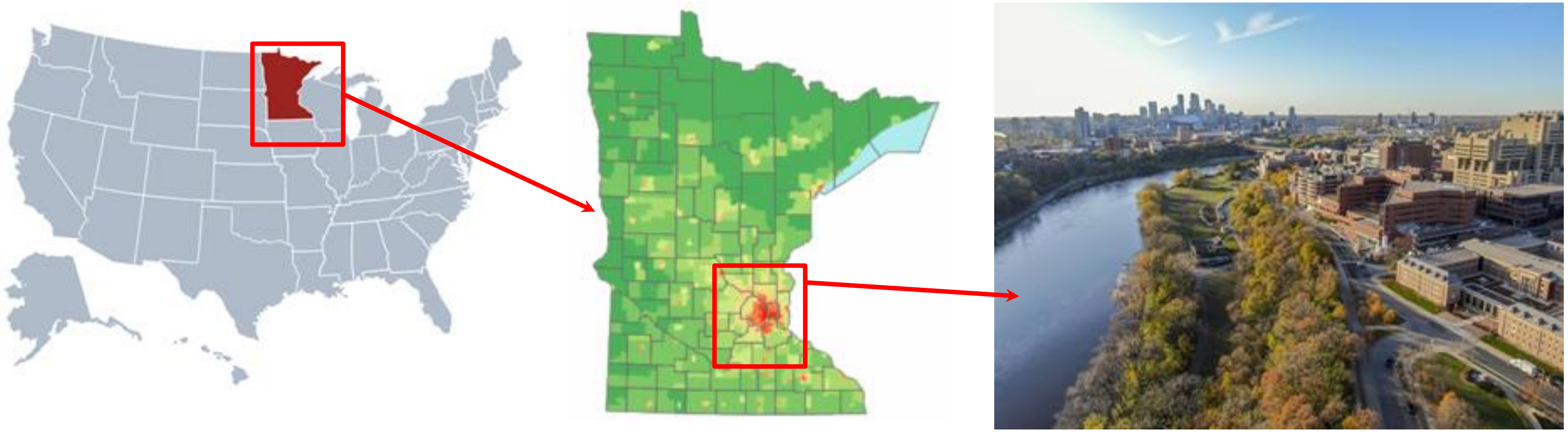
Minneapolis / St. Paul



Home to 19 Fortune 500 Companies

Vibrant area with award-winning parks, bike trails, and culture

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University of Minnesota Mechanical Engineering

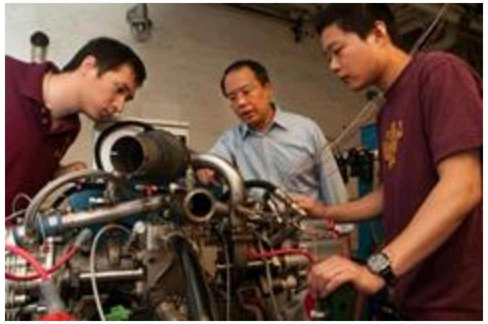
National Research Centers

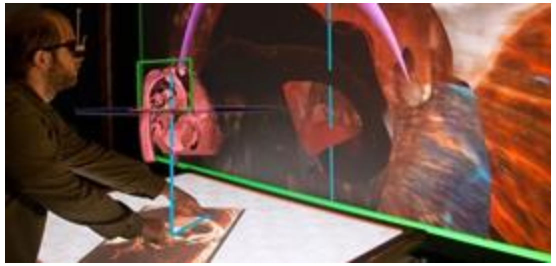
Advanced Technologies for the Preservation of Biological Systems (ATP Bio)

Center for Compact and Efficient Fluid Power (CCEFP)

Bakken Medical Devices Center

Center for Transportation Studies





University of Minnesota Mechanical Engineering

Unique Relationships and Resources

Medical devices

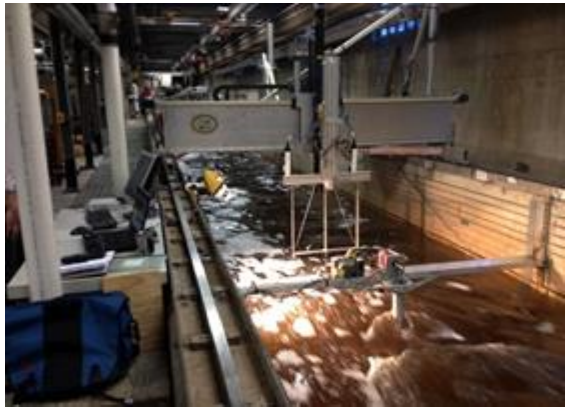
- Major medical device companies
- UMN hospital
- Medical Devices Center
- Mayo Clinic

Saint Anthony Falls Laboratory

Murphy Engines Laboratory

Anderson Labs

Minnesota Supercomputing Institute



University of Minnesota Mechanical Engineering

540 undergraduate students

339 graduate students

47 professors

10 National Academy of Engineering members

18 professors hired in the last 12 years

Technical Areas

Mechanical Engineering is a broad, interdisciplinary field, our technical areas include:

Biosystems & Bioengineering | Combustion & Engines
Fluid Mechanics | Fluid Power | Materials & Mechanics
Particle Technology | Plasmas | Sensing & Controls
Thermodynamics & Heat Transfer

Impact Areas

ENERGY TRANSITION
- solar energy
- wind & wave energy
- energy storage

ENVIRONMENT & SUSTAINABILITY
- air pollution
- climate change
- greener industry
- water & life

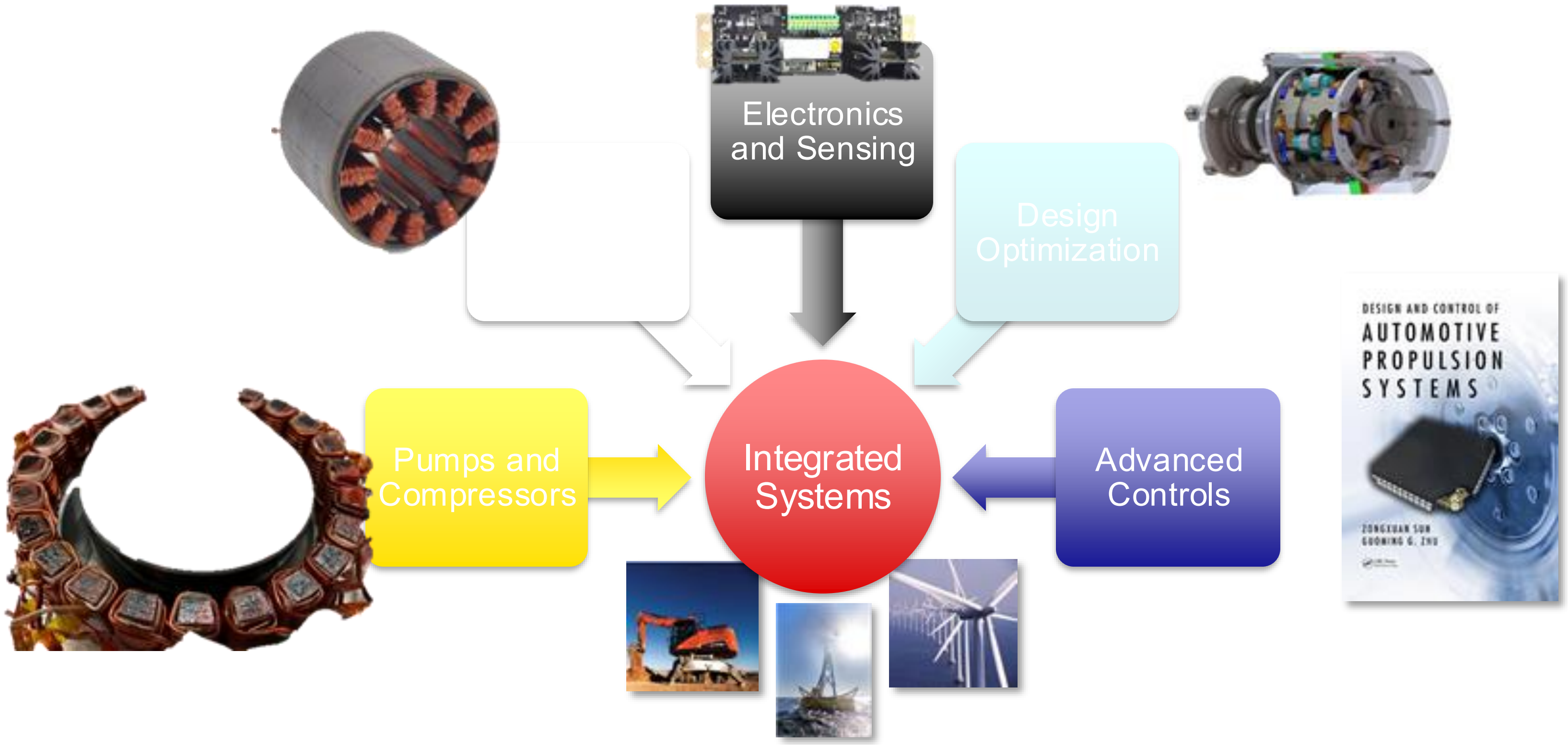
HUMAN HEALTH
- biomedical & robotics
- sensors & diagnostics
- drug delivery & treatments

NEXT-GEN MANUFACTURING
- biomedical devices
- robotic assembly

Center for Compact and Efficient Fluid Power (CCEFP)

Mission

To be a center of research excellence in fluid power, fluid transfer, and off-road vehicle systems.



