ARTEMIS
INTELLIGENT POWER

Dr Niall Caldwell
Managing Director
Artemis Intelligent Power Ltd.

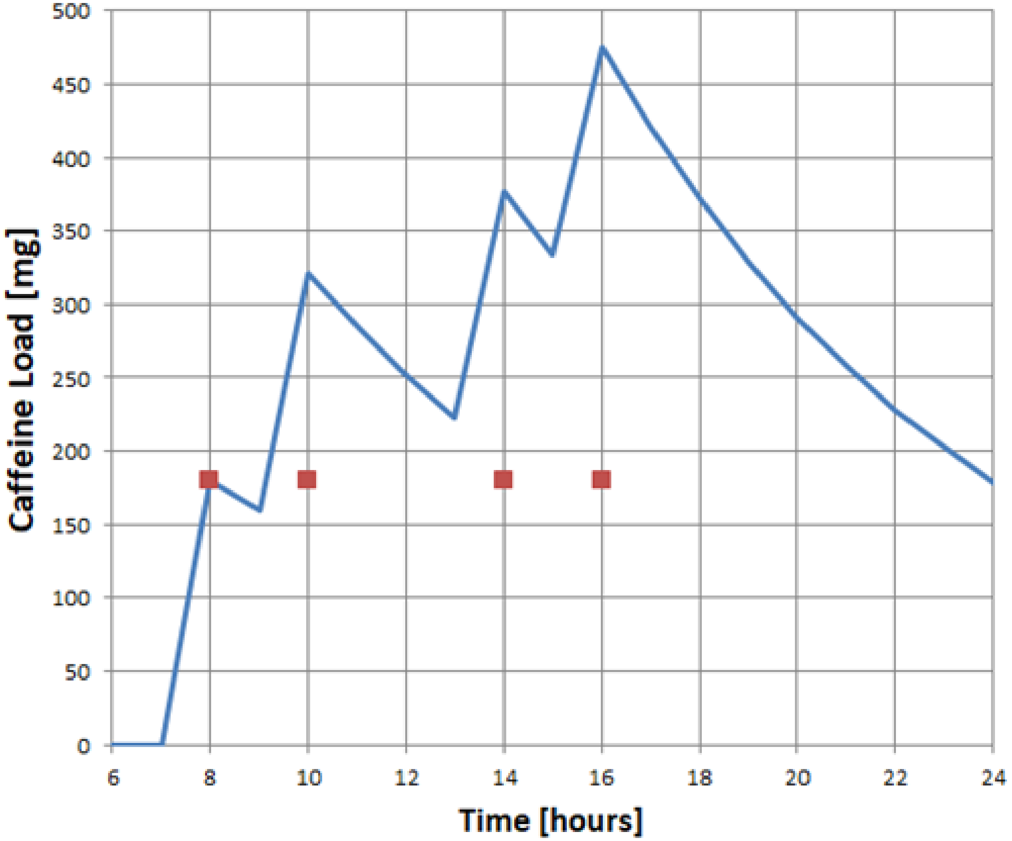
Digital Displacement® Technology

or

“It’s electric so it’s green by definition!”

Let’s start with a coffee…

Metabolism of caffeine….

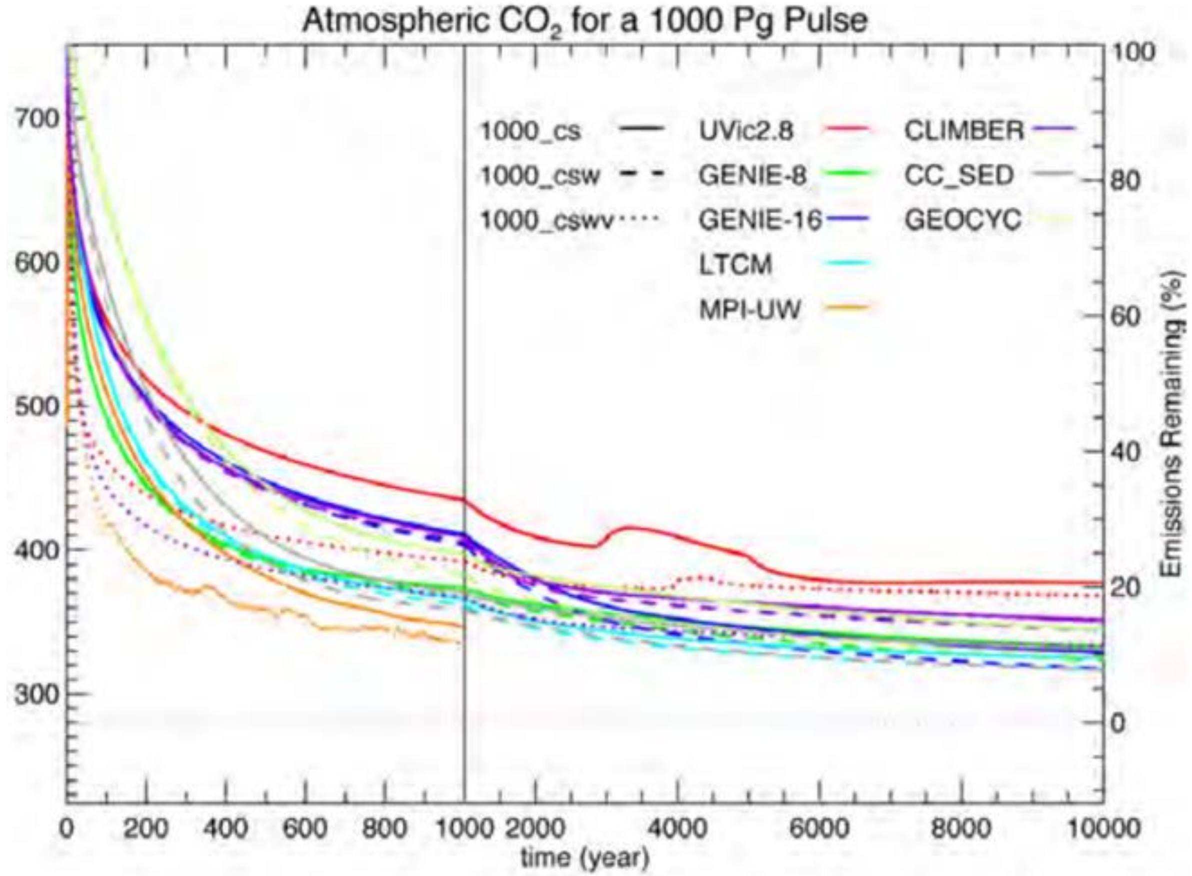


I really need to
cut down on
coffee…

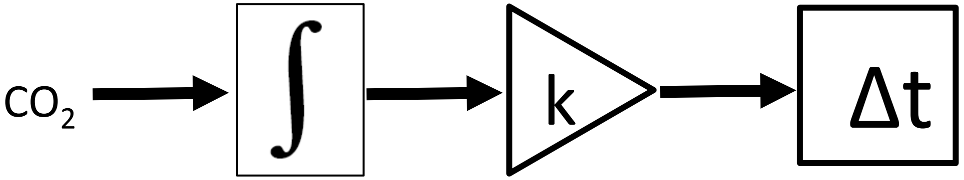
Half Life = 5.7 hours

Is CO2 like caffeine?

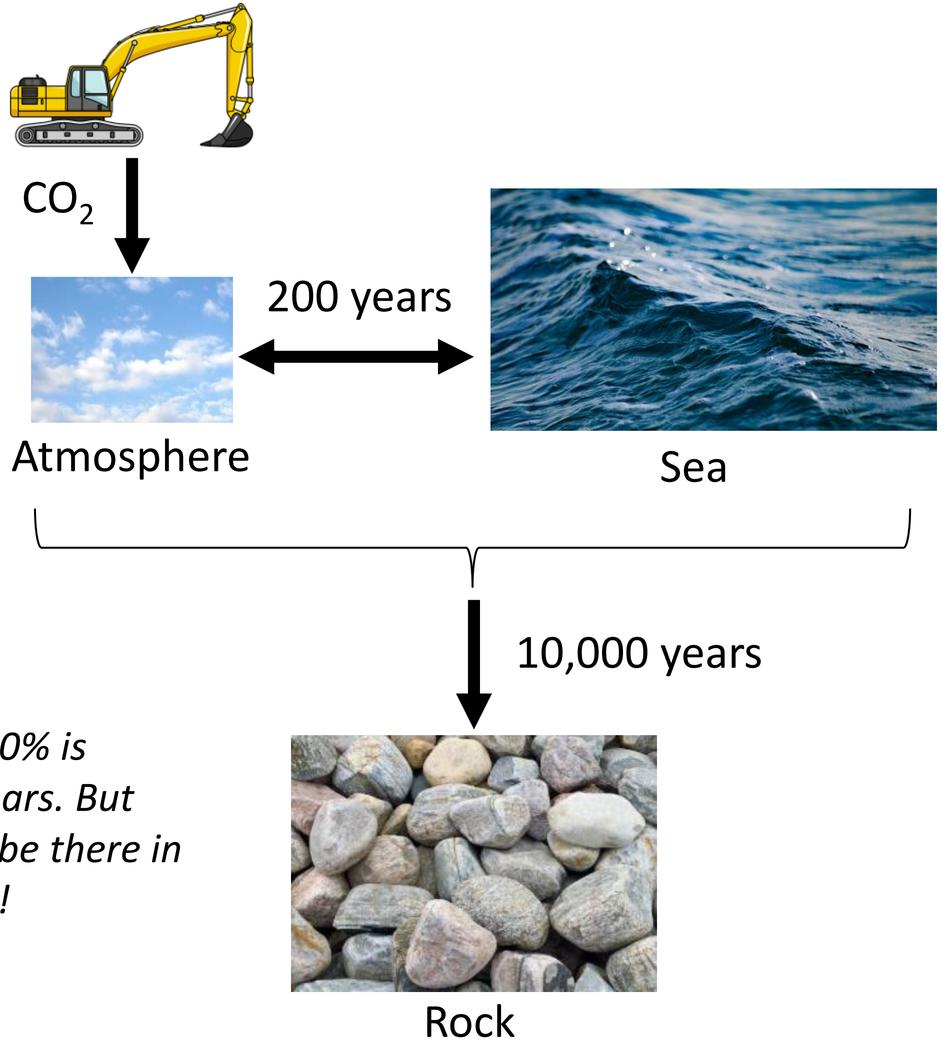
Is CO2 like caffeine?



Atmospheric Lifetime of Fossil Fuel Carbon Dioxide, Archer et al.
Article in Annual Review of Earth and Planetary Sciences · May 2009
DOI: 10.1146/annurev.earth.031208.100206 · Source: OAI



A simple model of the system on the human time scale



Half life for 80% is about 200 years. But 20% will still be there in 10,000 years!

- **CO2 is not like caffeine…**
- **On the human time scale, it does not decay – it just accumulates.**
- **We don't need solutions in 20 years, we need them now!**

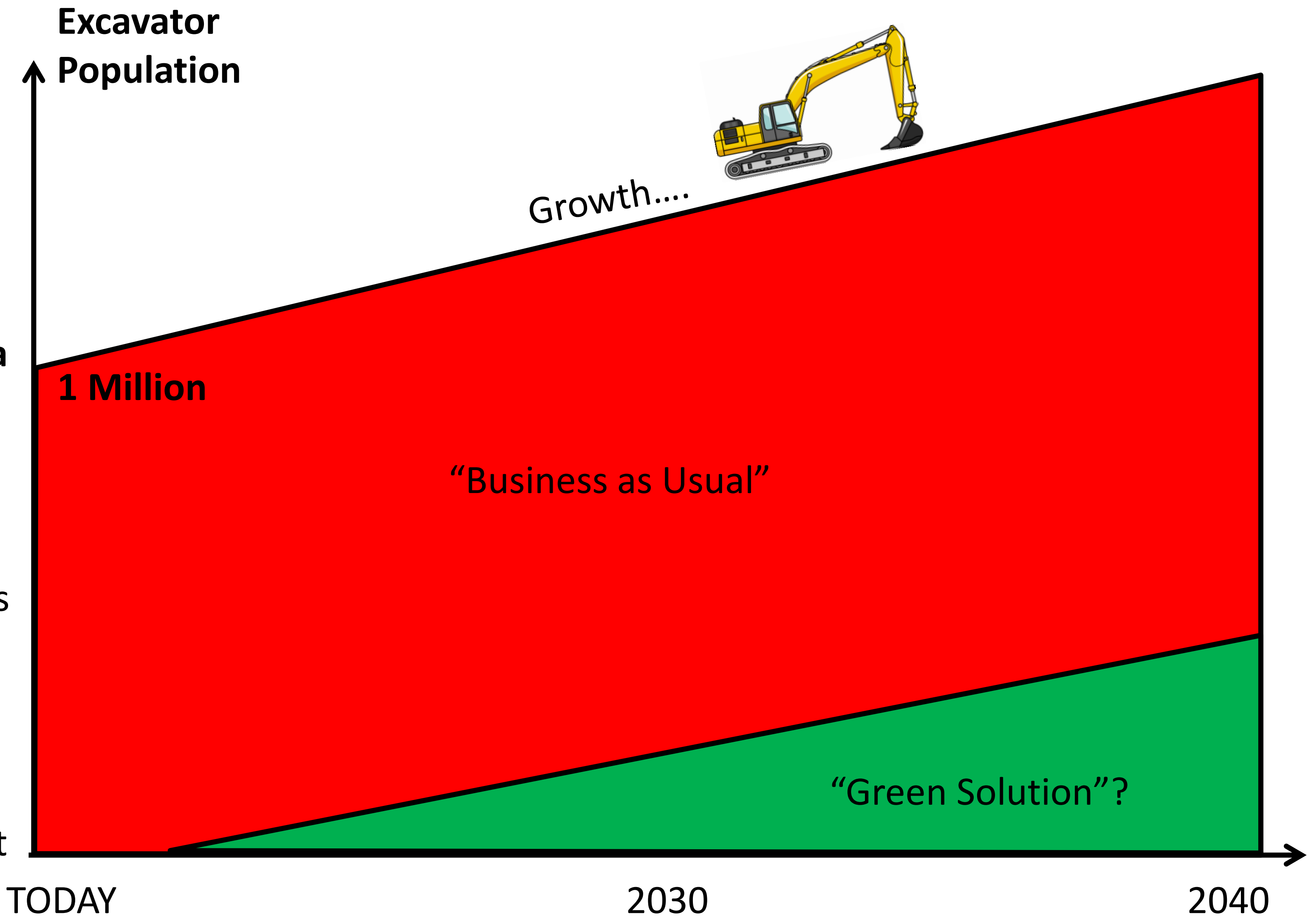
Do we need a “Green Solution”?

- Example: Excavator emissions.
  8-40T Excavators
  Average 70T CO2/year each
  220,000 per year made
  est. 1,000,000 population in heavy operation
  Market is growing (5% CAGR)

- CO2 is accumulating, so what matters is the **area under the curve**. A “Green Solution” needs to take over the market quickly and overtake natural market growth.

- Much of that growth is in “developing” countries => no subsidies, no sentiment, weak carbon-intensive grids.

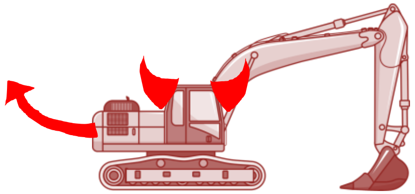
- An expensive “Green Solution” which requires sustained subsidies will not take over the market quickly enough.



We need a “Green Solution” which is also a “Business Solution”

Battery-electric?