Faculty Leadership

Prof. Zongxuan Sun

- Dynamic systems and control
- Automotive propulsion systems
- Energy storage
- Mechatronic actuators
- Instrumentation and testbeds

Prof. James Van de Ven

- Applying machine design to efficient energy conversion, storage, and generation
- Fluid Power
- Kinematics
- Dynamics
- Flywheel energy storage

Prof. Kim Stelson

- Fluid power systems
- Sustainable off-road vehicles
- Mechanical design and manufacturing
- System modeling
- Actuation and control

Prof. Perry Li

- System dynamics and control
- Mechatronics and intelligent machines
- Fluid power
- Compressed air energy storage

Prof. Eric Severson

- Electric motor design and control
- Magnetic bearings
- High speed rotors
- Vehicle and hydraulic system electrification
- Flywheel energy storage
- Energy and sustainability

US DOE Funded Fluid Power & Off-Road Vehicle Research: ($19.5M issued)

CCEFP

Project Title	PI - Lead Institution	Award Amount ($)
Efficient, Compact and Smooth Variable Propulsion Motor	Prof Jim VandeVen University of Minnesota	$1,750,000
Individual Electro-Hydraulic Drives for Off-Road Vehicles	Prof Andrea Vacca Purdue University	$1,875,000
High Performance Fluids and Coatings to Improve Efficiency, Productivity, Durability, and Environmental Compatibility of Off-Road Hydraulic Components	Various Pis ANL, ORNL & PNNL	$2,000,000
Hybrid Hydraulic Electric Architecture for Mobile Machines	Prof Perry Li University of Minnesota	$1,891,000
Optimization and Evaluation of Energy Savings for Connected and Autonomous Off-Road Vehicles	Prof Zongyuan Sun University of Minnesota	$1,670,000
A new approach for Increasing Efficiency of Agricultural Tractors and Implements.	Prof Andrea Vacca Purdue University	$2,500,000
Development of a Heavy-Duty Electric Vehicle Integration and Implementation (HEVII) Tool	Prof Will Northrop University of Minnesota	$400,000
Fully Electric Powered, Hydraulic Assisted, Compact Track Loader	Prof Perry Li University of Minnesota	$2,365,000

Two Truths:

1. Humans have caused climate change.

2. Humans have the agency to slow or reverse climate change.

Climate Inactivists Use Many Ds

Disinformation, Deceit, Divisiveness, Deflection, Delay, Despair-Mongering, Denial, Dissembling, Downplaying, Deflection and Doom.

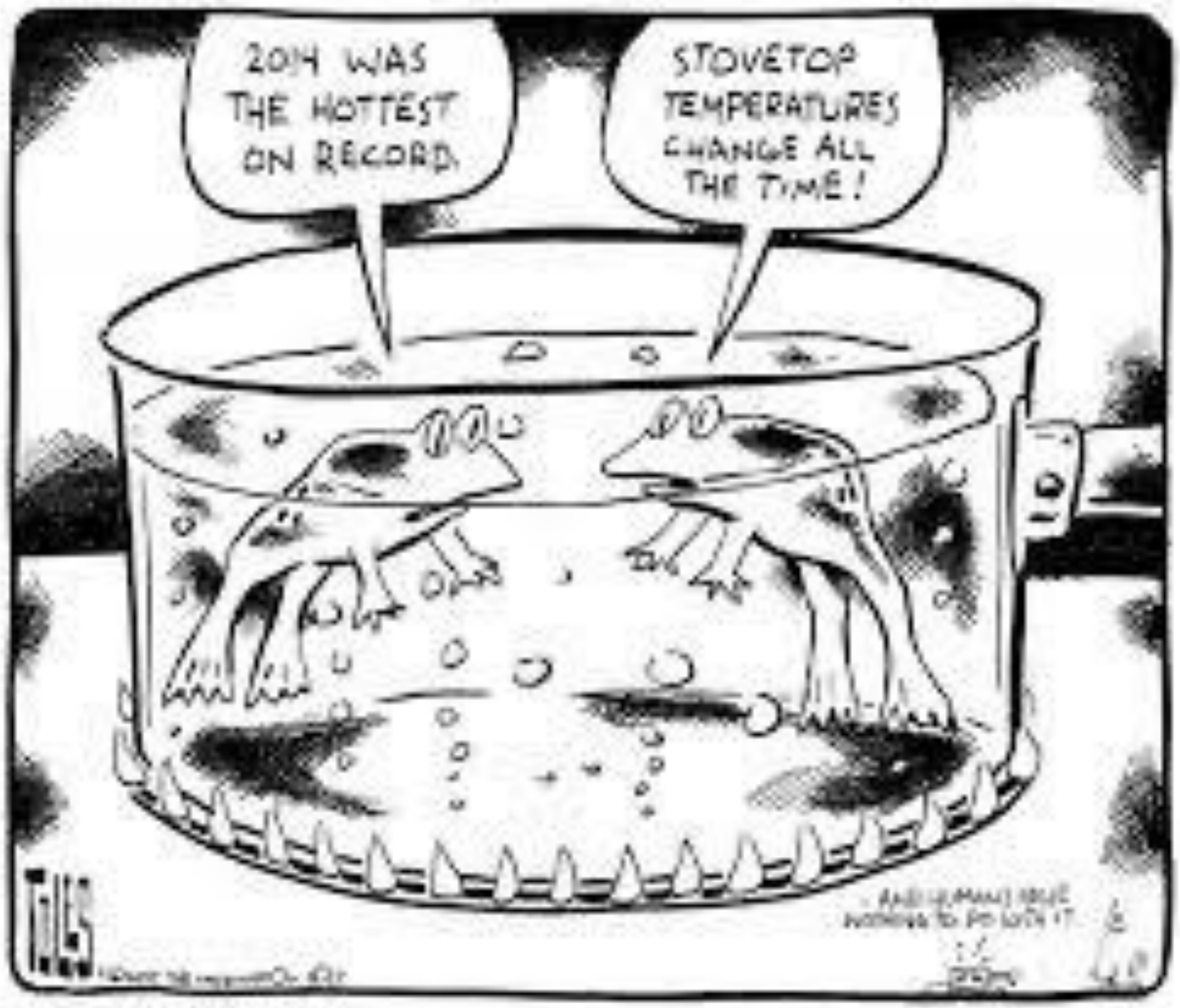
Consider these three Ds:

1. Denialism

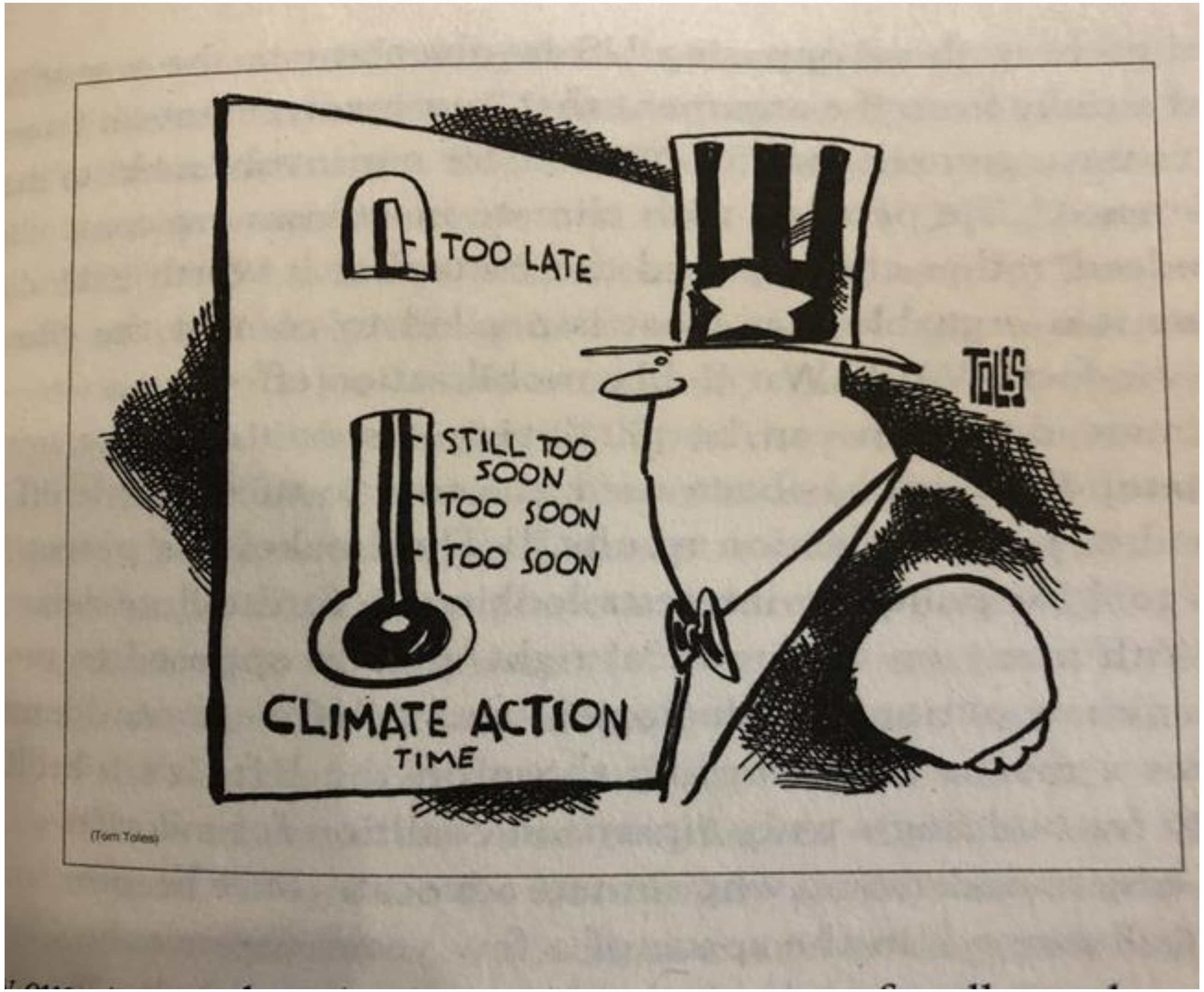
2. Deflectionism

3. Doomism

Denialism


2014 WAS THE HOTTEST ON RECORD.
STOVETOP TEMPERATURES CHANGE ALL THE TIME!

Denialism and Doomism



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Difficult to De-Carbonize Applications