- **Diesel is much more energy dense**
- **But efficiency of the engine is poor compared to the battery-electric system.**

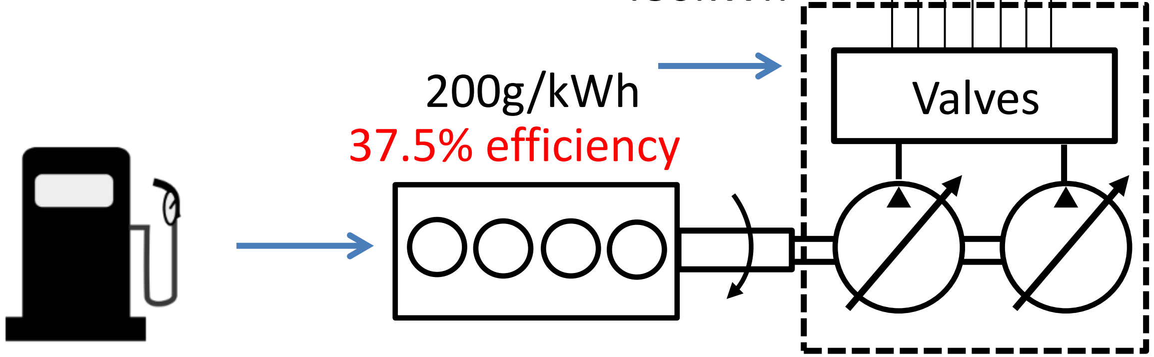


Diesel

14.4L / h

=1275kWh per day

=96kg of diesel



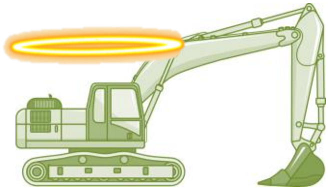
200g/kWh

37.5% efficiency

60kw x 8 hours

=480kWh

Work



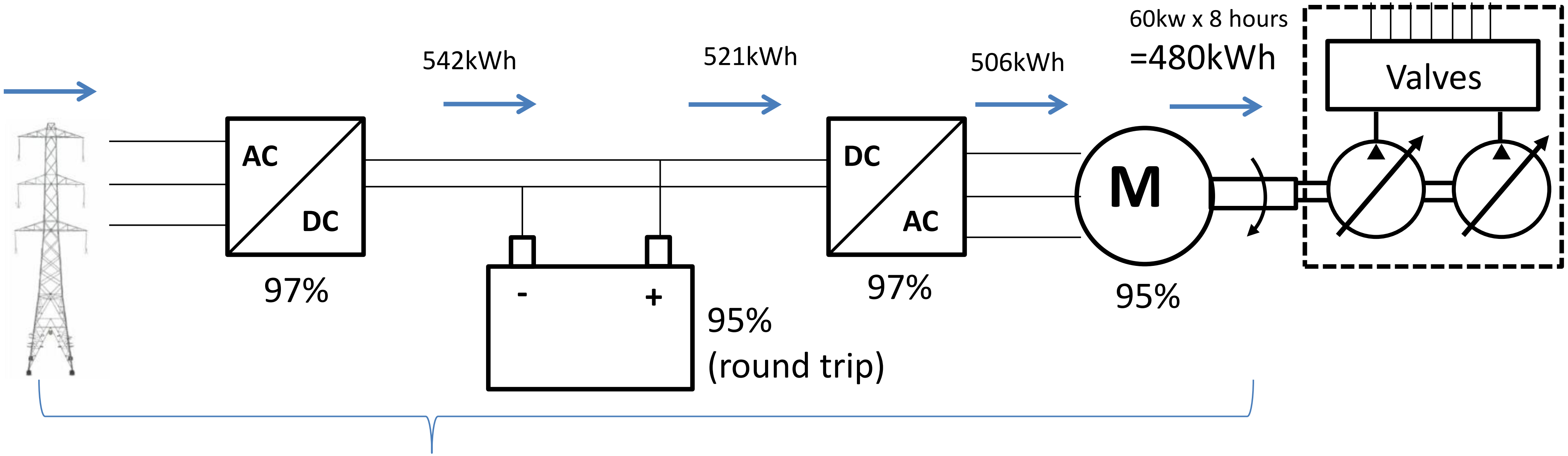
Electricity

559kWh

per day

2500kg of battery

(@200 Wh/kg)



542kWh

521kWh

506kWh

60kw x 8 hours

=480kWh

Work

97%

95%

(round trip)

97%

95%

85% overall efficiency

(grid to shaft)

Let’s go battery-electric!

2.1% of the world’s new cars were plug-in electric in 2018

Challenges of Battery-Electric at scale
- Lack of charging infrastructure
- Extreme energy requirements
- Tough physical environment
- No subsidies (unlike cars)
- Too expensive today for mass market

Compact utility machines
- <10kW
- On-grid sites
- Low power & light duty
- Regulated emissions zones

- *Zero local emissions*
- *Lower noise*
- *Green image*
- *Perfect for city centres with ZEV regulations*

SCALE x5 … x50

Mainstream productivity machines
- > 50kW
- Off-grid sites
- High power & heavy duty
- Hard-nosed customers just want to make money by shifting dirt – not save the world

So it’s difficult… but surely it will be worth it for the CO2 saving?

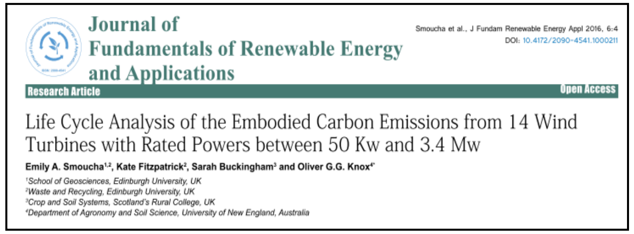
Lifecycle CO2

1280 hours/year
Total life = 6 years = 7680 hours

Vehicle Manufacture

Steel = 2.49 kg CO2/kg

Life cycle analysis of Wind Turbine



Journal of
Fundamentals of Renewable Energy
and Applications

Smoucha et al., J Fundam Renewable Energy Appl 2016, 6:4
DOI: 10.4172/2090-4541.1000211

Research Article Open Access

Life Cycle Analysis of the Embodied Carbon Emissions from 14 Wind Turbines with Rated Powers between 50 Kw and 3.4 Mw

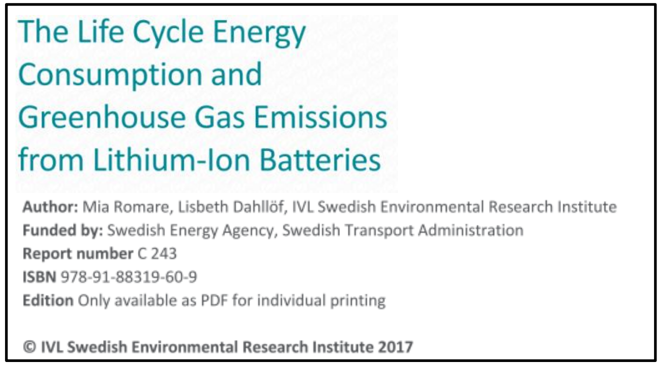
Emily A. Smoucha[1,2], Kate Fitzpatrick[2], Sarah Buckingham[3] and Oliver G.G. Knox[4*]

[1]School of Geosciences, Edinburgh University, UK
[2]Waste and Recycling, Edinburgh University, UK
[3]Crop and Soil Systems, Scotland's Rural College, UK
[4]Department of Agronomy and Soil Science, University of New England, Australia

Battery Manufacture

175 kg CO2/kWh

Swedish Environmental Research Institute 2017
(also figure used by ICCT)



The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries

Author: Mia Romare, Lisbeth Dahllöf, IVL Swedish Environmental Research Institute
Funded by: Swedish Energy Agency, Swedish Transport Administration
Report number C 243
ISBN 978-91-88319-60-9
Edition Only available as PDF for individual printing

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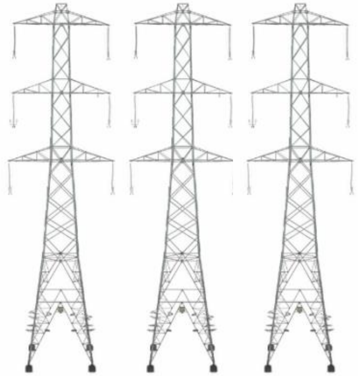
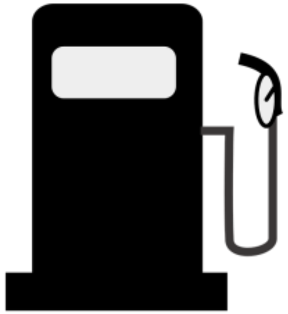
Electrical Energy



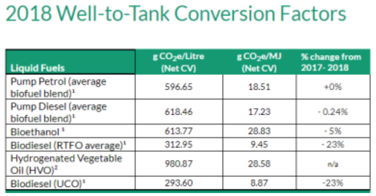
	g CO2e/kWh
World Average	**460**
China	576
Japan	516
USA	420
Germany	396
UK	272
Wind Power	*25*

June 2018 | BP Statistical Review of World Energy

Diesel Energy



Diesel:
2.68kg CO2e/l (fuel)
+0.618kg CO2e/l (WTT factor)
=3.30 kg CO2e/l

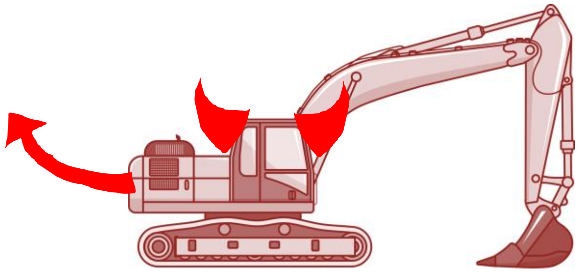
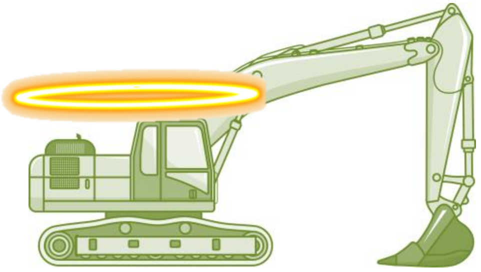


2018 Well-to-Tank Conversion Factors

Liquid Fuels	g CO_2e/Litre (Net CV)	g CO_2e/MJ (Net CV)	% change from 2017- 2018
Pump Petrol (average biofuel blend)[1]	596.65	18.51	+0%
Pump Diesel (average biofuel blend)[1]	618.46	17.23	- 0.24%
Bioethanol [1]	613.77	28.83	- 5%
Biodiesel (RTFO average)[1]	312.95	9.45	- 23%
Hydrogenated Vegetable Oil (HVO)[2]	980.87	28.58	n/a
Biodiesel (UCO)[1]	293.60	8.87	-23%

UK Government Conversion Factors

20T Excavator: Life Cycle CO2 [kg per hour of operation]

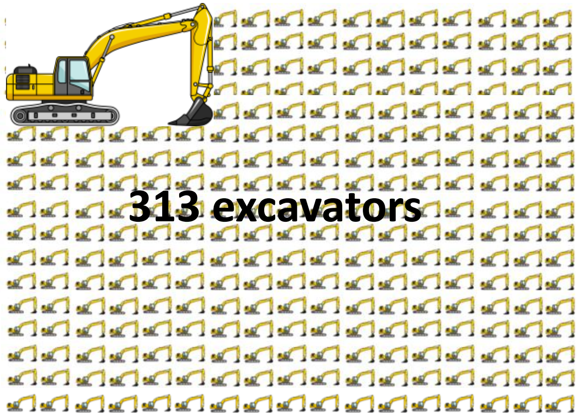
	Vehicle Manufacturing	Battery Manufacturing	Operating Energy	Total
 **Diesel**	*22500kg steel* *@ 2.49 kg CO2/kg* *= 56.0T CO2* */ 7680 hours life* **=7.3**	**(zero)**	14.4 l/h @ (2.68 + 0.618) kg CO2e/l WTT emissions **= 47.6**	**54.9** **kg CO2/h**
 **Electric**	**=7.3**	*521kWh out @ 80% DOD* *= 651kWh capacity* ** 175kg CO2/kWh capacity* *= 113.9T CO2* *Let's hope the battery lasts for lifetime of Excavator (>1000 charges)* */ 7680 hours life* **=14.8**	69.9kWh grid per hour of operation	

Source	*g/kWh*	*kg/h*	*Total kg/h*	*CO2 vs Diesel*
World Average	**460**	**32.2**	**54.3**	**-1.2%**
China	576	40.3	62.4	13.6%
Japan	516	36.1	58.2	6.0%
USA	420	29.4	51.5	-6.3%
Germany	396	27.7	49.8	-9.3%
UK	272	19	41.1	-25.1%
Wind Power	*25*	*1.7*	23.8	-56.6%

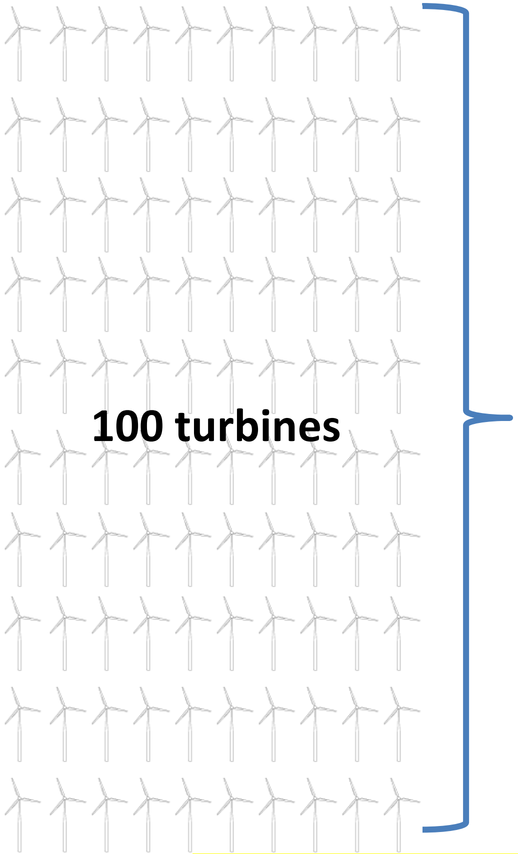
Today, replacing all the world's excavators with battery-electric would hardly save any CO2!
In many countries, it's worse than diesel…. it NEEDS a low-carbon energy source like wind!

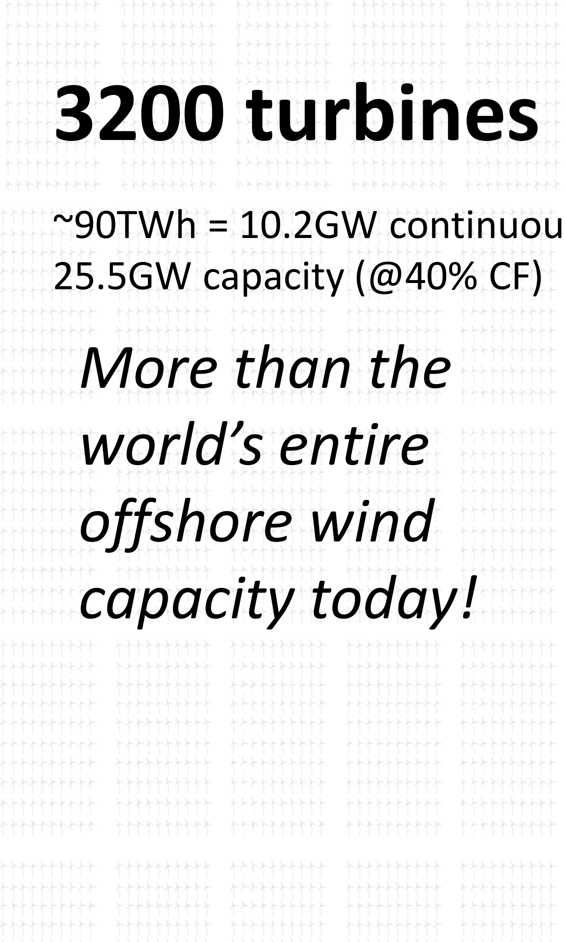
How to power all the world's excavators from offshore wind?

Total population, 8-40T = 1,000,000
Each uses 90 MWh/year => 90TWh per year



7MW offshore turbine
(3.2MW average output)





3200 turbines

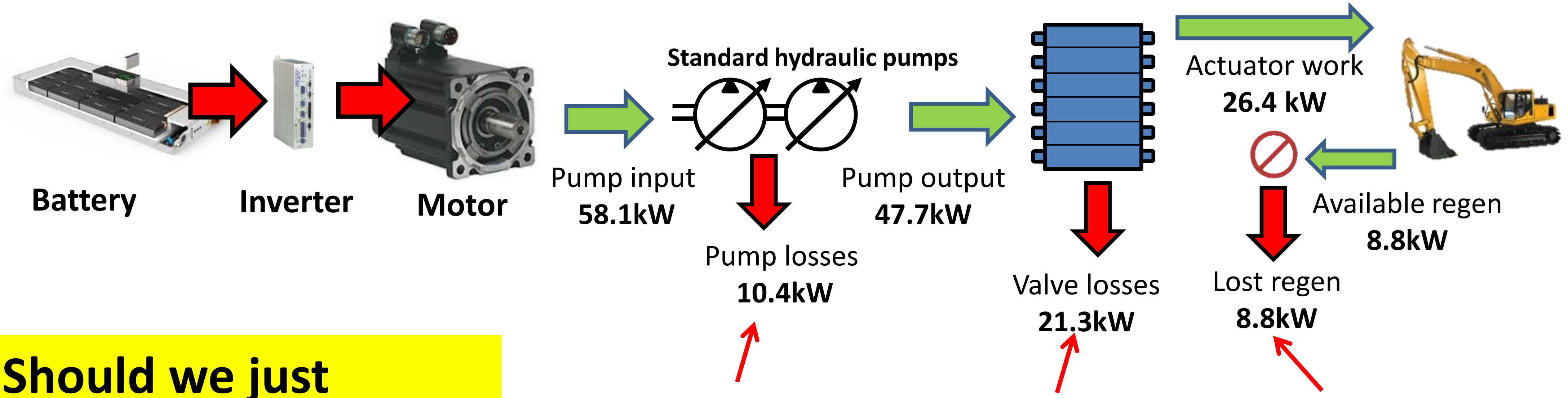
~90TWh = 10.2GW continuous = 25.5GW capacity (@40% CF)

More than the world's entire offshore wind capacity today!

- **There is not enough green energy to go round today**
- **It will take a long time (and huge investment) to fully de-carbonise the grid, and have enough to spare**
- **So can we reduce the energy consumed by excavators in the first place?**

What’s the problem?

16T excavator – trenching duty cycle



Battery

Inverter

Motor

Pump input
58.1kW

Standard hydraulic pumps

Pump losses
10.4kW

Pump output
47.7kW

Valve losses
21.3kW

Actuator work
26.4 kW

Available regen
8.8kW

Lost regen
8.8kW

Pump is not efficient

Valves dissipate too much energy

Recoverable energy is wasted

Should we just replace the diesel engine with a battery-powered electric motor?

Net work delivered = **17.6kW**
Pump input power = **58.1kW**

⇒ Overall efficiency of hydraulic system is 30%

“It’s electric, so it’s green by definition”

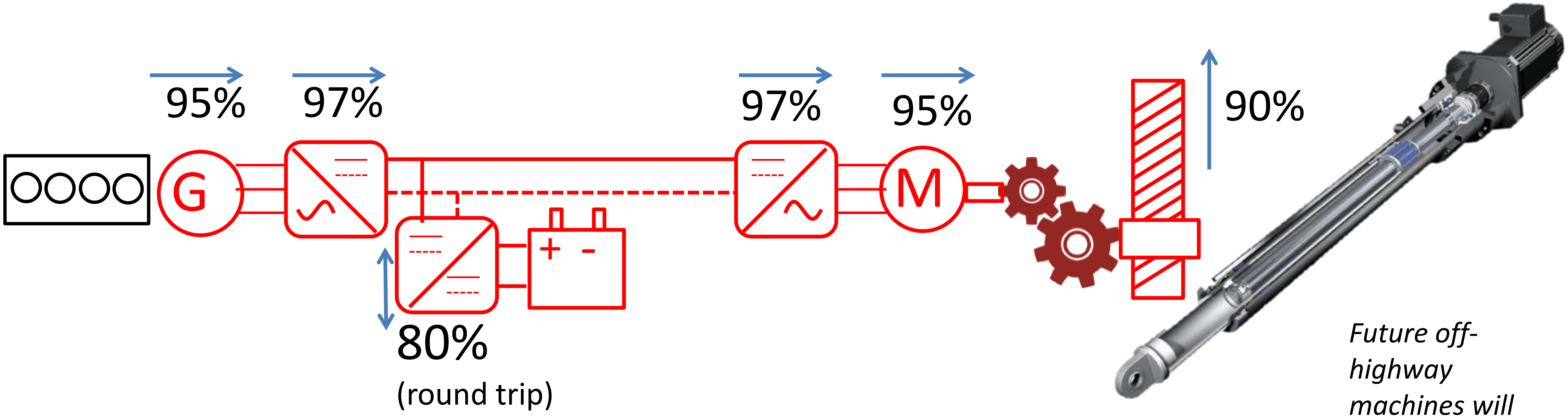
(Quote: Electric & Hybrid Aerospace 2017, panel discussion)

Is an electric patio heater a “Green Solution”?

A real “Green Solution”!

- **Electrifying an inefficient system is not the best idea**
- **Why waste expensive renewable energy making waste heat?**
- **We should reserve low carbon energy for efficient systems**
- **So let’s improve vehicle system efficiency first…**
  ….then electrification starts to make sense

Can we just eliminate hydraulics completely?



Future off-highway machines will be all-electric!

- Remove all hydraulics
- Change hydraulic actuators to electromechanical

⇒ Power transmission efficiency increased
⇒ Mechanical energy recovered

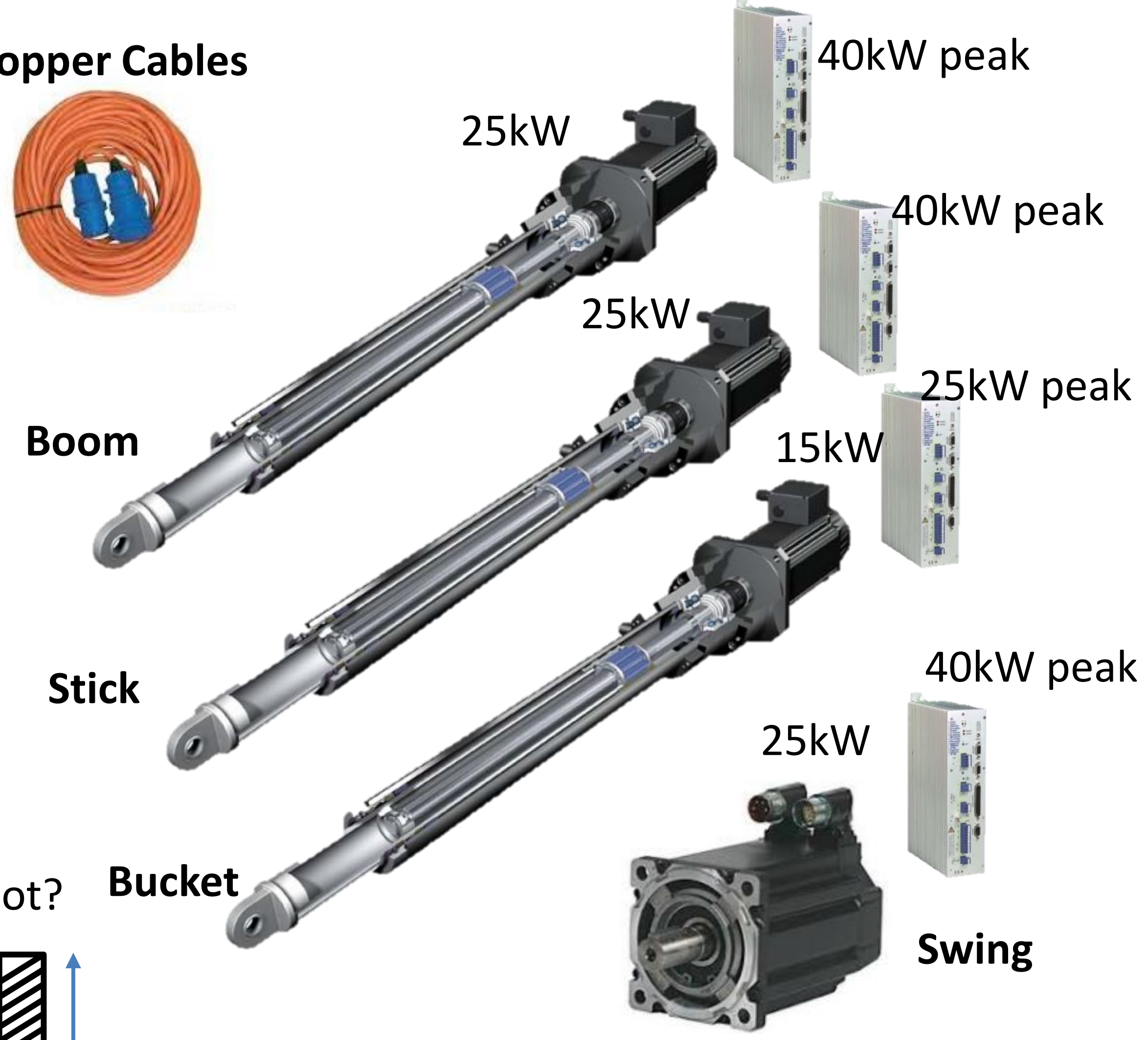
All-Electric prototypes on show… is this the future?

Volvo, 2017

Yanmar, 2019

Pure Electric 16T excavator

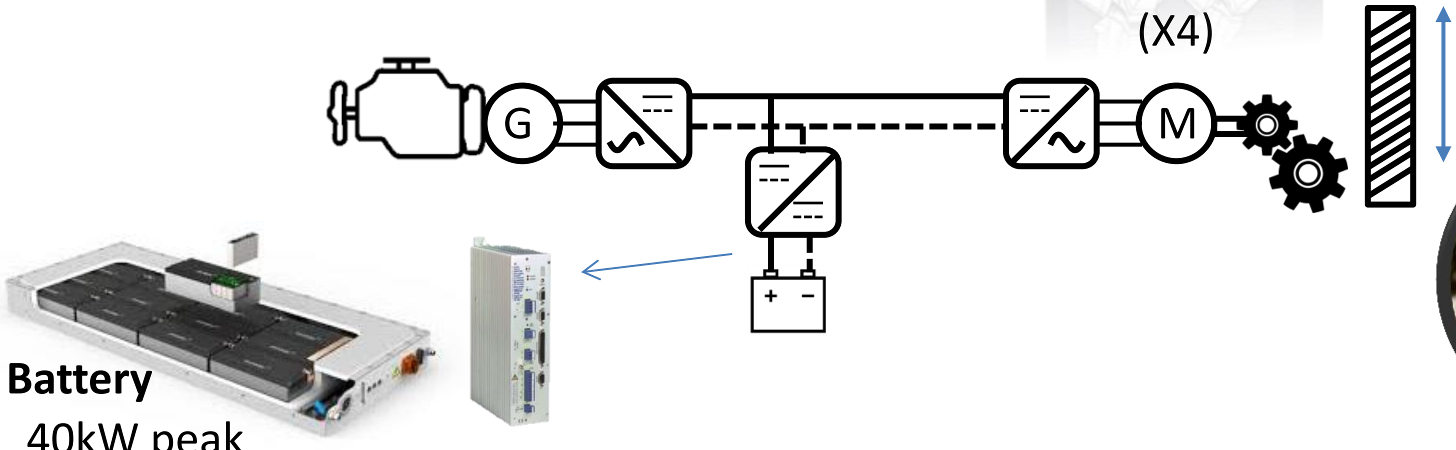
Copper Cables



Is this an excavator…

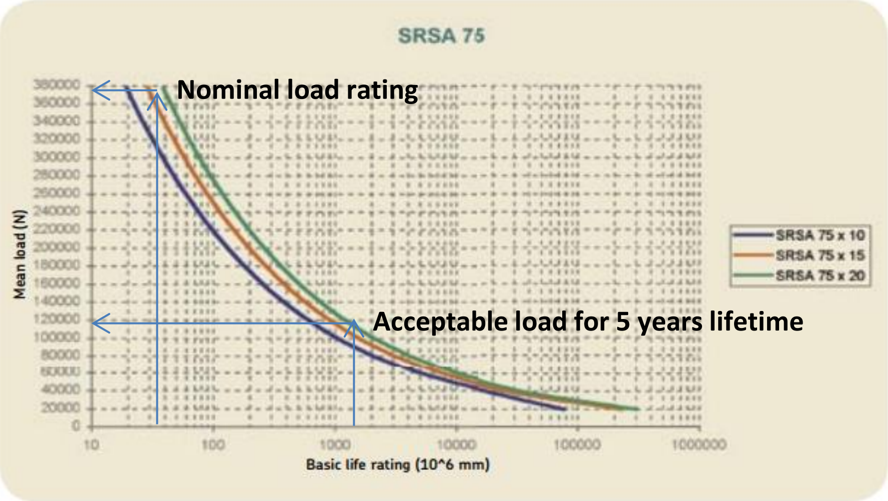
Omni Consumer Products
ED-209
Enforcement Droid Series 209
Service and Repair Manual
Includes Emergency Shutdown Procedure and Live Ammunition Protocols

… or a 16T killer robot?



Total electronic power = 325kW peak
Total motor power = 270kW cont
Looks expensive and complicated!
How thick is the service manual?
Will it last in the environment?

Are electric linear actuators viable?



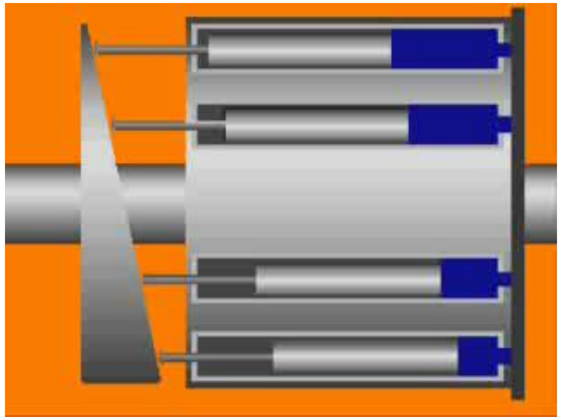
SKF E-truck (2002)

Hydraulics are needed for the foreseeable future!

	Electromechanical Cylinder	Hydraulic Cylinder
Proven at full scale?	No	Yes
Mechanical complexity	High	Low
Efficiency	90%	97%
Life-limiting factor	Hertzian contact fatigue (L10 life principle)	Seal wear
Tolerance of shocks & dirt	Low – hates mud and water	High – loves mud and water
Price	High	Low
De-rating required for 8,000hrs life in excavator duty cycle	30% of nominal load	None

Digital Displacement® Technology

Analog pump

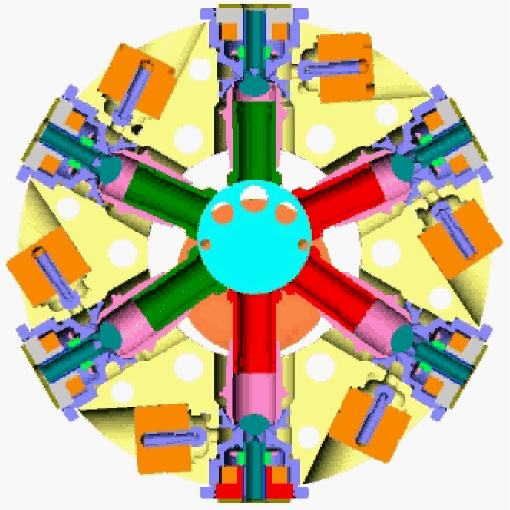


Controlled by varying the stroke of the pistons

- Limited part-load efficiency
- Mechanical control
- Limited response speed
- Does one function

"It's electric, so it's green by definition!"

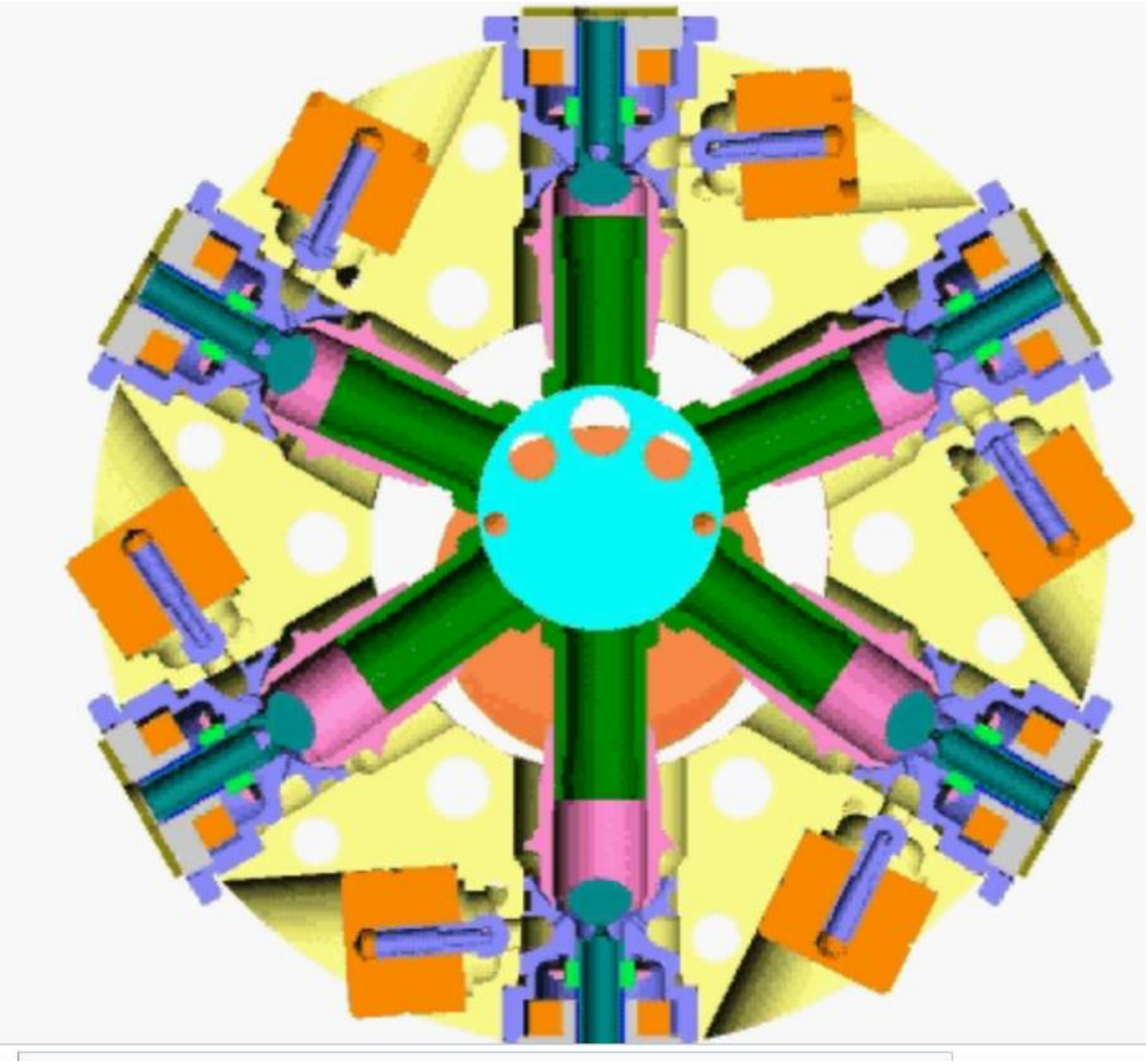
Digital Displacement® Pump



A radial piston machine, controlled by enabling/disabling cylinders in real time, using computer-controlled *electrical* valves