Off-road Vehicles

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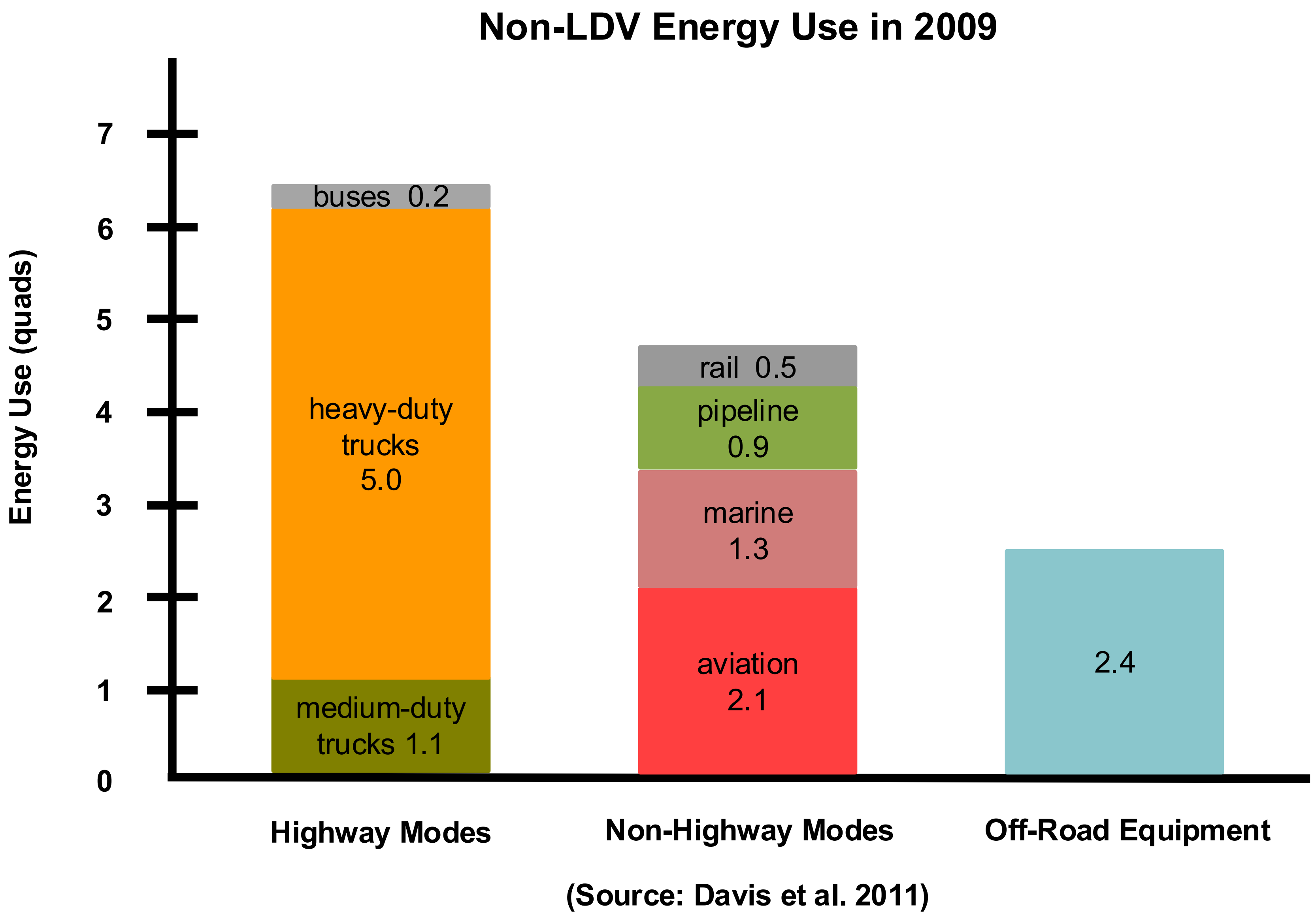

Off-road market consumes about 8% of the total transportation energy, 17% of the Non-LDV energy use, half of heavy-duty trucks, and larger than either marine or aviation markets.

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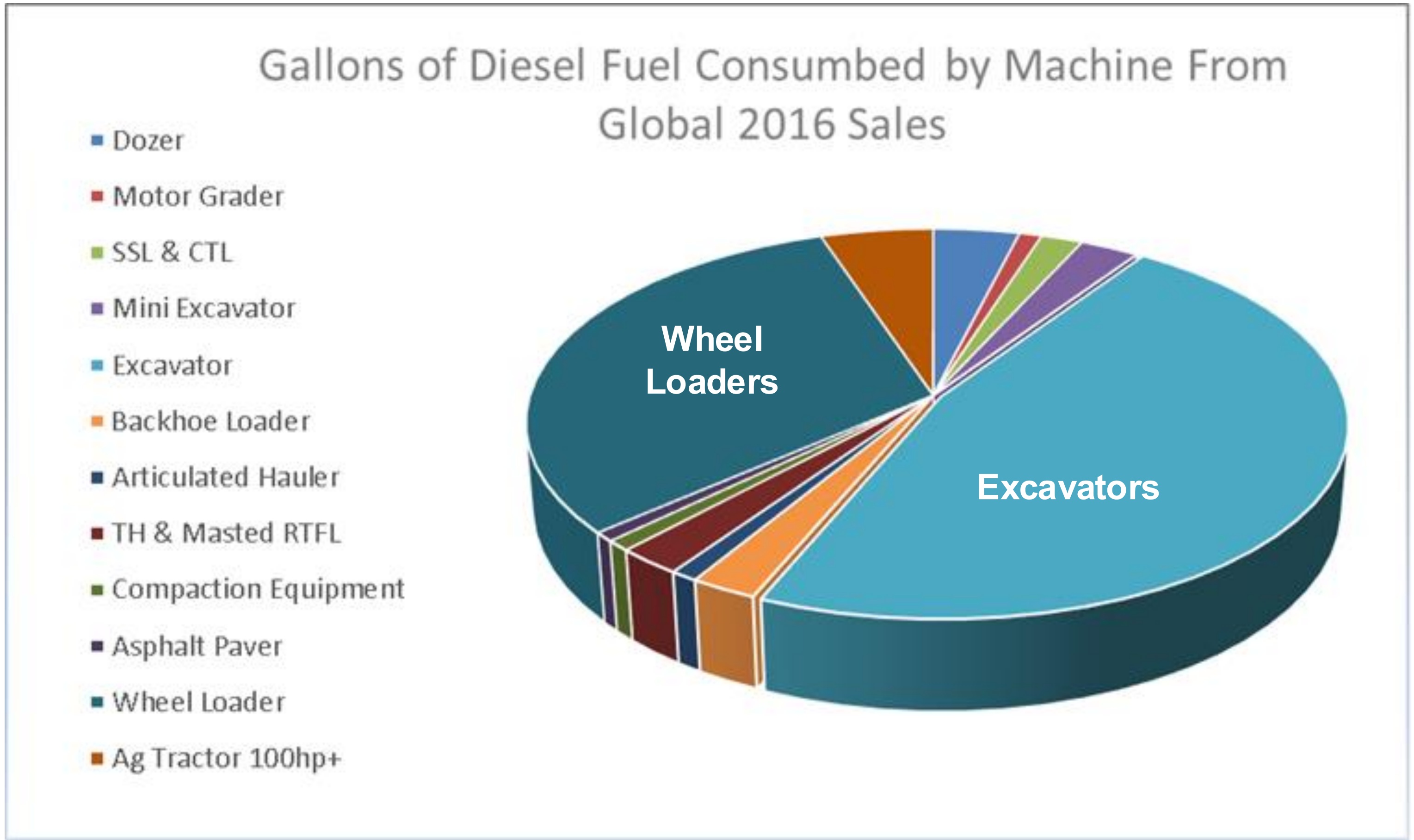
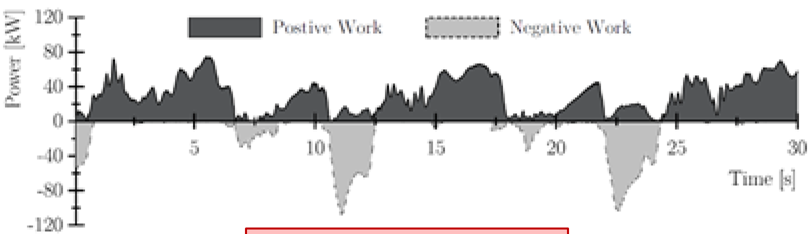
Energy Use in Construction Equipment

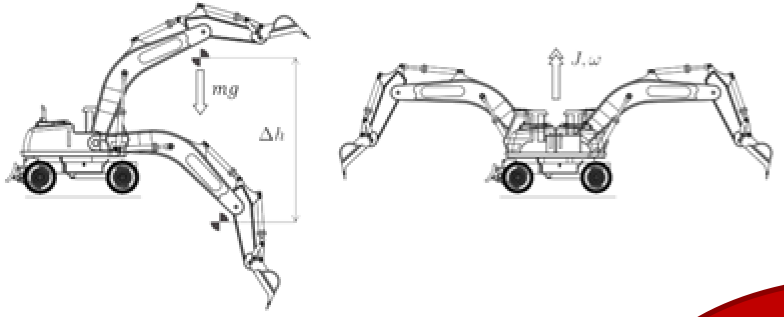


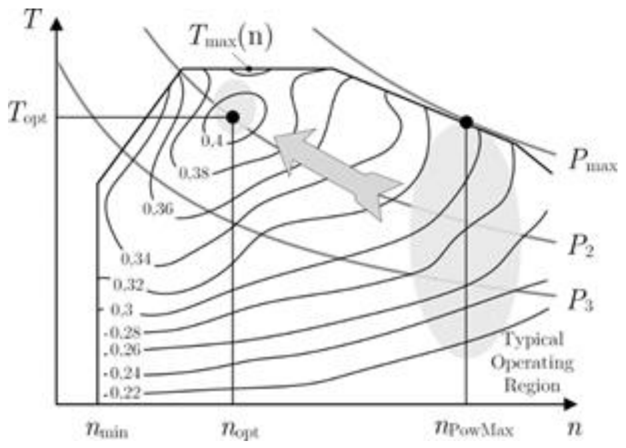
Excavators and wheel loaders are the largest consumers of fuel for construction machines.