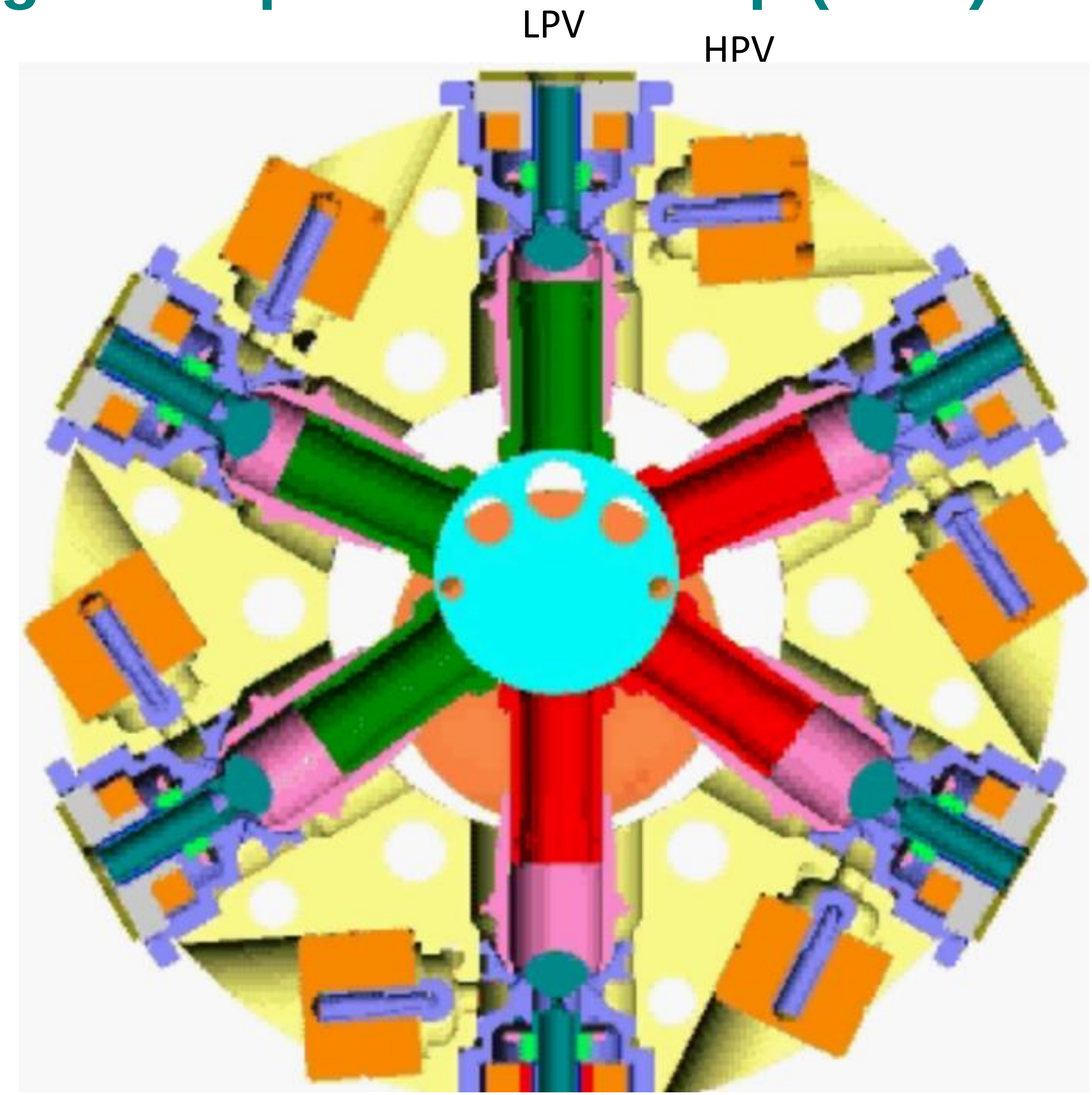
+ Much improved efficiency
+ Digital control built-in
+ Much faster response speed
+ Multiple functions = new architectures

Digital Displacement Pump (DDP): Idling Cycle

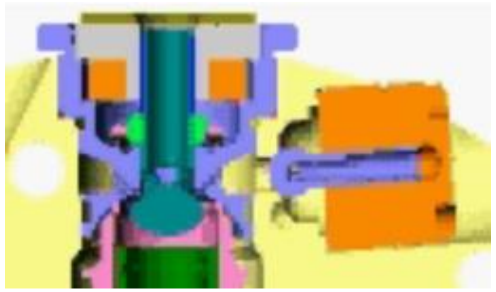


- Fluid flow from each cylinder of a radial piston machine is controlled by a **fast solenoid poppet valve**
- The valve is kept open by a **spring**
- When the valve remains **open**, fluid flows alternately into and out of the tank surrounding the pump
- That cylinder is **disabled**, does no work, is at tank pressure, and consumes very little idle power

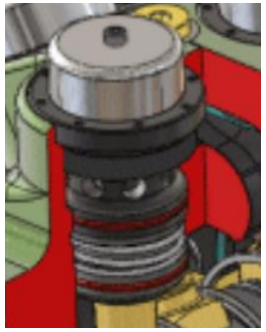
Digital Displacement Pump (DDP): Pumping Cycle



- The low pressure valve (LPV) can be shut within a few milliseconds by sending a **pulse** of current to a coil
- When the valve is shut at bottom dead centre, that cylinder is **enabled**, and does one pumping stroke
- After the pumping stroke, the valve reopens, the cylinder intakes from the tank and remains **idle** until the coil is pulsed again

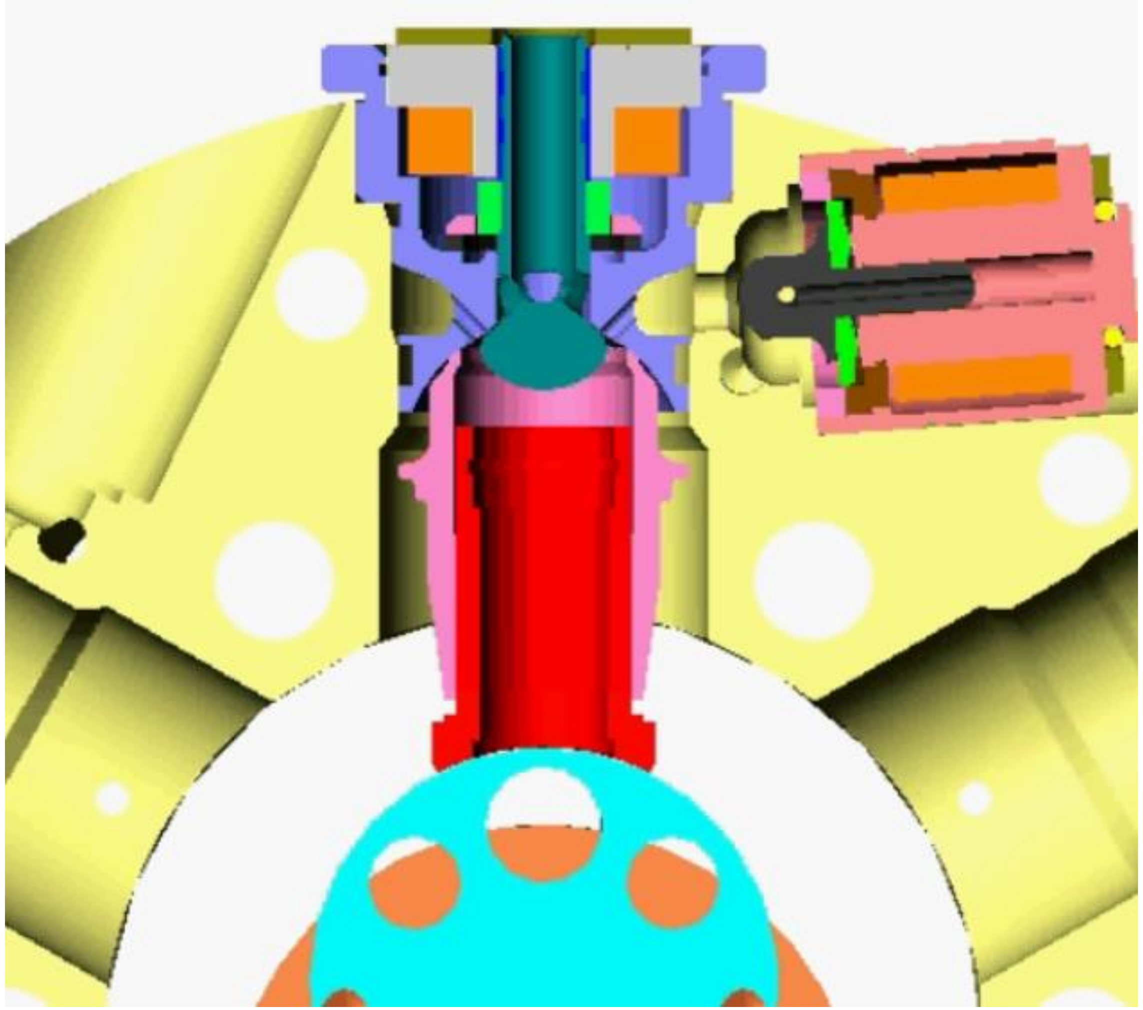


SeperateLPV + Passive HPV

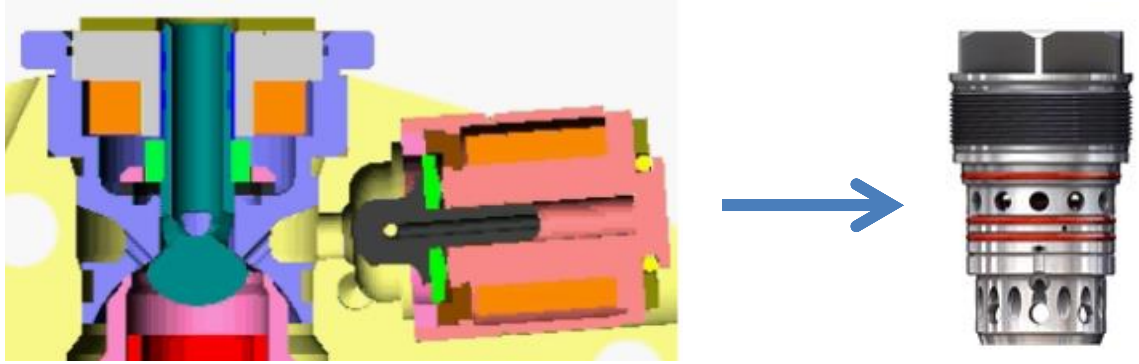


“PAV” Integrated Valve

Digital Displacement Pump/Motor (DDPM) : Motoring Cycle



- Cylinder exhausts to the tank through the open LPV
- Just before TDC the LPV is closed and the cylinder pressure equalises with the supply pressure
- The active HPV is opened by pulsing a solenoid coil. Once open it is held latched by switching the coil to low-duty PWM. The piston exerts torque on the shaft during the motoring stroke
- The HPV closes just before BDC, depressurising the cylinder



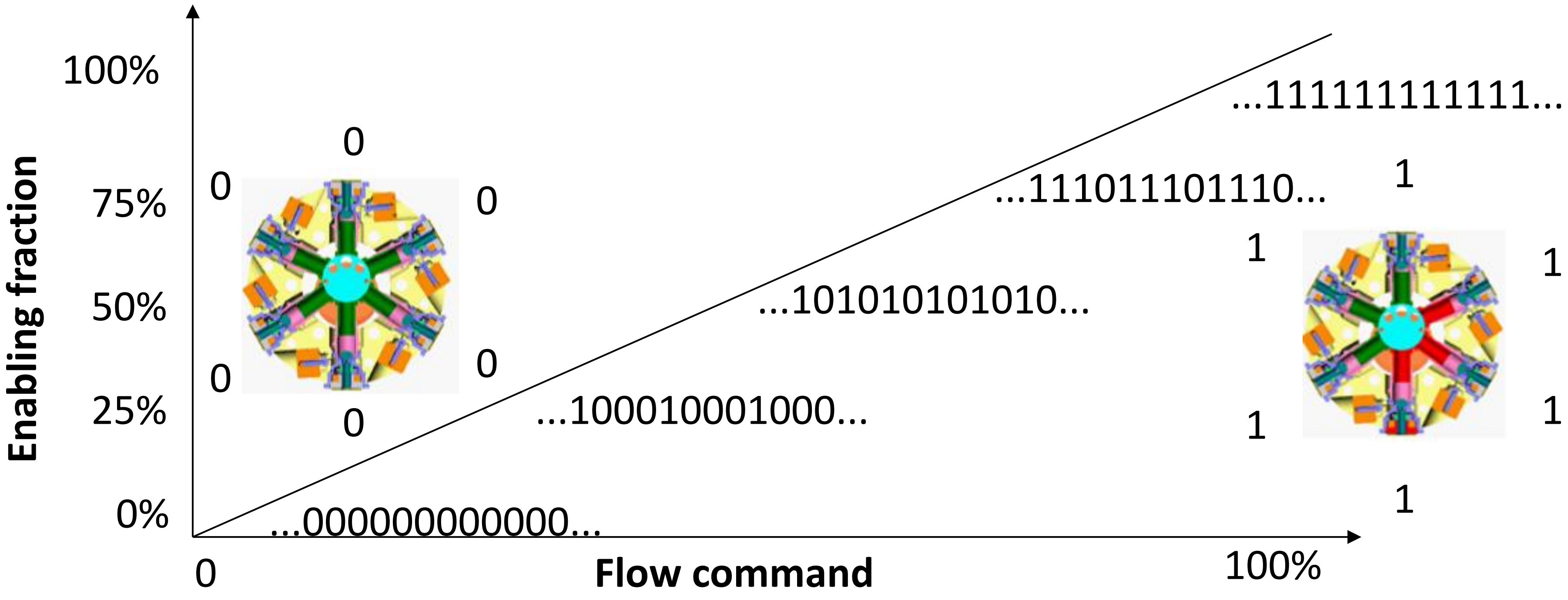
Separate LPV + HPV

MAV (single coil)

Variable displacement methods

1. Enabling sequence

A sequence of digital enabling decisions gives a continuously–variable displacement



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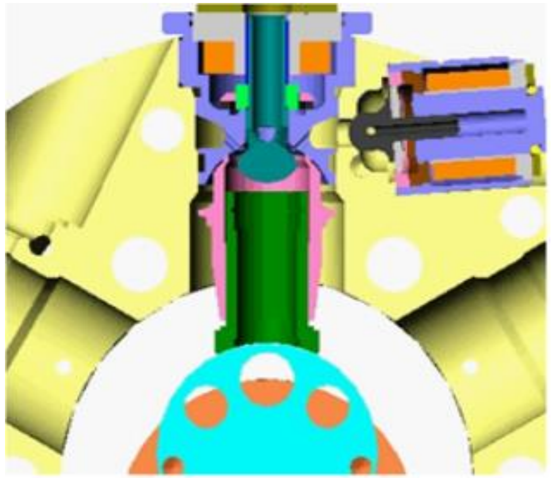
2. Partial stroke

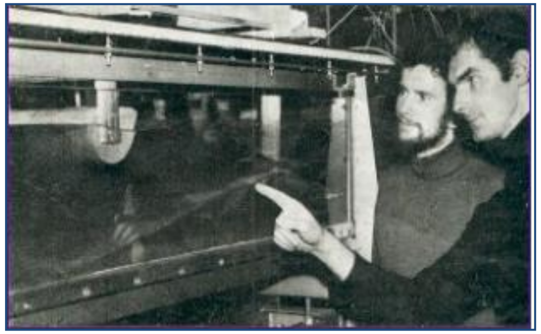
Closing the LPV part way between BDC and TDC delivers a partial stroke to the outlet.