Improving System Efficiency



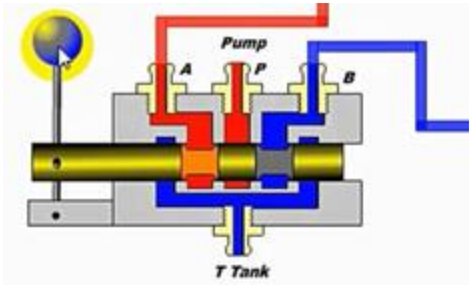
Energy recovery



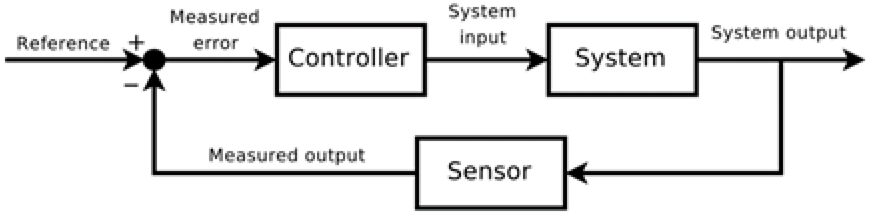


Engine management

1.2 quads of energy savings potential



Eliminate throttling valves



Intelligent controls

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Energy Savings Opportunity

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	Engine efficiency	system efficiency	Overall efficiency	consumed (Quads)	Saved (Quads)
Current system	30%	40%	12%	2.4	0.0
Improved System	40%	60%	24%	1.2	1.2*

***Note: a 5% improvement in engine efficiency for both on-highway (6.3 Quads) and off-highway (2.4 Quads) non light-duty energy sectors would save 0.43 Quads.**

Target fuel savings: 50%

Excavator

Wheel loader

To make these machines efficient we need: efficient engine operation, hybridization, throttling elimination and closed-loop control

The Future…

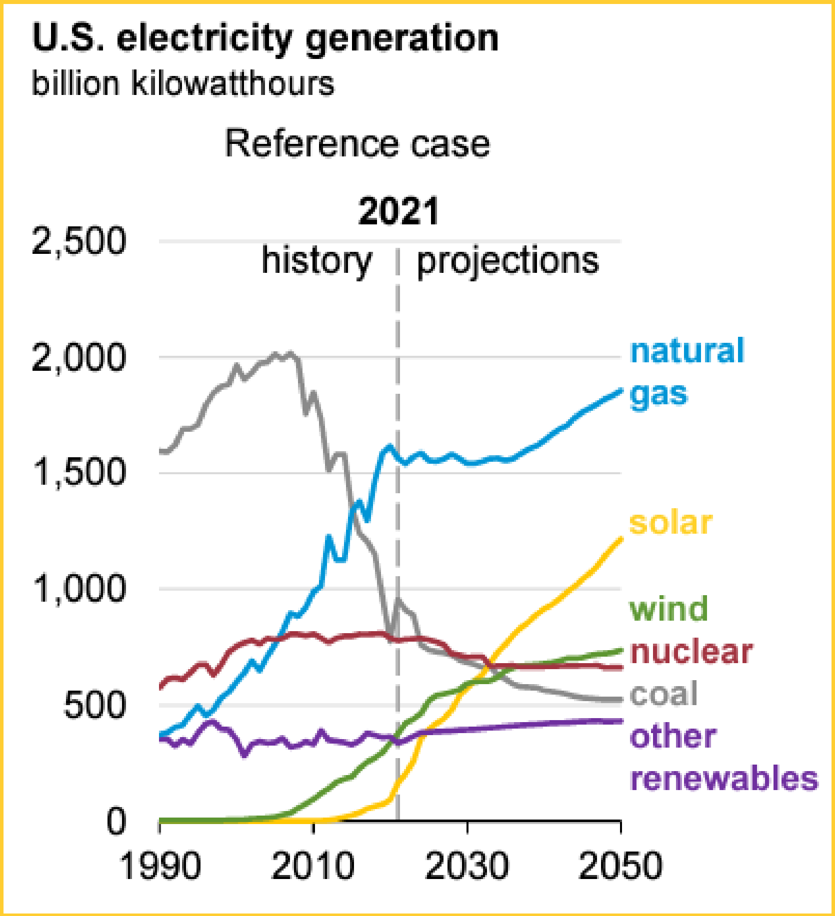
Getting to Net Zero for Off-Road Vehicles

Net Zero Carbon Commitments

- 2050: EU, UK, Norway, New Zealand, Japan, South Korea, Chile, South Africa, Switzerland, Costa Rica
- 2060: China
- US: 50% below 2005 levels by 2030. (Biden administration commitment, now in doubt)

The path to zero carbon is now becoming clear with major nations making a commitment to achieve zero carbon by 2050.

Wind and Solar Energy Future



Source: EIA, International Energy Outlook 2022

Net Zero Energy Sources

- *Solar, wind*, hydro, nuclear and biomass
- Nonrenewable with sequestration

- Renewable fuels
  - **<u>Biomethane</u>**, ethanol, DME, biodiesel, algae, **<u>hydrogen, ammonia</u>**

- Surplus renewable electricity can be used to create hydrogen, a cheap and plentiful net zero fuel.

Hydrogen Terminology

All hydrogen is not created equal…

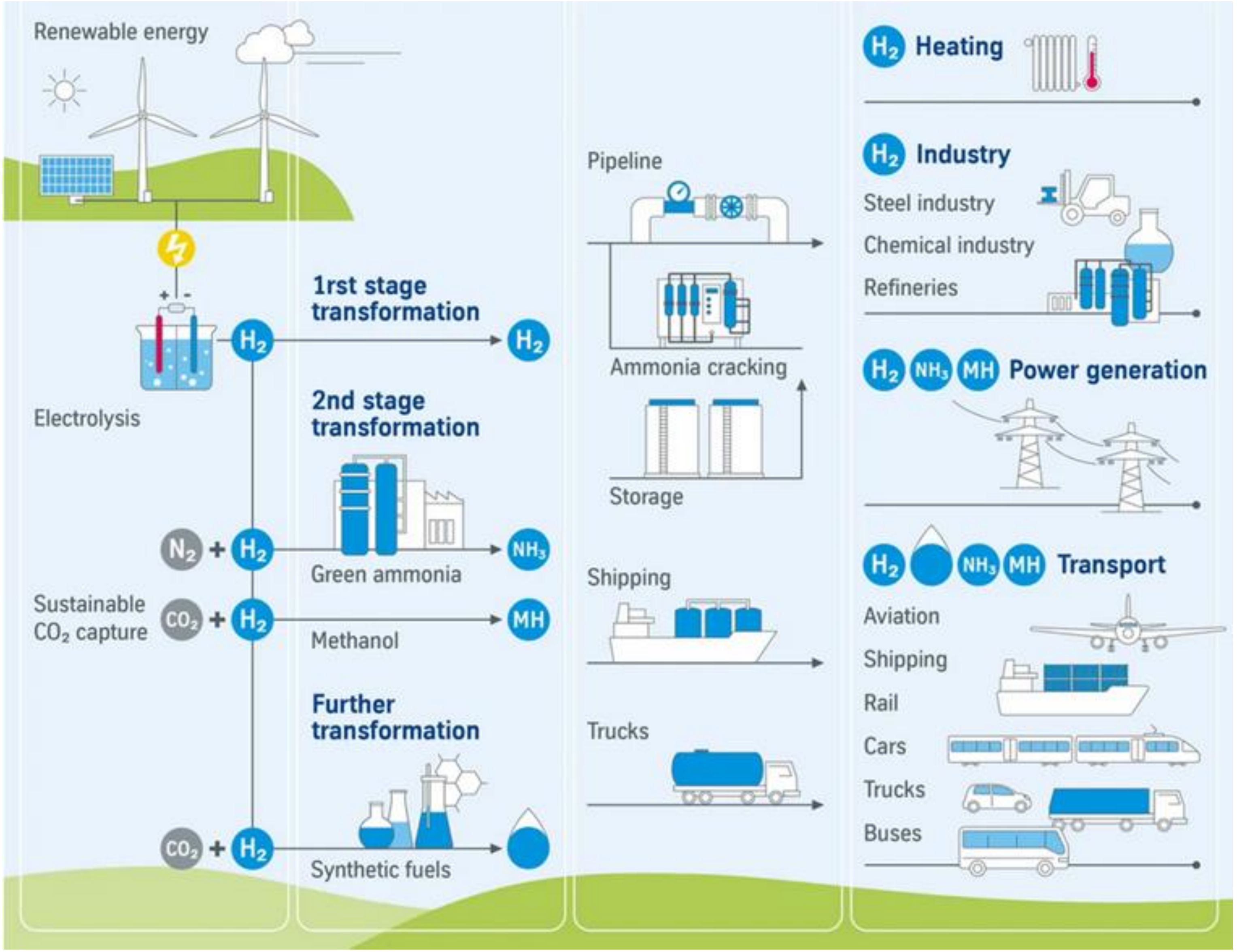
"Gray" hydrogen = Produced from natural gas or coal

"Green" hydrogen = Produced from renewable resources such as wind and solar

"Blue" hydrogen = Produced from natural gas or coal with carbon capture and sequestration

"Pink" hydrogen = Produced from nuclear power

Options for Green H2 Gases and Fuels



Credit: Thyssen Krupp

Green Hydrogen

- The Inflation Reduction Act provides a $3 /kg hydrogen production incentive, a game changer. (Biden administration initiative, now in doubt.)

- Green hydrogen production and utilization is no longer 10 years away – it is here now.

- DOE Hydrogen Energy "Earth-Shot" goal is 1-1-1. $1 for 1 kg clean hydrogen in 1 decade.

Midwestern Hydrogen Coalition ("M-H_2 Coalition") MOU

Accelerating and improving clean hydrogen production, processing, and use

A Regional Clean Hydrogen Memorandum of Understanding

Between

Illinois, Indiana, Kentucky, Michigan, Minnesota,
Ohio and Wisconsin

J.B. Pritzker Governor of Illinois

Eric Holcomb Governor of Indiana

Andy Beshear Governor of Kentucky

Gretchen Whitmer Governor of Michigan

Tim Walz Governor of Minnesota

Mike DeWine Governor of Ohio

Tony Evers Governor of Wisconsin

Seven US Midwest states have agreed to form a clean hydrogen production coalition.

U of MN Renewable Hydrogen and Ammonia Pilot Plant

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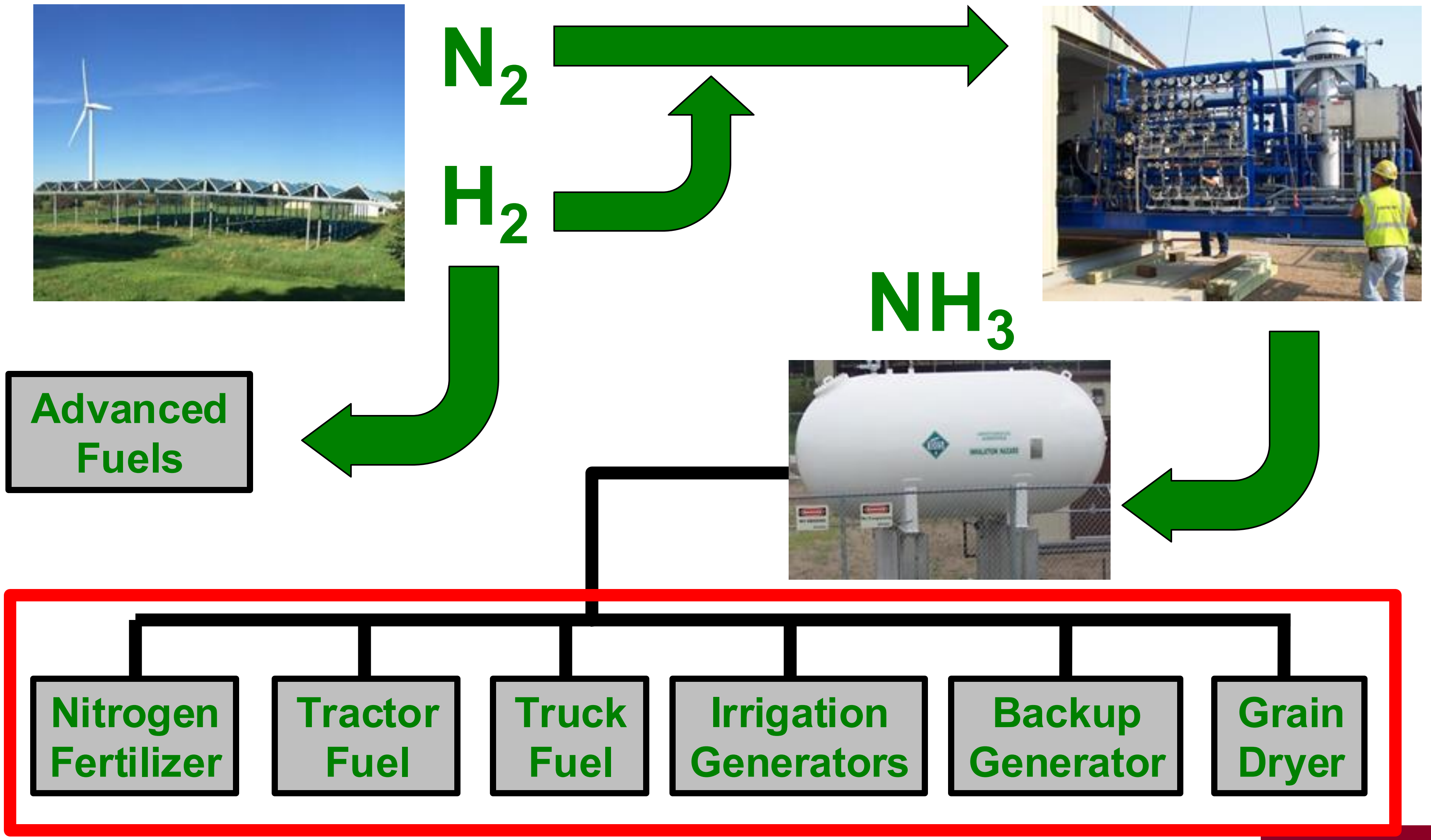
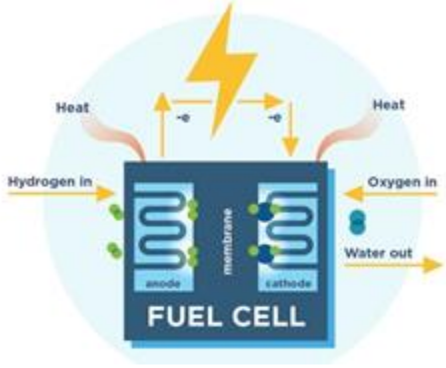
Green Ammonia: De-Carbonizing Farm Energy



Future Net Zero Off-Road Systems (1 of 2)

Compressed H_2
350-700 bar

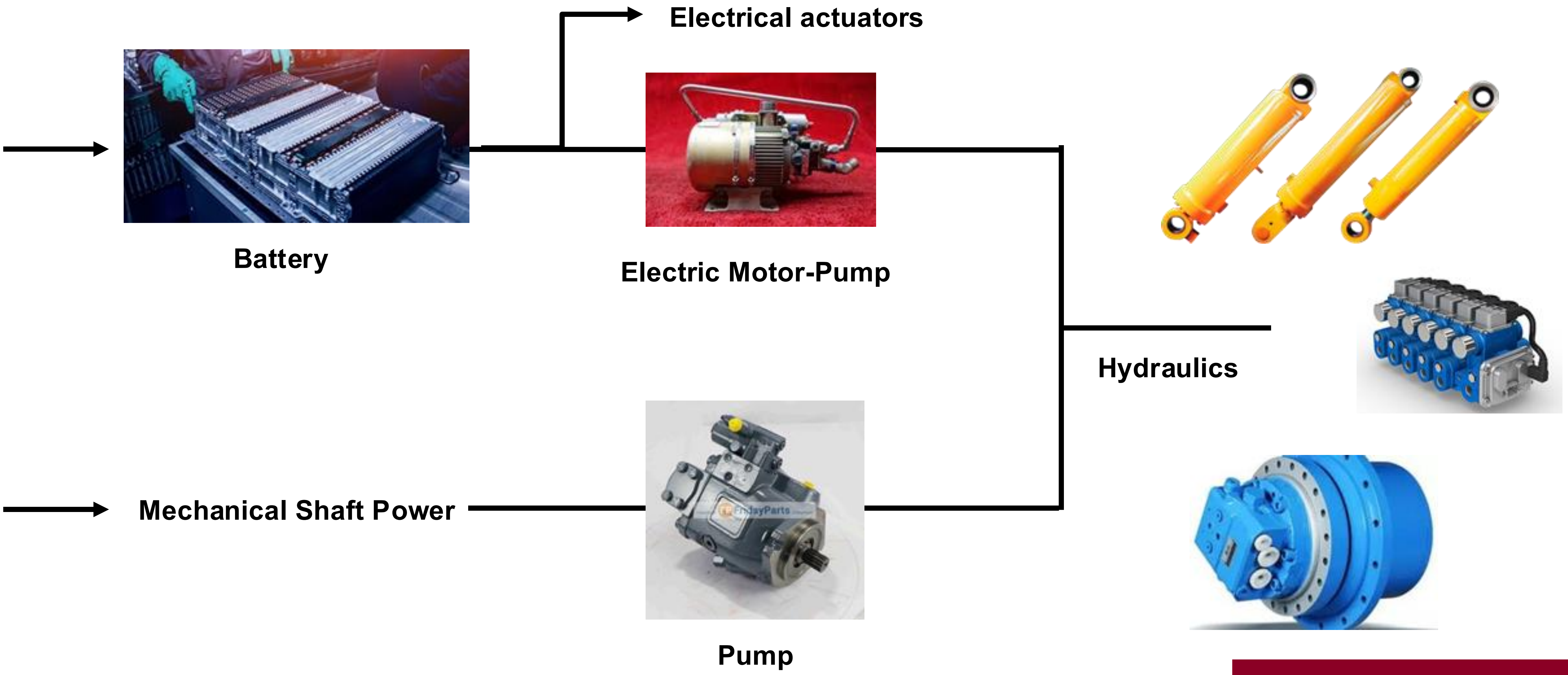


Reformer

NH_3
8-20 bar

Engine

Future Net Zero Off-Road Systems (2 of 2)