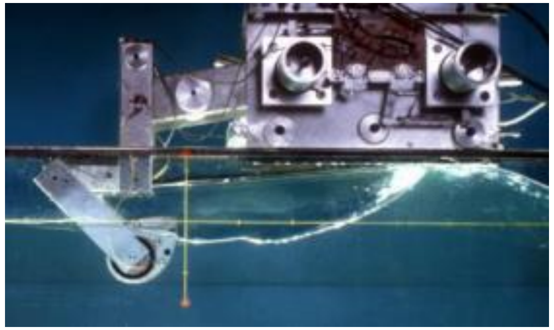
3. Combination of 1 & 2

We can combine partial, full and idle strokes in a sequence.

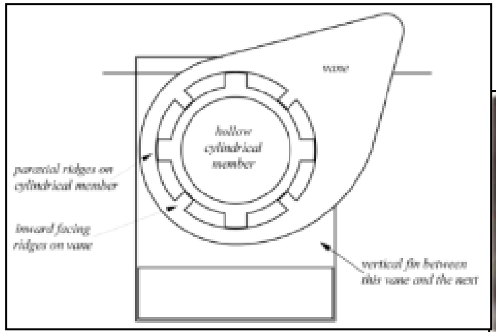
Origins of Artemis - *wave energy research at University of Edinburgh*



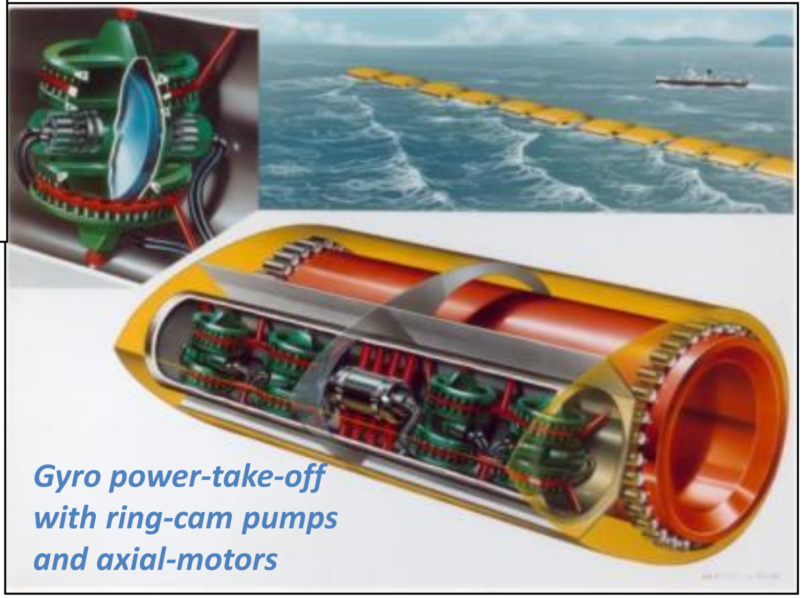
Stephen Salter, David Jeffrey & first Duck



Extreme wave at 1/100th scale

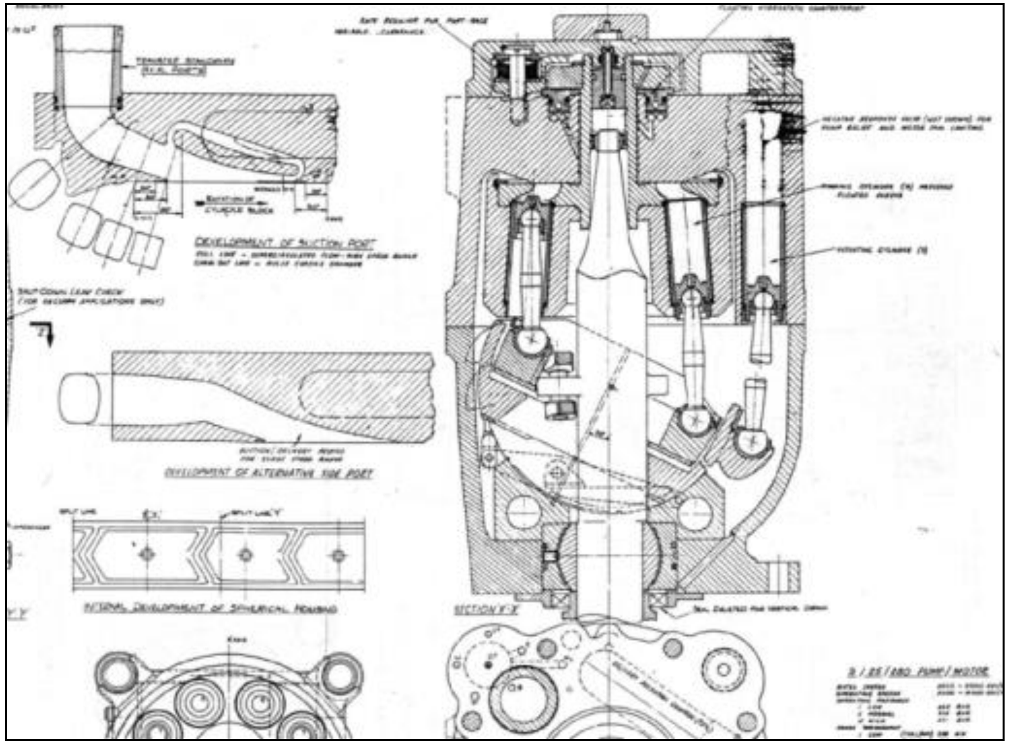


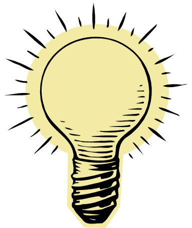
Spline-pump power-take-off



Gyro power-take-off with ring-cam pumps and axial-motors

Robert Clerk





Prof Win Rampen

Digital Displacement® Technology

History of Digital Displacement® and Artemis

1984 – First concepts published for Wave Energy generator

1990 – First prototype, 18 cc/rev axial piston design

1994 – First radial piston design, formation of Artemis Intelligent Power

1998 – 1.5kW pump powerpack demonstrated

2003 – 6.0kW DDP propel system demonstrated

2004 – Aerial work platform demonstrated

2008 – BMW hybrid car: uses half the fuel of a manual transmission on EU city cycle

2010 – Acquisition by Mitsubishi Heavy Industries for Offshore Wind

2011 – AIP demonstrates 1.6MW wind transmission

2014 – Hybrid city bus

– 7 MW wind turbine begins operation in Scotland

– First commercial sale of E-dyn 96cc/rev DD industrial pump

2015 – 7 MW wind turbine begins operation off the coast of Japan

The world's largest floating wind turbine

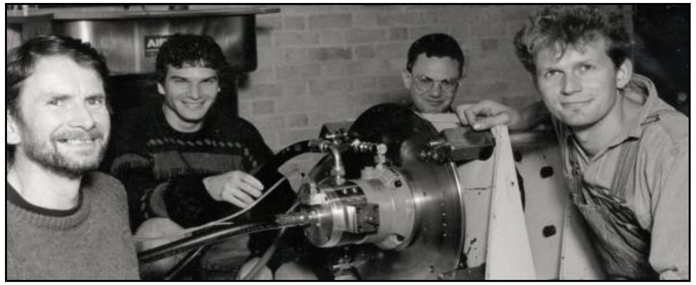
The world's most powerful hydostatic transmission

2016 – DD excavator demonstration "DEXTER"

2017 – New Danfoss / Artemis cooperation in Edinburgh

2018 – Danfoss acquires majority stake of Artemis

2019 – Danfoss announce targetted launch of E-dyn96 pump



The first DD pump/motor

The first DD power-pack

First DD propel transmission

The first DD vehicle

The first full-size DD off-highway demonstrator

BMW with DD Hybrid System

1.6MW DD Wind Transmission

7MW Wind Turbine with DD Transmission

E-dyn96 and controller

Tandem E-dyn96 in Excavator

Majority ownership announced: October 2018

“Danfoss will establish a manufacturing presence in Edinburgh to deliver products to the market based on the Digital Displacement technology, while establishing Edinburgh as the Centre of Excellence for this technology”

“So, with this digital displacement technology we’re very well positioned to enter the excavator market in what we think will be the breakthrough technology. But it’s not limited to excavators by the way. It is very, very versatile technology, so we are looking at a number of other off-highway applications,” Alström said.

Eric Bretey
Director - Digital Displacement,
Danfoss Scotland

New manufacturing facility

“Digitalization is a key driver in our industry and AIP constitutes a strategic fit with our ambition for technology leadership, innovation speed and the core product differentiators of efficiency and controllability”

Eric Alström
CEO,
Danfoss Power Solutions

Jeff Herrin, Phd
VP R&D,
Danfoss Power Solutions

ARTEMIS
INTELLIGENT POWER

- We develop Digital Displacement® core technology
  - Simulation and concept development
  - Design: Mechanical, Electronic, Software
  - Experimental development and verification

- We develop applications and products with partners
  - Application demonstration
  - Technology licensing
  - Product development
  - Manufacturing for pilot production

ROYAL ACADEMY OF ENGINEERING
MacRobert Award 2015






10kW → **100 kW** → **1MW** →



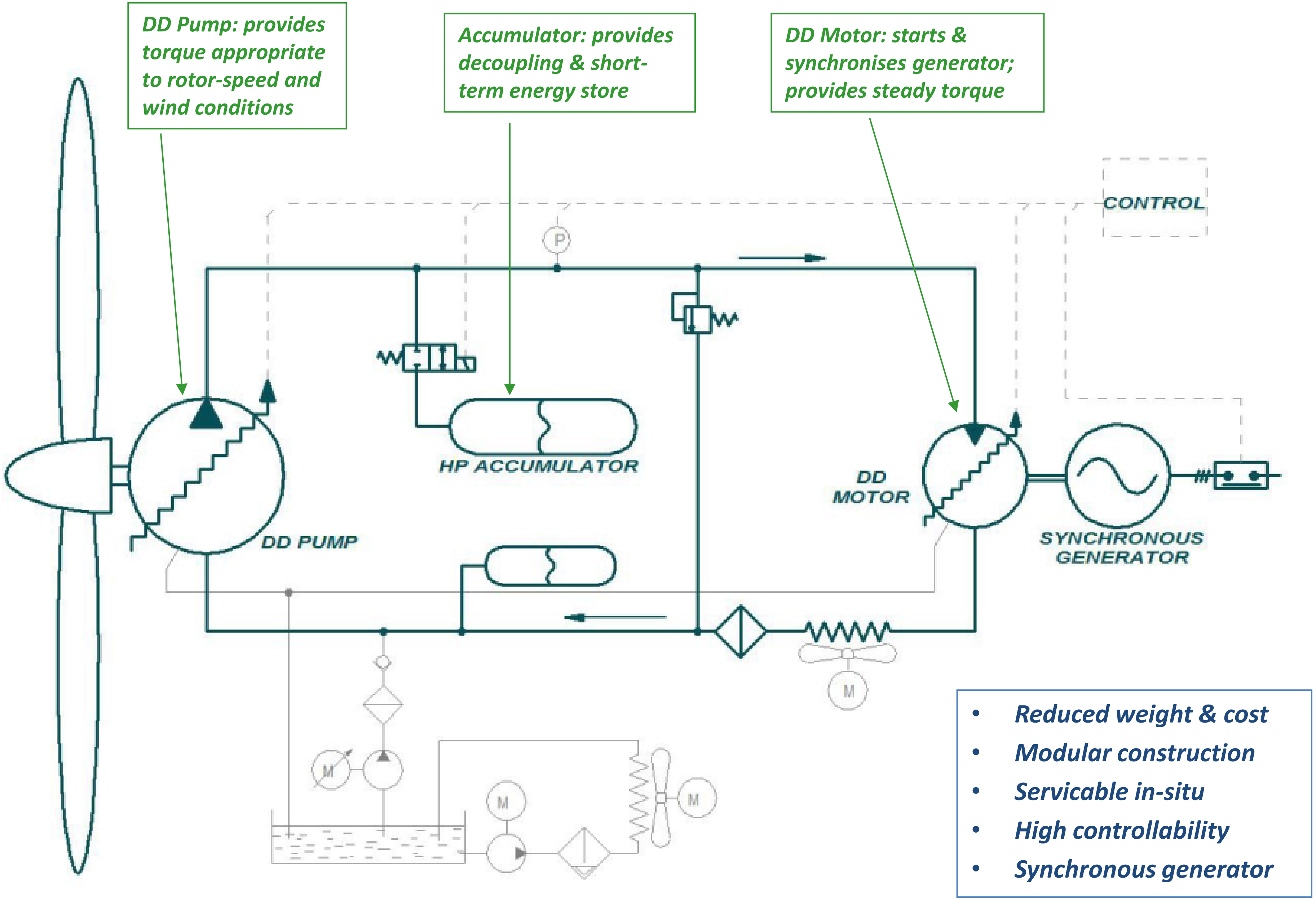


The World's
Largest Floating
Offshore Wind
Turbine… has a
DD transmission

7MW

Digital Displacement® Wind Turbine

Digital Displacement® Transmission (DDT)



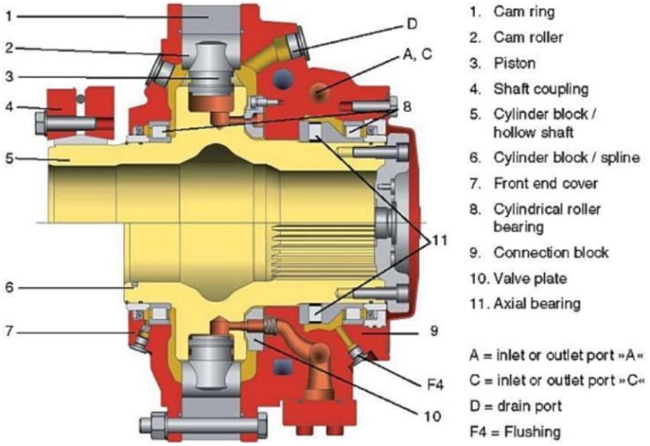
DD Pump: provides torque appropriate to rotor-speed and wind conditions

Accumulator: provides decoupling & short-term energy store

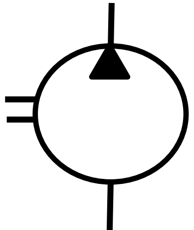
DD Motor: starts & synchronises generator; provides steady torque

- Reduced weight & cost
- Modular construction
- Servicable in-situ
- High controllability
- Synchronous generator

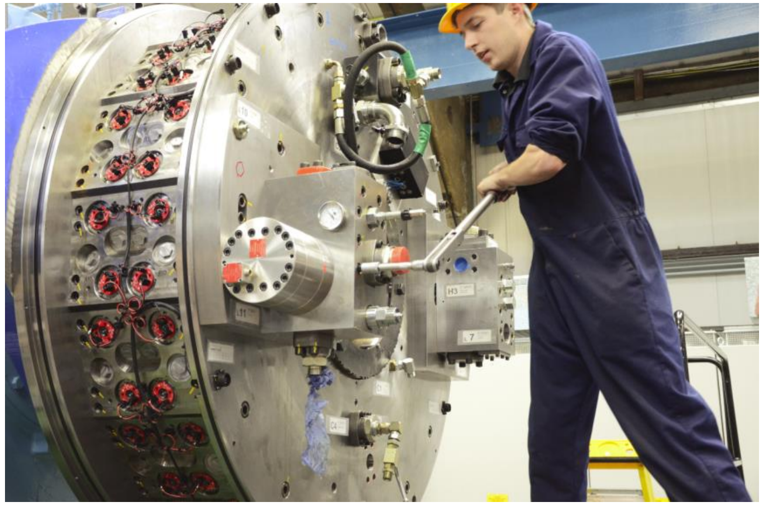
Conventional



- One piece design
- Fixed displacement
- No control
- Slow response



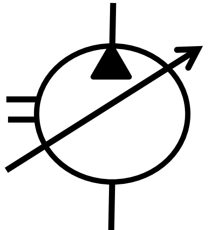
1.6MW DDP



7480cc/rev
Overall efficiency
97% peak @ 15rpm

LPV
< 0.5 bar
@ rated flow

- Modular design
- Variable displacement
- Smart digital control
- Fast response

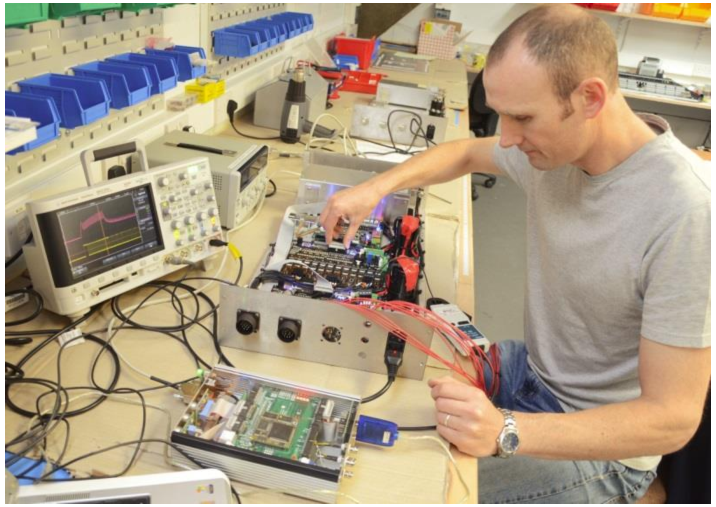


Q40 DDM

960cc/rev

Overall efficiency 96.5% peak @ 1500rpm

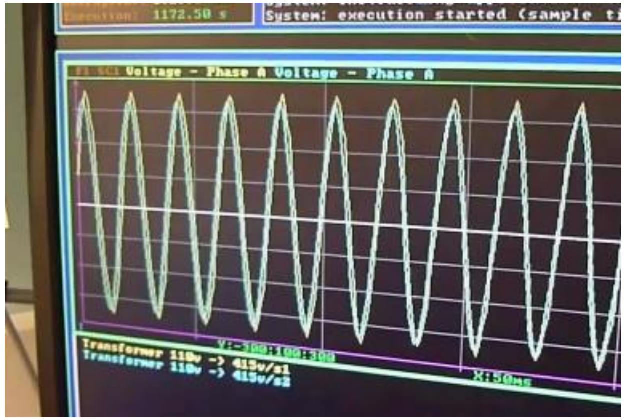
Piston/cylinder and solenoid valves for the 800kW DDM



Matt Feldberg tests the controller and power electronic module for the 800kW DDM

David Cruikshank fitting the 800kW DDM (with cover removed) to the generator.