Hybrid Powertrain with Renewable Fuel Engine: Agricultural Sprayer Demonstration

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Challenge Being Addressed

Large off-road machines with long run times are hard to decarbonize

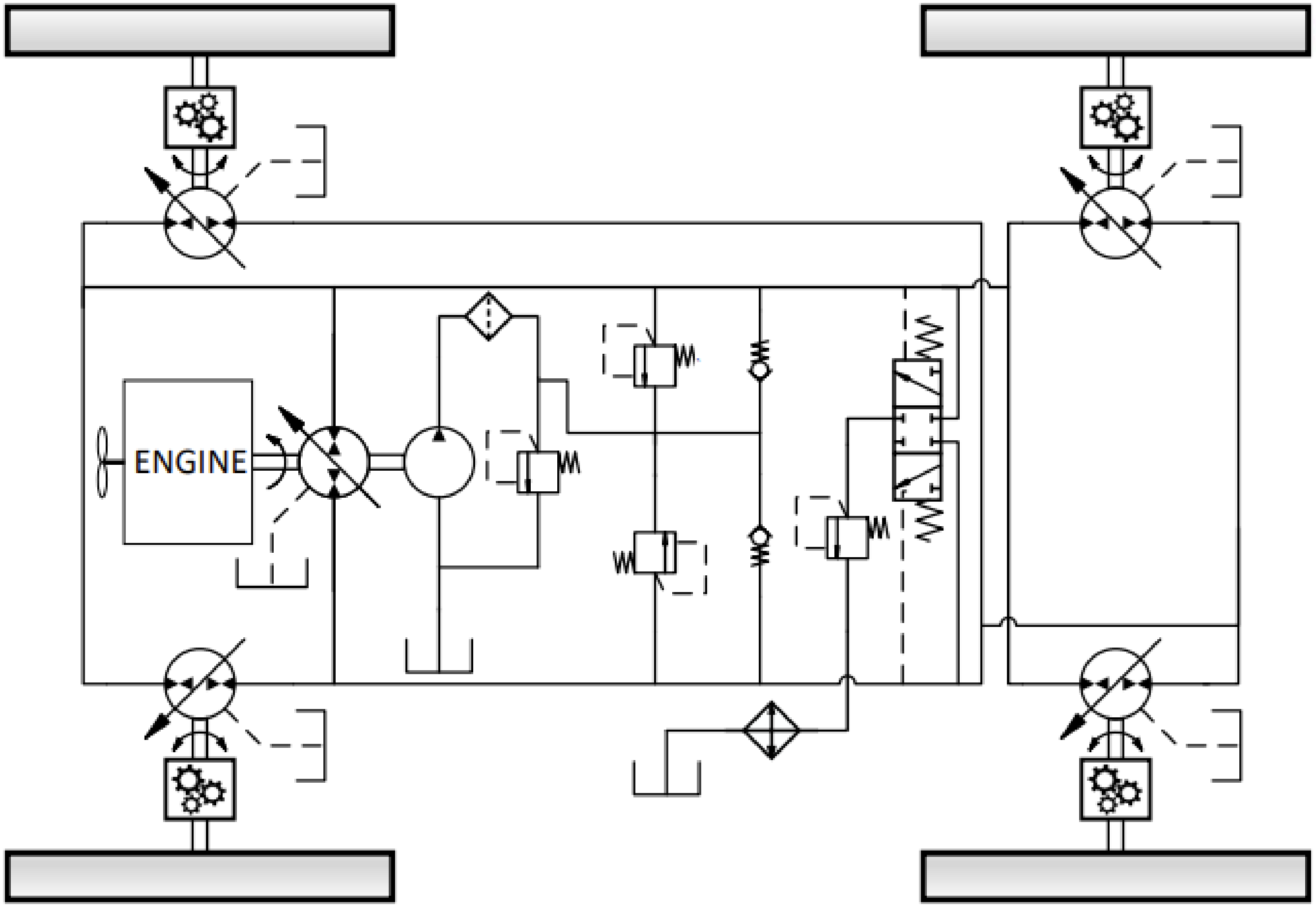
Pure battery solution not feasible

Example sprayer:

250 kW engine, 12 hour run time, 150 gallon diesel tank

Equivalent capacity Li-Ion battery: 41 metric tons, 16,227 liters, $1.35M.

Baseline Powertrain Architecture



Hydrostatic transmission
Engine run at “high idle”

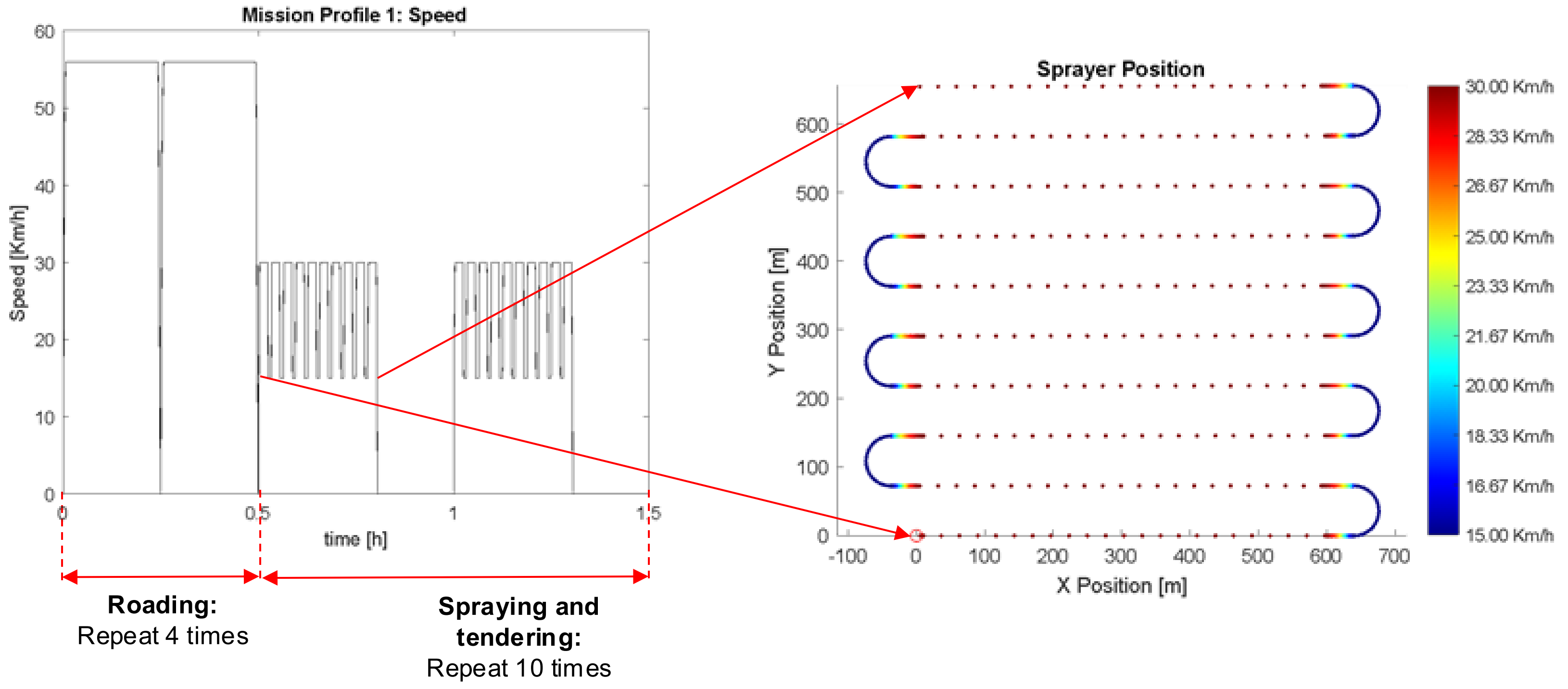
Not shown:
Product spray circuit
Brake & steer circuit
Boom ride height and fold circuit

Mission Profile

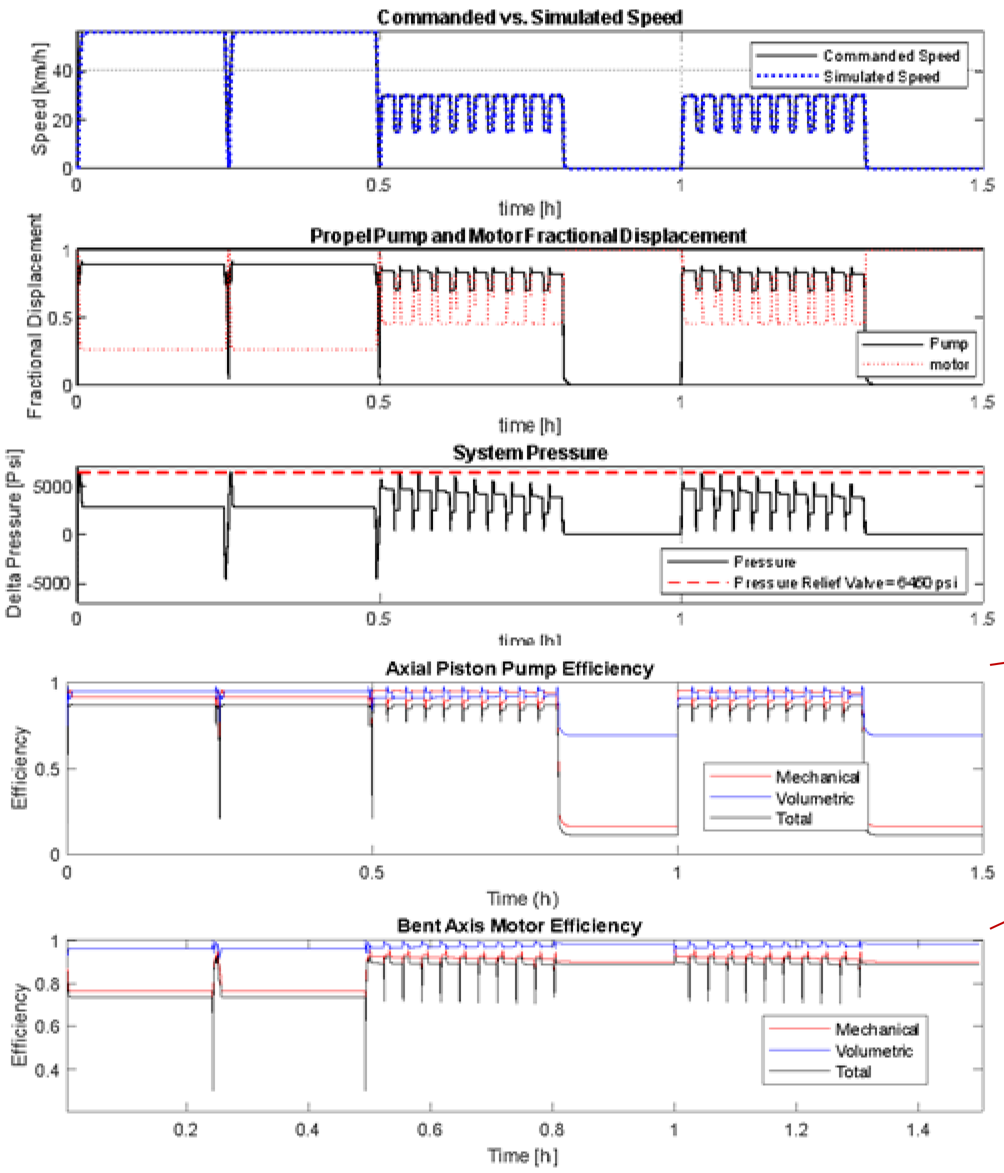
- A mission profile is specified to determine fuel consumption and total energy.
- Several inputs are specified:

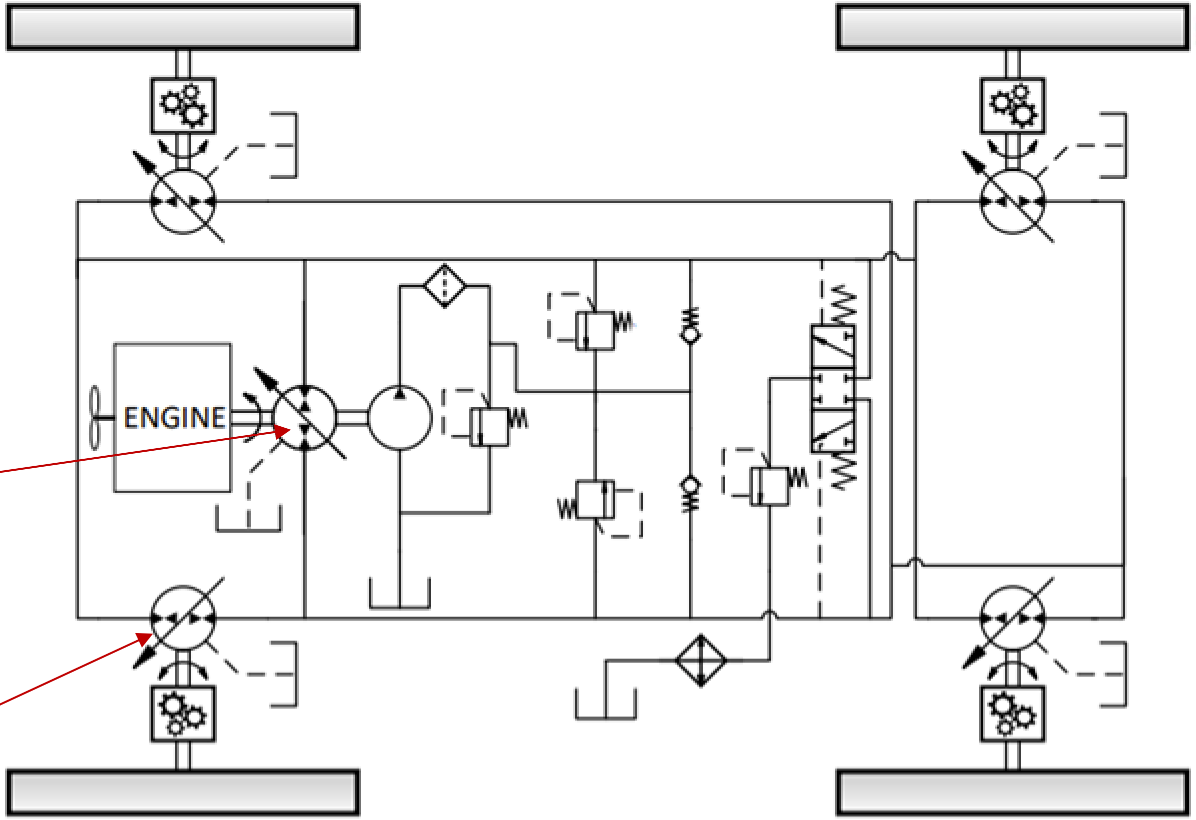
Normal Field Flat	Roading			Spraying											
	Hours	Speed	Stops	Tender	Minimum Speed	Duration	Spray	Grade	Product Pump Power	Aux Pump Power	Repetitions	Total	Incr. Reps	Total	Soil - Rolling Resistance
Increment		KPH		Seconds	KPH	Seconds	KPH		kW	kW		Seconds		Hours	Normal
1	1	56	4					0	0	5	1	3600	2	2	0.02
2					15	100	30	0	8	12	10	1100	20	10.00	0.1
				700				0	18	0	1	700			
													Sum	12	

Credits: *CNH Industrial*



Baseline Vehicle Simulation

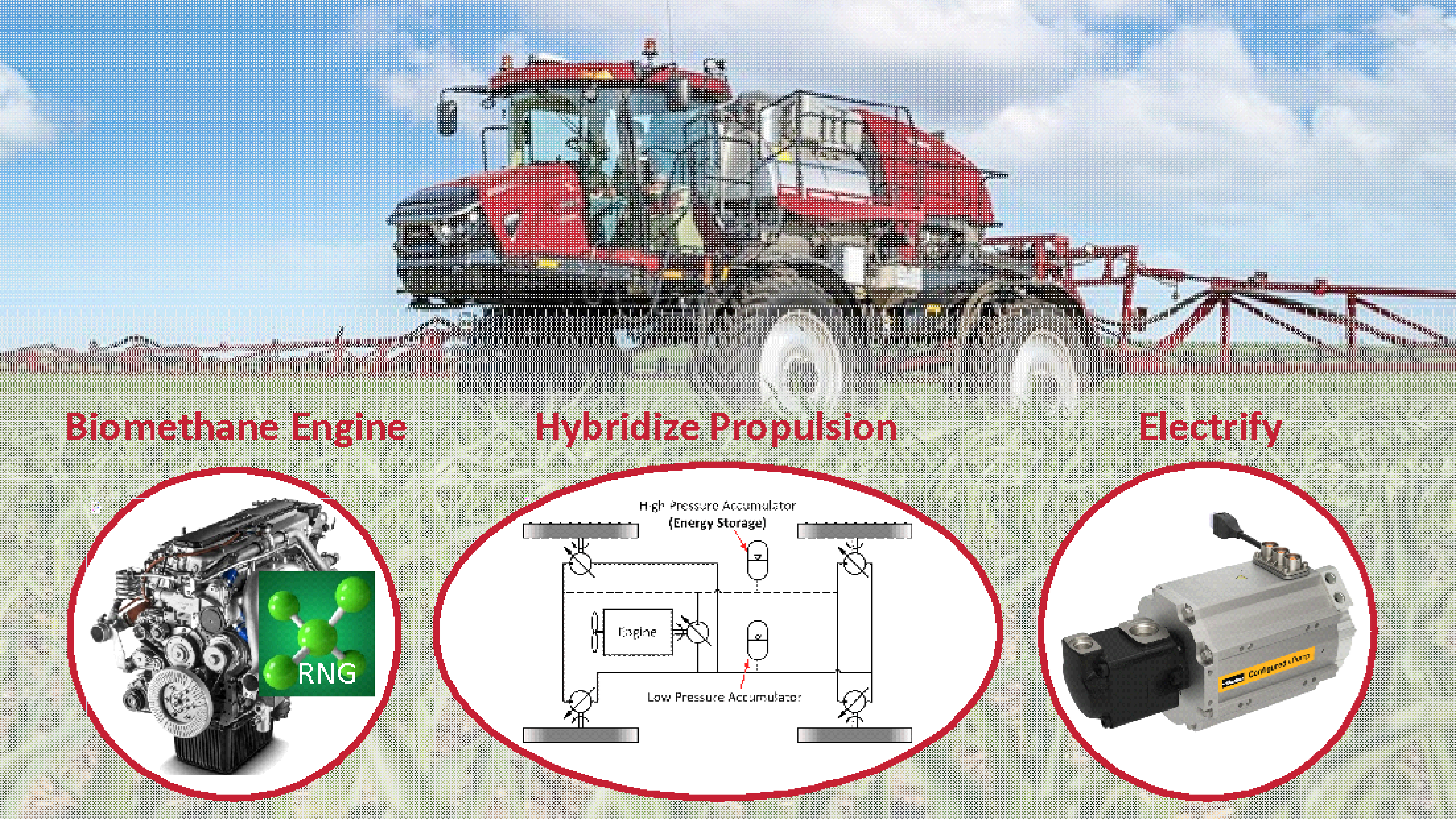




Baseline Powertrain Simulation Summary

Operating Condition	Fuel consumption [gal/hr]	Fraction of mission profile by time	Average power [kW]	Average engine BSFC [g/kWh]	Average pump and motor efficiency
Roading	10.6	0.193	158.88	214.17	
Tendering	4.07	0.3	25.8	507.38	N/A
Accelerating in field	24.7	0.045	179.11	444.3	
Steady Field Driving	13.2	0.421	201.82	210.46	
Braking in field	14.3	0.04	102	451.6	

1. Steady-speed field operation: largest fraction of the mission profile, best engine and pump and motor efficiency
2. Roading: poor motor efficiency
3. Tendering: significant fraction of the cycle, poor BSFC
4. Acceleration: Highest fuel consumption rate
5. Braking: poor BSFC, fuel consumption rate similar to steady field driving


Biomethane Engine
Hybridize Propulsion
Electrify
RNG
High Pressure Accumulator
(Energy Storage)
Engine
Low Pressure Accumulator

Approach: Renewable Fuel Engine

Replace diesel engine with biomethane engine
Study H_2 engine in simulation
Renewable Natural Gas (RNG) production:
Riverview Dairy (Morris, MN)
(3) 10,000 head dairy farms
Process 700,000 gallons of manure daily in anaerobic digester into 2000 SCFM of RNG
RNG prevents release of methane into atmosphere
Methane has 30X greater Global Warming Potential (GWP) than CO_2 (approach is GWP negative)