7480cc ; 15rpm 2 x 960cc ; 1500rpm



Startup and synchronisation with grid in less than 10 seconds

Efficiency

~ 93.5% overall indicated

Response

Sudden loss of grid (<30ms response)

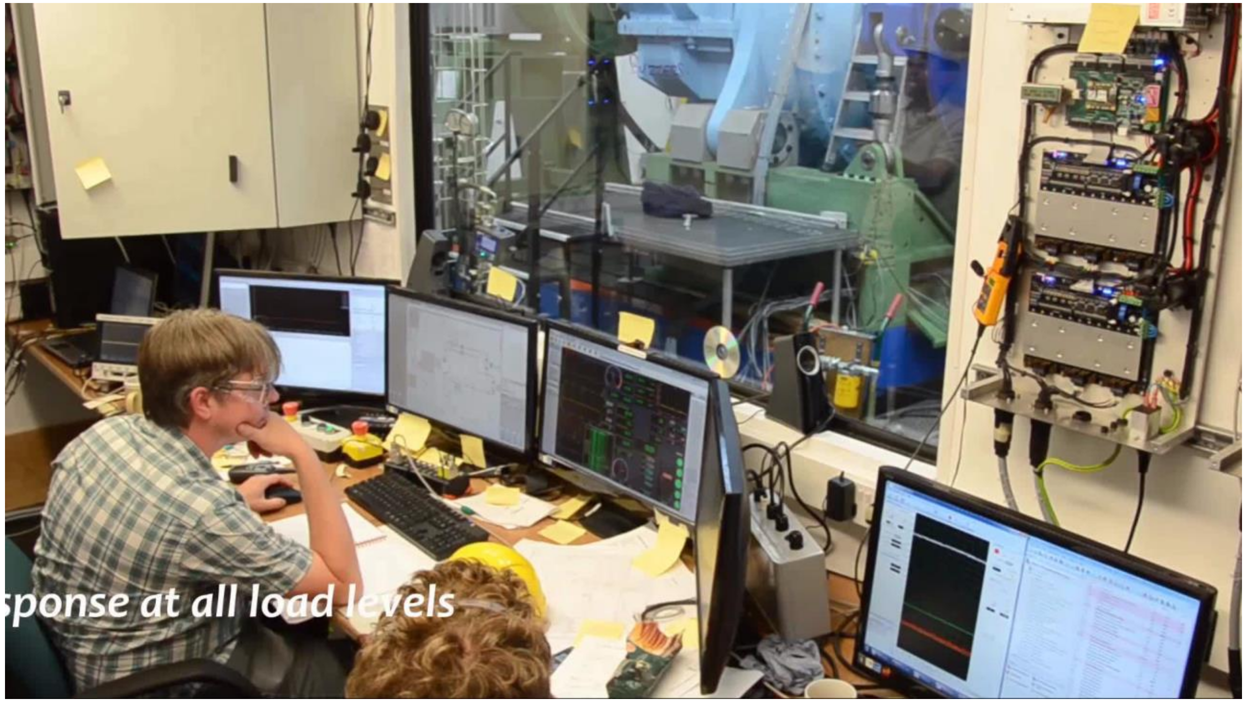
Synchronisation of generators (<5 degrees)

Control features

Detect & compensate for valve failure

Self tuning of valve timing

Realtime monitoring of bearing loads

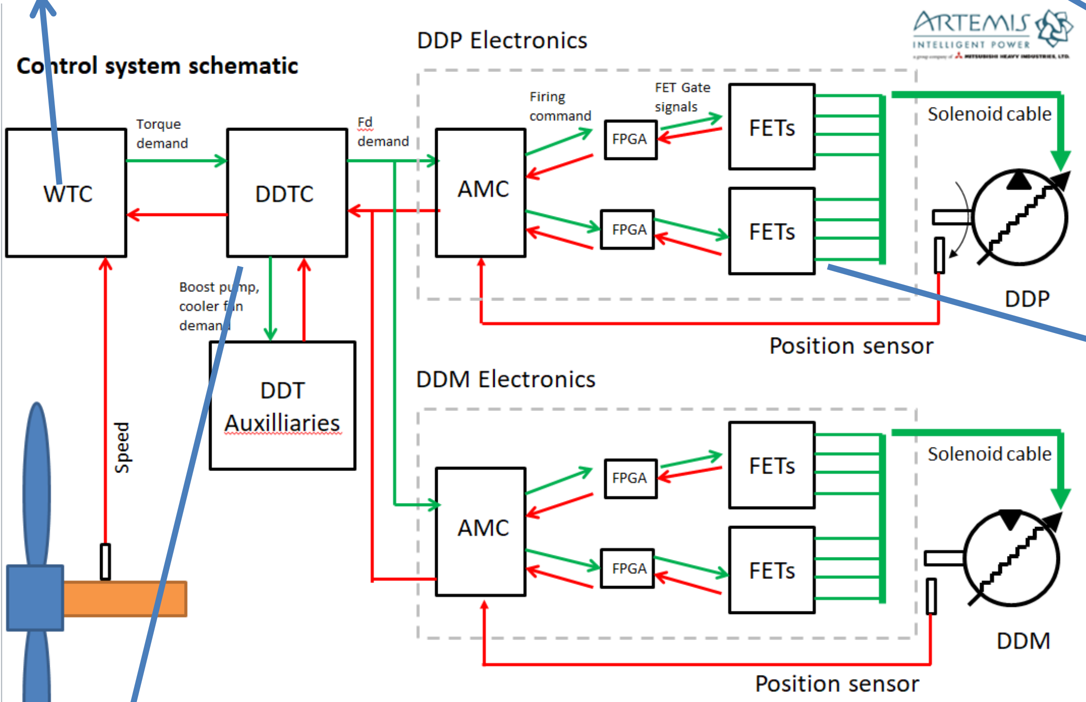


Electronics and Software in the 7MW DDT

AMC
(DD Machine Controller)
Software: AIP
Hardware: AIP

FET Modules inc FPGA
Software: AIP
Hardware: AIP

MHI



3 x DDP/DDM Cabinets
2 x AMC
9 x FET Module (DDP)
4 x FET Module (DDM)

Complete system : AIP

DDTC
(Digital Displacement Transmission Controller)
Simulink model running on Bachmann M1

Software: AIP
Hardware: Bachmann

Control Hierarchy

1. Wind Turbine Controller:
Master state machine
Torque/speed strategy
Blade pitch strategy

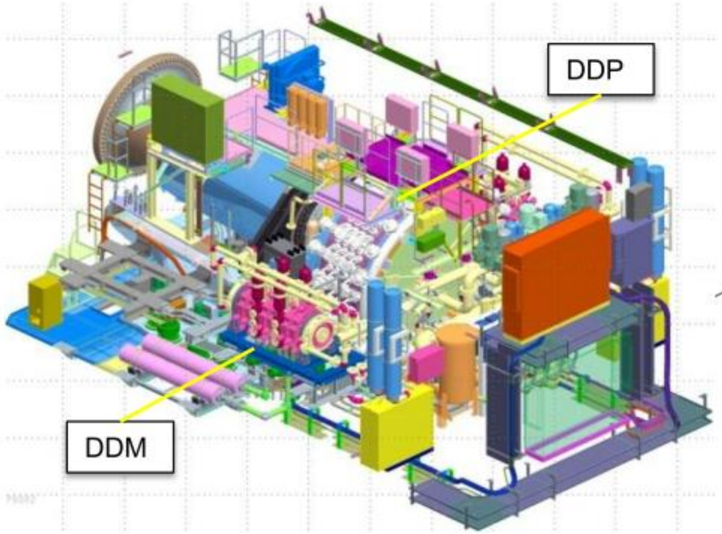
2. DDT Controller:
Hydraulic system state machine
(startup, warmup, run, shutdown….)
Torque strategy
(pressure, displacement)
System level fault management
Start-up synchronisation

3. DD Machine Controller:
Enabling algorithm
Pressure limiting
Valve fault management
Closed loop valve timing

4. FPGA:
Pulse timing
Solenoid Protection
Valve Motion Detection

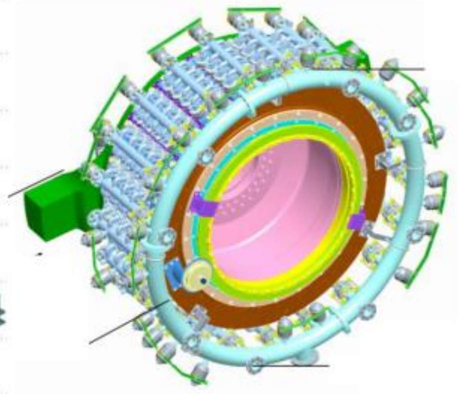
The world’s most powerful hydrostatic transmission….

DDT



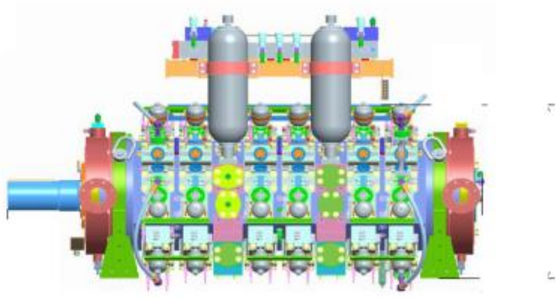
Wt Nacelle(Without Enclosure)

Pump



DDP (Pump)

2 x Motors



DDM (Motor)

7MW continuous
350 bar, 12500L/min
(0.21 m3/s)

305c x 168 x 32
1640 L/rev , 10.3rpm

2 x 210cc x 36
2 x 7.5 l/rev , 1000rpm

The SI unit of flow rate is almost useful!

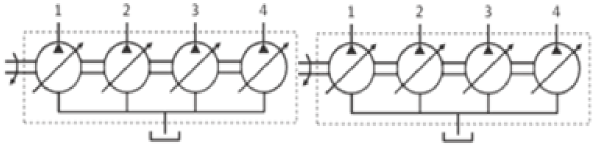
Artemis cooperation with MHI engineers

7MW MHI turbine at full load, Hunterston, Scotland

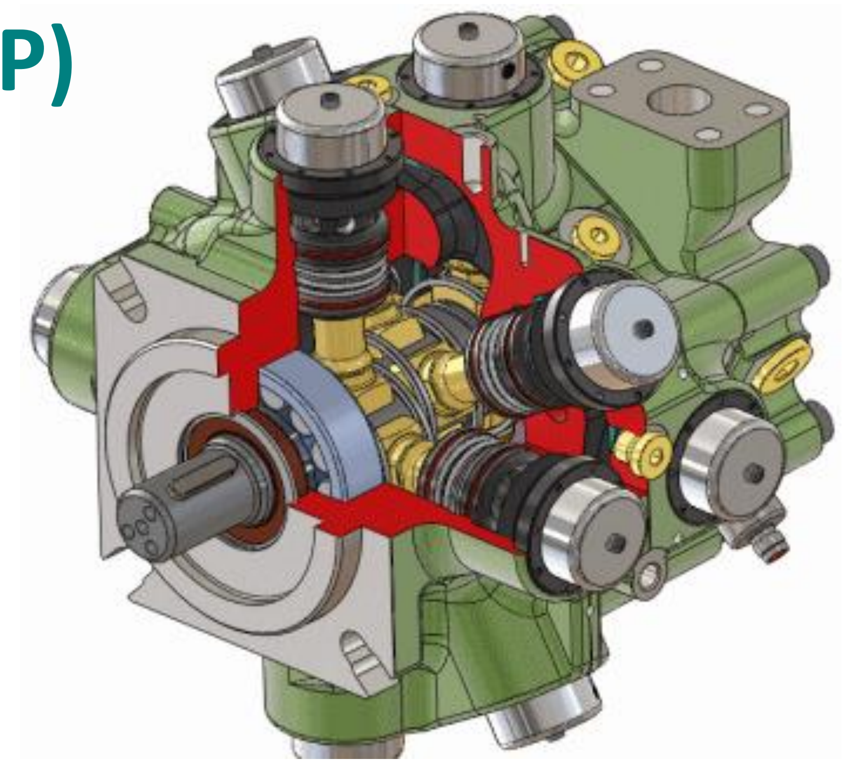
DD for mainstream hydraulic systems

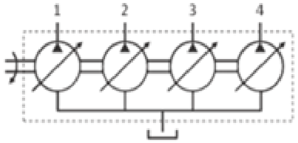
E-dyn 96 Digital Displacement® Pump (DDP)

- 96cc/rev variable high-pressure pump for work & propel
- CAN bus controlled, but also backwards-compatible with analogue pumps
- Configuration by software interface – no screwdrivers!
- A data-gathering node in your IoT system, enabling whole system diagnostics
- Enables new architectures
- Compatible with model-based control system design methods
- Now scaling up production
    - Single service
    - Multi service
    - Tandem



8 variable outlets from tandem

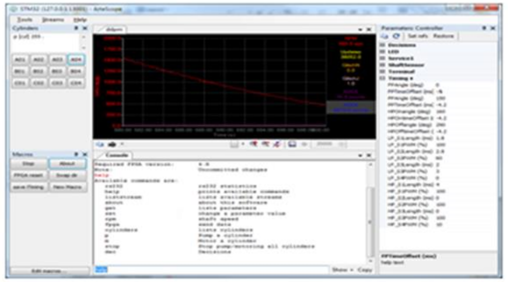




4 variable outlets from one machine

Acceptance tests completed:

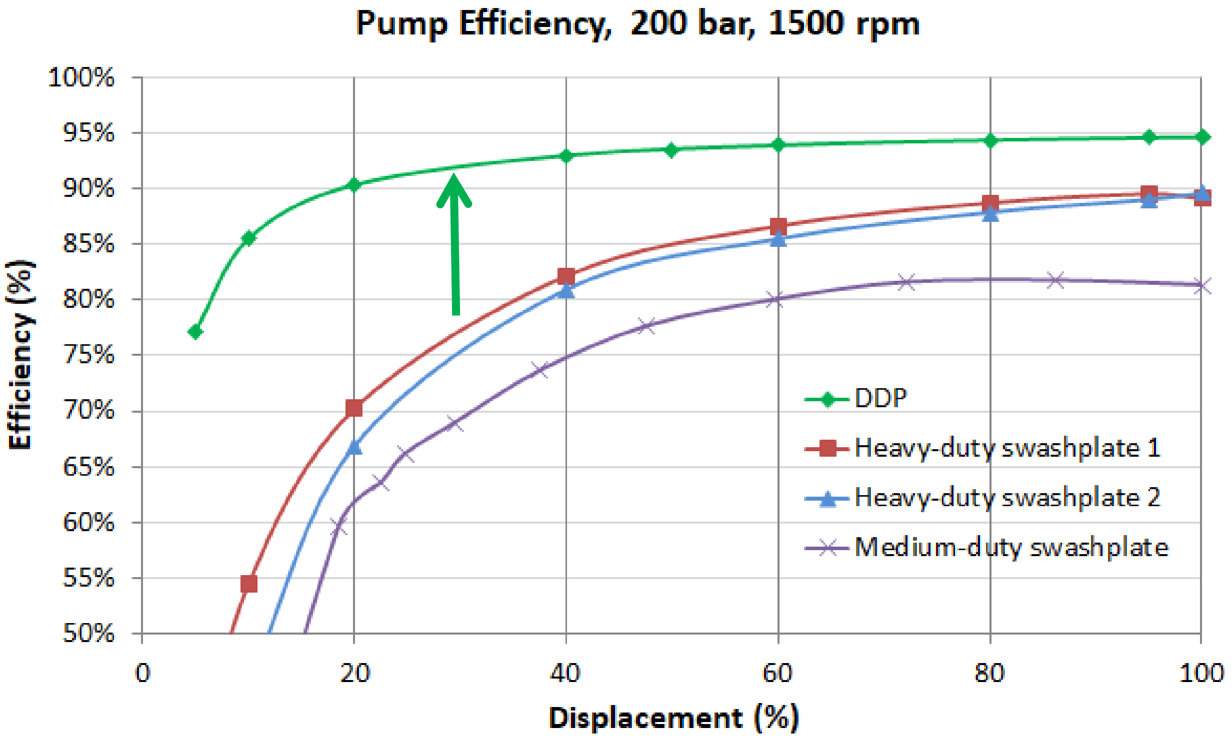
- *Lifetime test @ high pressure*
- *Pressure cycling fatigue*
- *Extreme viscosity*
- *Cold start*
- *Aeration tolerance*
- *Contamination tolerance*
- *Non-mineral fluid compatibility*