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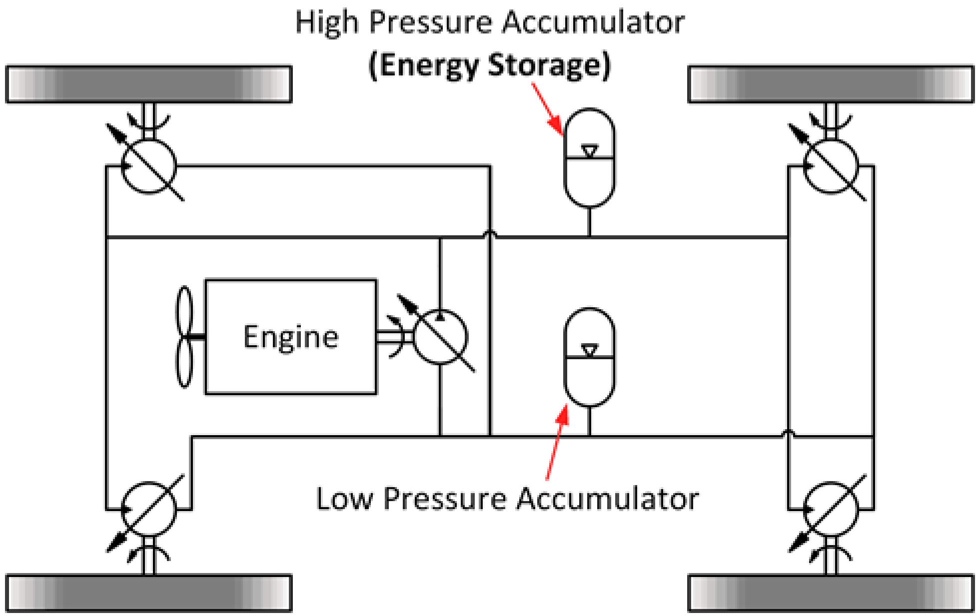
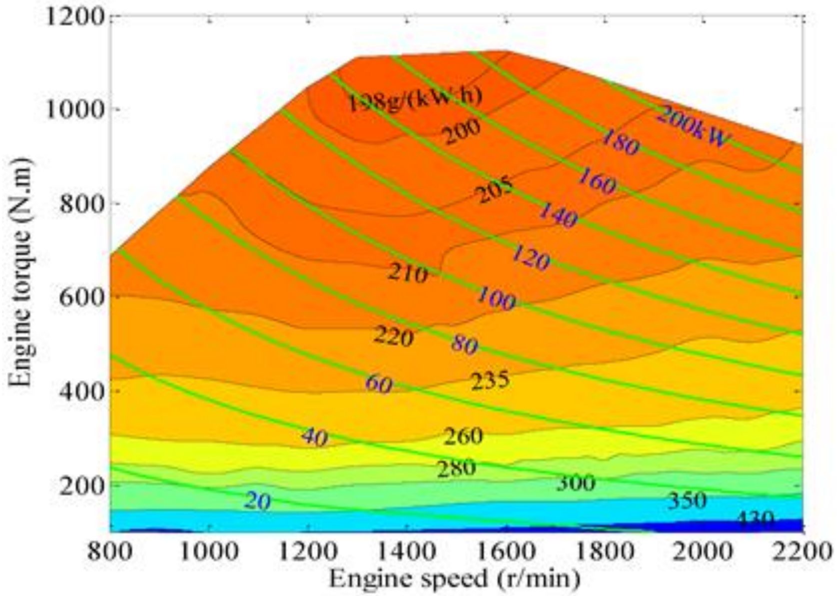
Approach: Series Hydraulic Hybrid Transmission

Decouple engine power and wheel power
Regenerate energy at end of field
Increase acceleration (productivity)
Engine-off tendering
Wheel torque control
Avoids kinematic mismatch
2WD on-road operation





Approach: Electrification of Auxiliary Hydraulics

E-Pumps driving auxiliary functions:

Liquid product pump

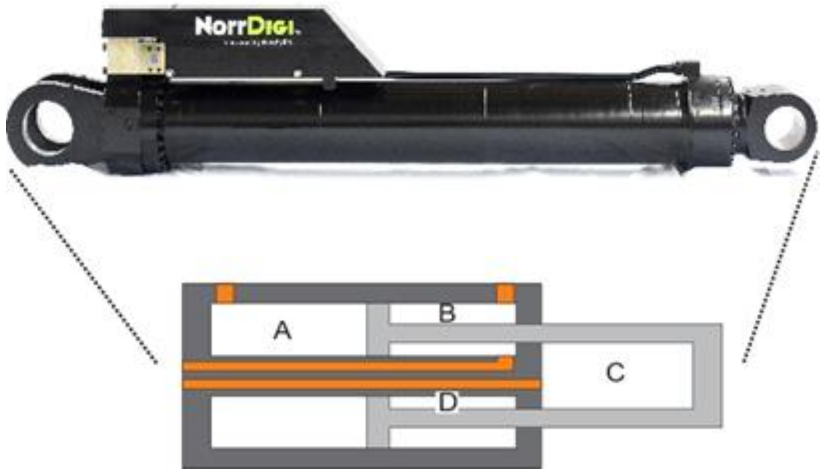
Steering

Brakes

Boom height control cylinders

Axle width adjustment cylinders

Boom fold cylinders



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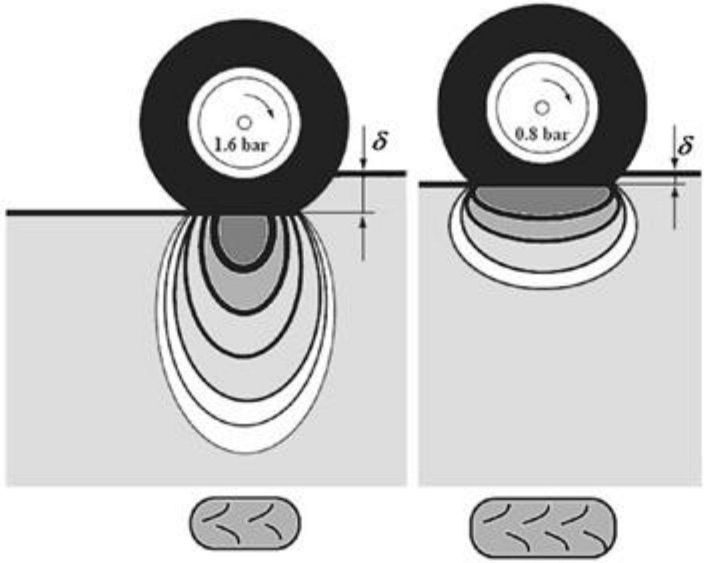
Approach: Tire Pressure Study

On-road: High tire pressure
Lower rolling resistance
Improve vehicle stability
Reduce tire wear and heat
Off-road: Low tire pressure
Reduce soil deflection
Improve traction
Reduce soil compaction
Tires dissipate 20-50% of propulsion power in soft soils
Optimal pressure depends on soil conditions (locally changing)



Project Team: Hybrid Renewable Fuel Sprayer

CNH INDUSTRIAL

- Donate sprayer rental
- Performing vehicle retrofit
- Expert operator for testing
- Powertrain engineering guidance

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- Manage overall project schedule and budgets
- Prepare & submit required reports to DOE
- Power train modeling, design, and analysis
- Control system design
- Overs ation and retrofi

FPT POWERTRAIN TECHNOLOGIES

- Donate biomethane engine
- Addressing barriers for renewable fuel engines

STATE

- Test baseline and retrofit vehicle in field and dyno cell
- Tire terramechanics studies

Parker

- Donate E-pump and inverter for auxiliary hydraulics
- Electrification expertise

Danfoss

- Powertrain propulsion system software and control expertise
- Powertrain component modeling input

Conclusions

- Off-road vehicles consume 2.4% of US energy. It is possible to reduce this energy use in half to 1.2%.
- The US Department of Energy has invested $37 million in R&D to realize this reduction.
- The long-term goal is to achieve net zero carbon for off-road vehicles. This will require “green” fuels such as biomethane or hydrogen from solar or wind generated electricity.
- Hydraulics is expected to play a key role in future off-road vehicle systems.

Final Thought

Our long-term goal is to achieve net zero carbon in all sectors. This will require “green” electricity and “green” fuels such as biomethane or hydrogen from solar or wind generated electricity.

Achieving zero net carbon requires both individual and collective action. We must stop using fossil fuels. This is technically feasible, but it requires unprecedented international concerted coordinated effort. We must stay focused on this goal.

Recommended Reading

M. Alvera, *The Hydrogen Revolution: A Blueprint for the Future of Clean Energy,* Basic Books, New York, 2021.

B. Gates, *How to Avoid a Climate Disaster: The Solution We have and the Breakthroughs We Need,* Alfred, Knopf, New York, 2021.

K. Hayhoe, *Saving Us: A Climate Scientist's Case for Hope and Healing in a Divided World,* One Signal Publishers, New York, 2022.

M. E. Mann, *The New Climate War: The Fight to Take Back Our Planet,* Public Affairs, New York, 2021.

M. E. Mann and T. Toles, *The Madhouse Effect: How Climate Change Denial Is Threatening Our Planet, Destroying Our Politics, and Driving Us Crazy,* Columbia University Press, New York, 2016.

N. Oreskes and E. M. Conway, *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming,* Bloomsbury, New York, 2010.

Not Recommended (Denialism or Doomism)

B. Lomborg, *False Alarm: How Climate Change Panic Costs Us Trillions, Hurt the Poor, and Fails to Fix the Planet,* Basic Books, New York, 2020.

D. Wallace-Wells, *The Uninhabitable Earth: Life After Warming,* Tim Duggan Books, New York, 2019.