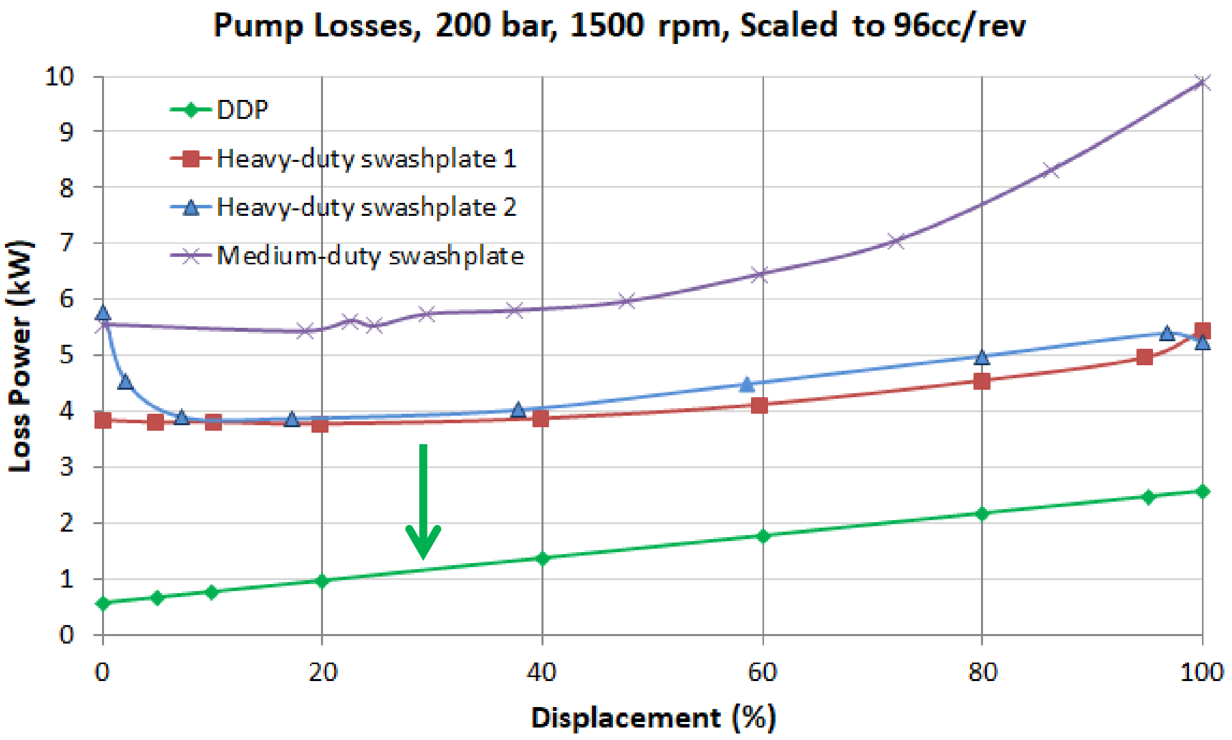
Configuration software

Improving pump efficiency

Efficiency:



Losses:

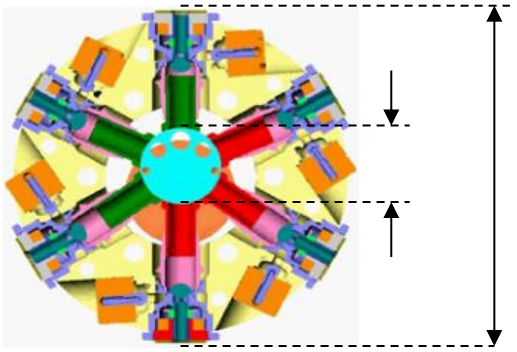


Very high efficiency at part load
Similar to electric machines

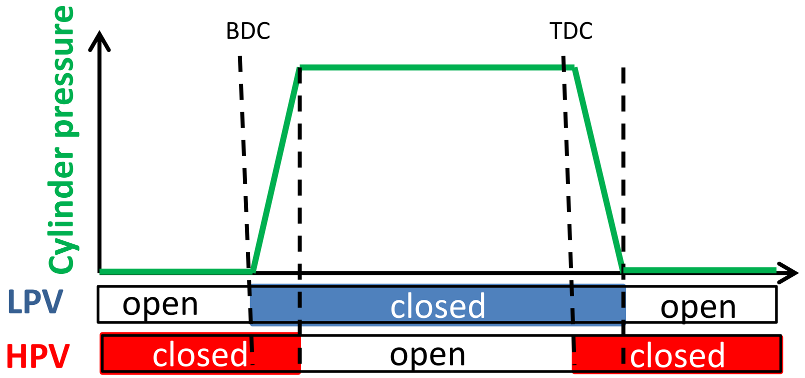
1/3rd – 1/5th of the losses of analog pumps over a duty cycle

Why is a DDP more efficient?

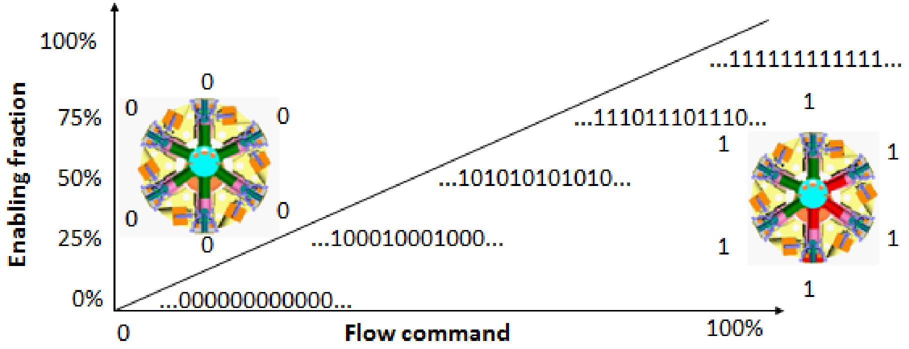
- **Radial piston mechanism** is inherently efficient
  - Ideal kinematic arrangement
  - Small diameter for main high-speed piston bearing
  - Large diameter for flow area



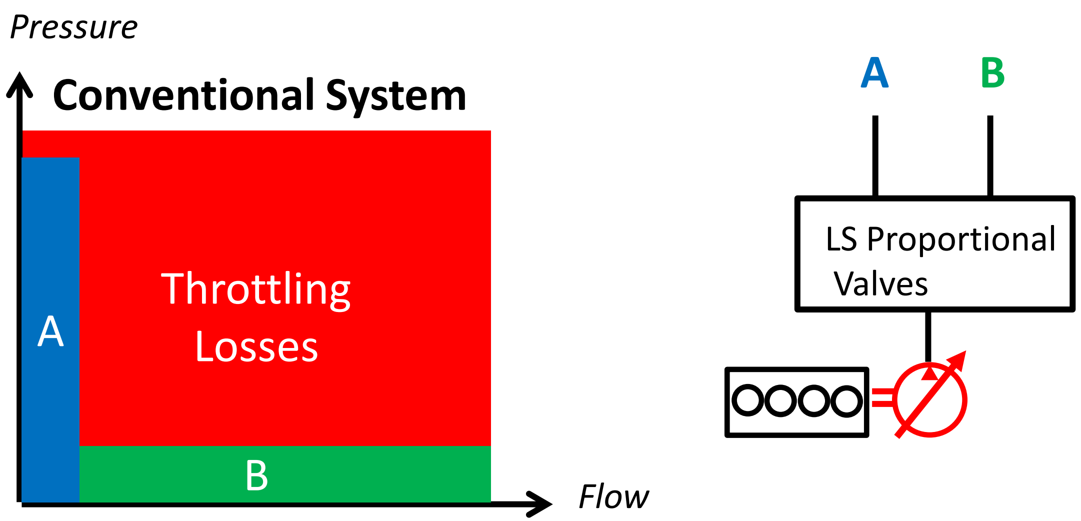
- **Elimination of compressibility losses** (~2% @ 350 bar)
  - Valves do not open or close against pressure
  - Compressibility energy is automatically recovered after TDC

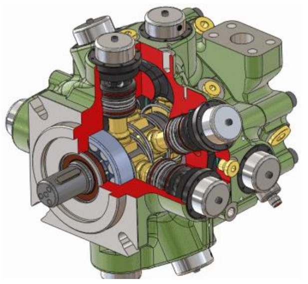


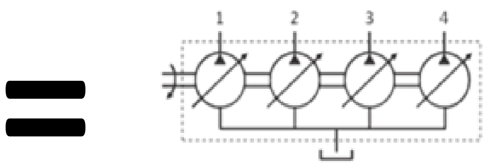
- **Digital method of displacement control**
  - DDP cylinders are either idle, or working
  - Idle cylinders are not pressurised, so have zero leakage and little bearing losses.
  - Working cylinders have leakage and higher friction losses.
  - So DDP losses reduce strongly with displacement



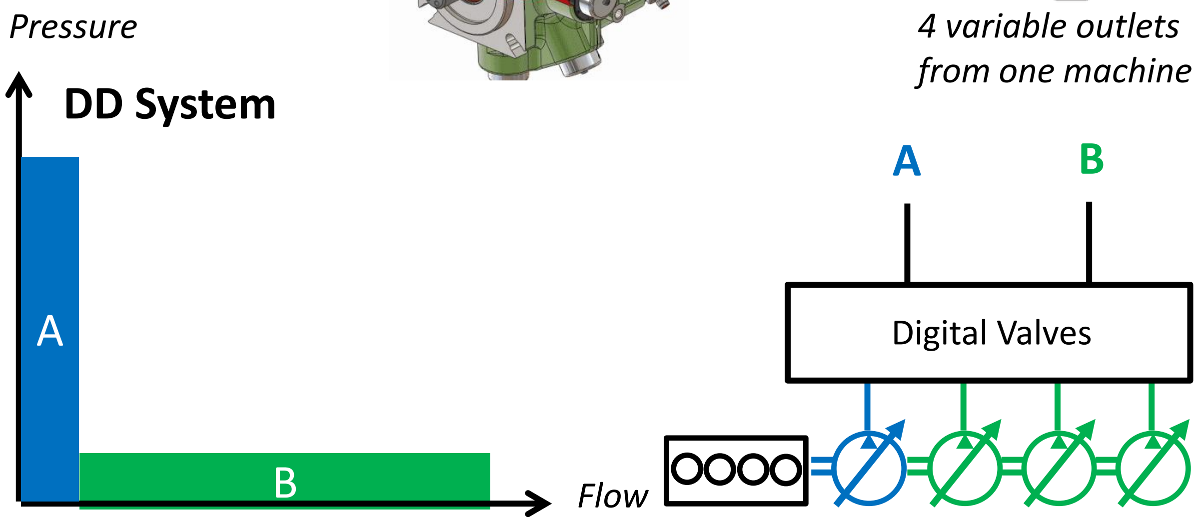
Reducing valve losses with new system architectures







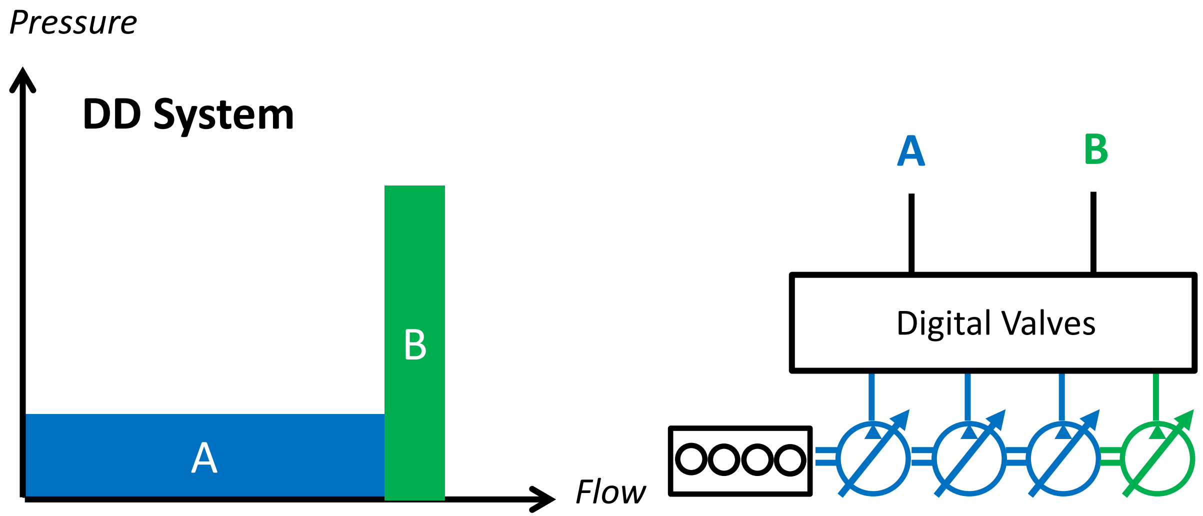
4 variable outlets from one machine



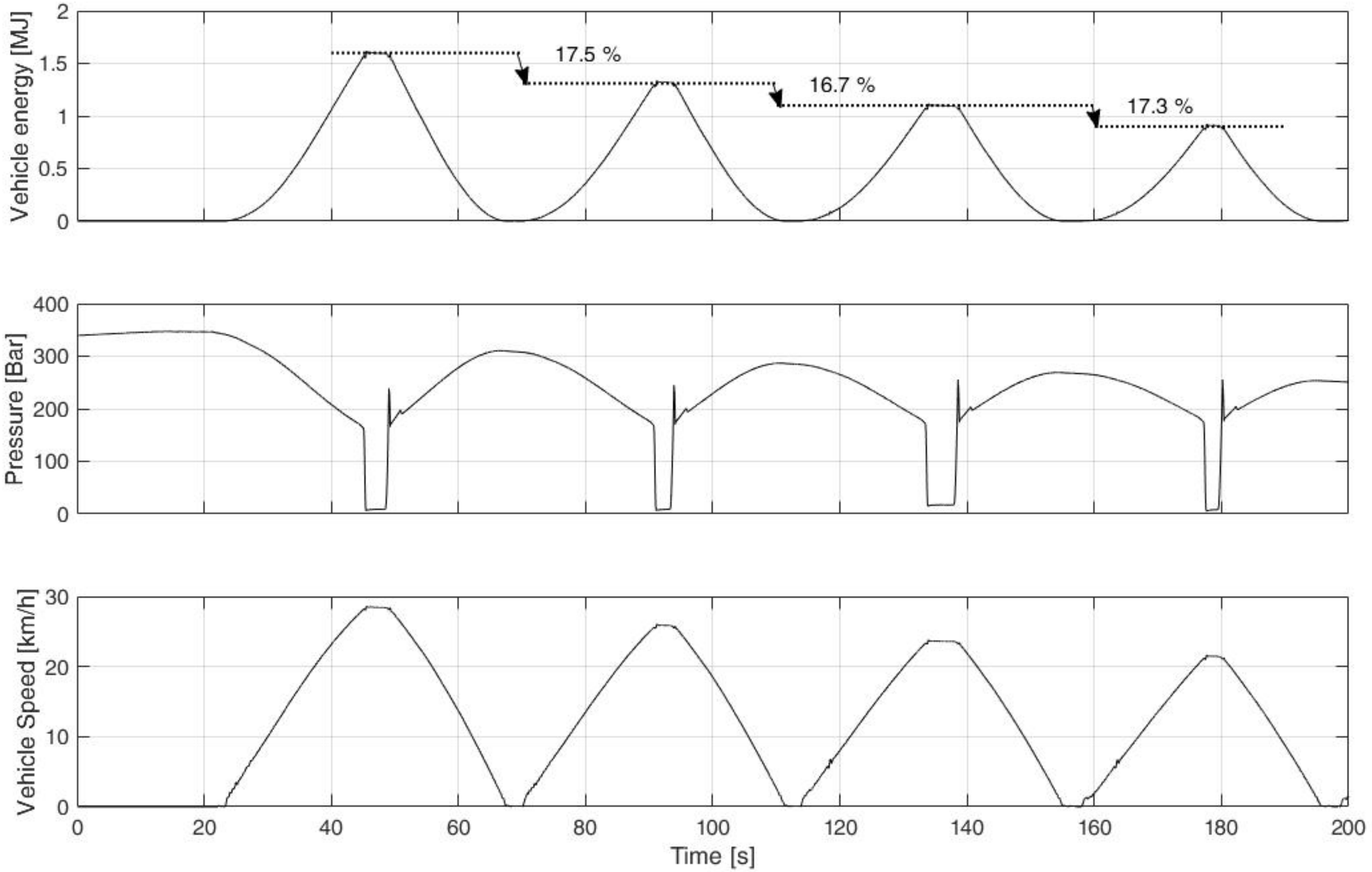
Conventional proportional valve systems throttle energy because multiple loads must “share” a single pump.

DD Systems eliminate this by dynamic allocation of multiple pump outputs to loads, depending on demand, using digital valves.

This dynamic allocation is enabled by multiple independent outputs, and unprecedented response speed and control accuracy of DDP.



Recovering energy



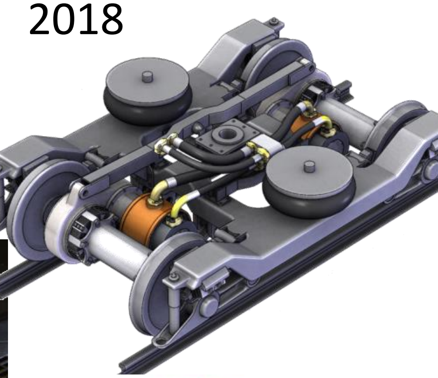
DDPM + Hydraulic accumulator:

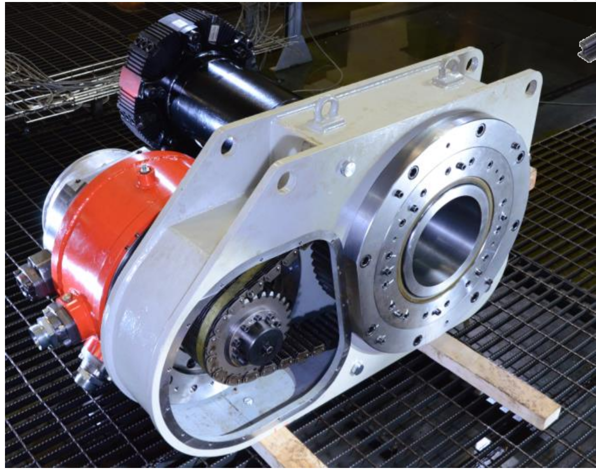
Proven 82.5% round-trip efficiency (much better than battery-electric)

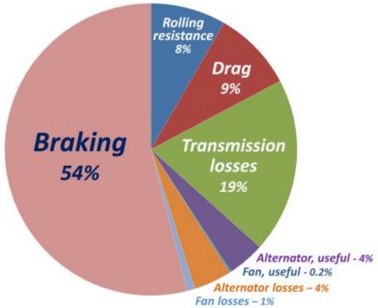
=> ideal for low-cost, high-power kinetic energy recovery

=> can be combined with battery-electric drivetrain

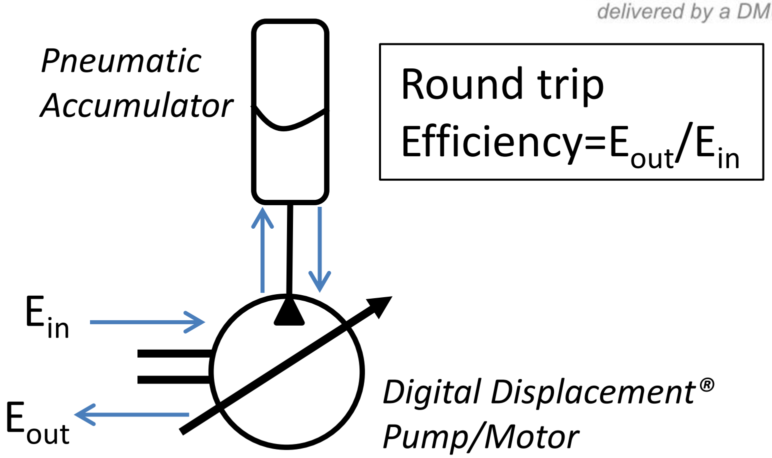
Rail series hybrid demonstrator, 2018





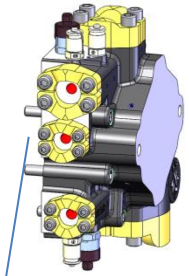


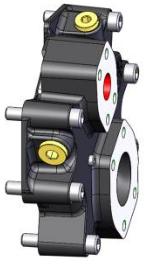
Typical analysis of the end-destination of the shaft energy delivered by a DMU engine.

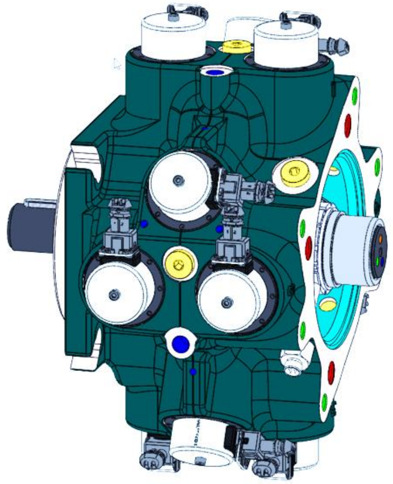


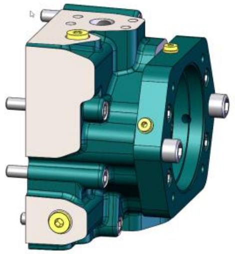
Round trip Efficiency=E_{out}/E_{in}

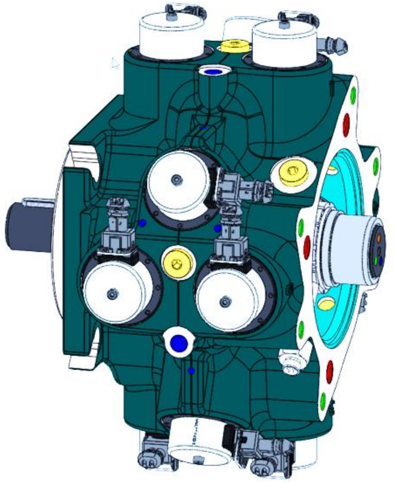
Modular design

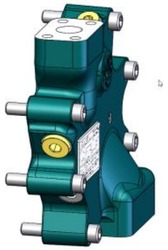

Multi-service

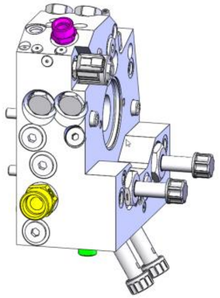

Single service, axial


E-dyn 96


Tandem adaptor


E-dyn 96


Single service, radial


Propel + Work


Mobile Controller

OR


Industrial Controller

Software features

Control interface
- *CAN*
- *Analog*

Control mode
- *Displacement*
- *Flow*
- *Pressure*
- *Load sensing*

Limits
- *Torque*
- *Power*
- *Flow*
- *Speed*

Anti-stall

Alarms

Diagnostic data stream

Data logging

Application-specific features

.....

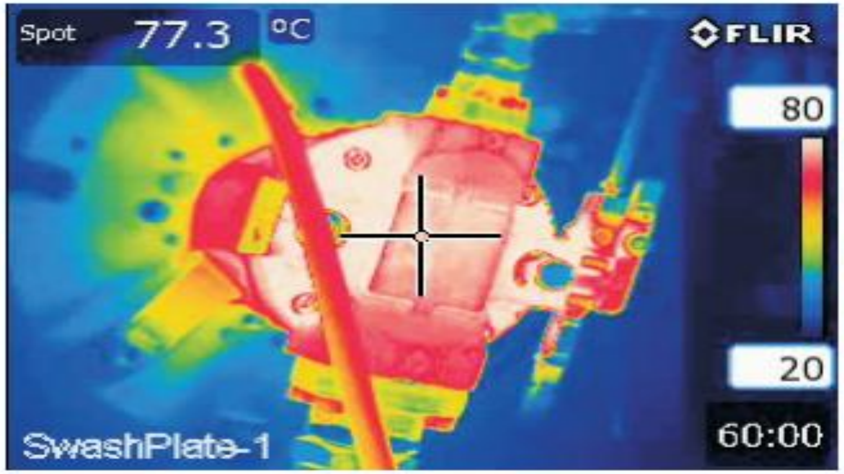
A flexible, modular platform to enable system innovation

Applications

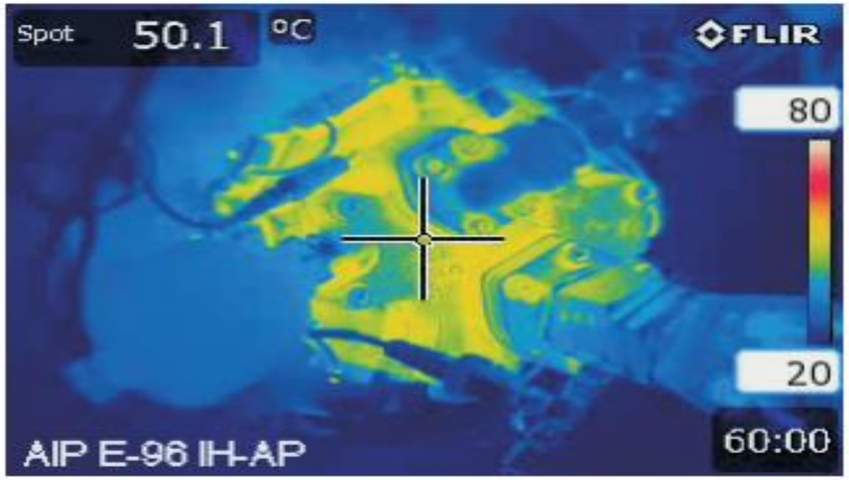
Industrial Power Pack

- Industrial power-pack for a test lab
- 50kW, 210 bar
- Originally used a pressure compensated open circuit swashplate pump
- Compare with E-dyn96:
  - Efficiency, Response, Noise
- In operation since 2015 at customer site in UK (test lab)

Efficiency and losses



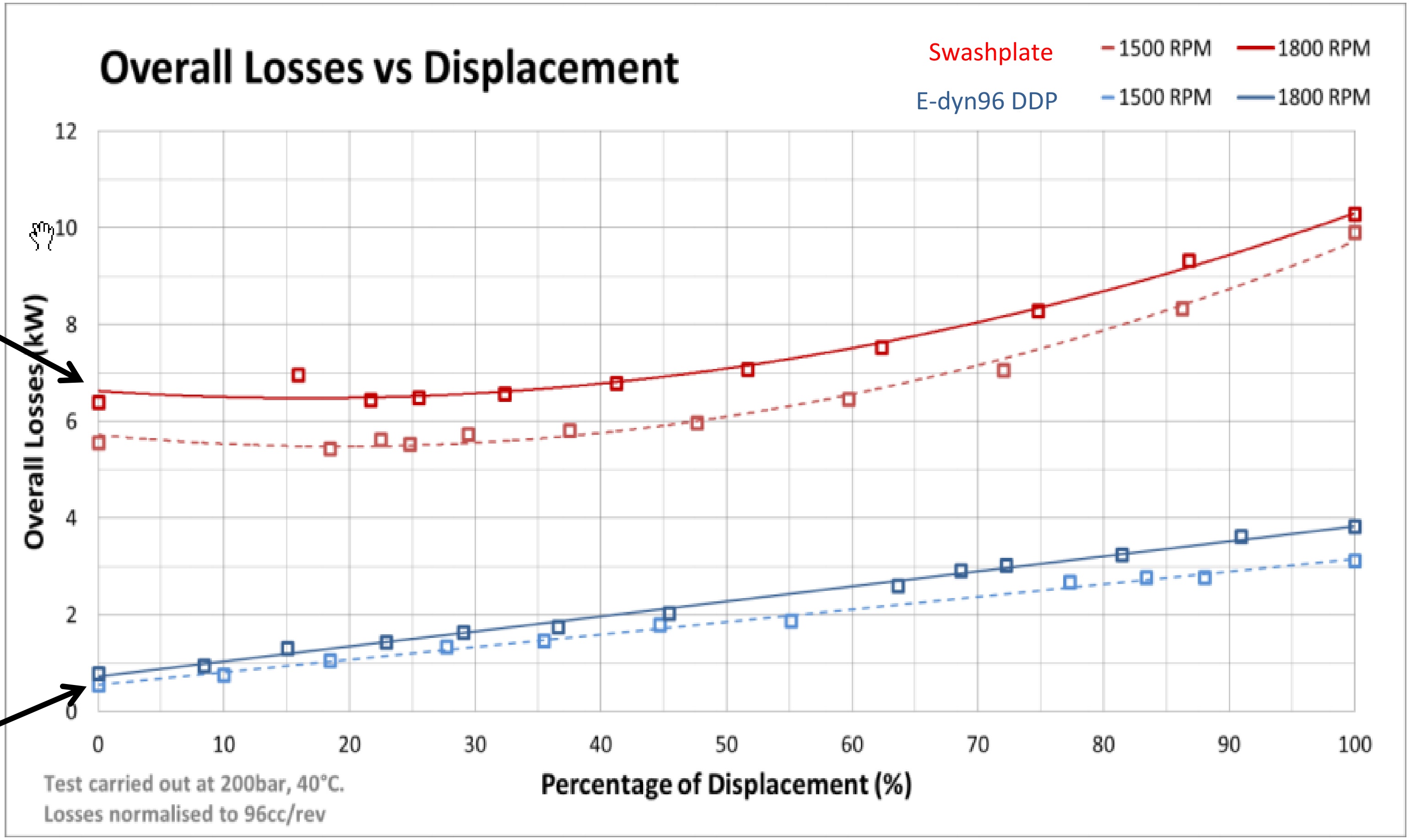
Swashplate: 6kW at 200 bar stand-by



Artemis E-dyn96: 0.5kW at 200 bar stand-by

Less than 10% of loss

96cc/rev, 1500/1800rpm, 200 bar



Test carried out at 200bar, 40°C.
Losses normalised to 96cc/rev

Customer feature request:

"Can you please make it waste some energy occasionally… we need some flow in the oil cooler to prevent Legionnaire's Disease!"

Pressure control response

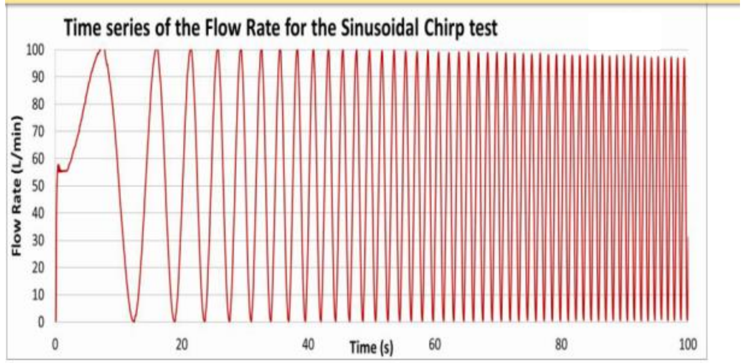


Figure 4-1: A10 output flow during the sinusoidal chirp test

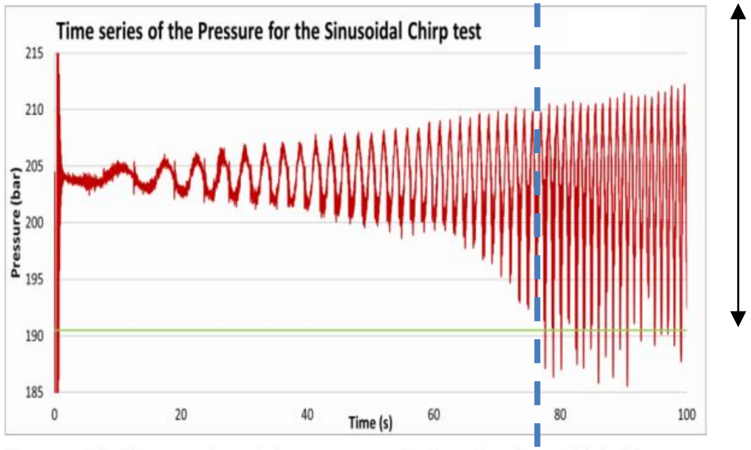


Figure 4-2: Time-series of the pressure during the sinusoidal chirp test

+/- 200 psi

→

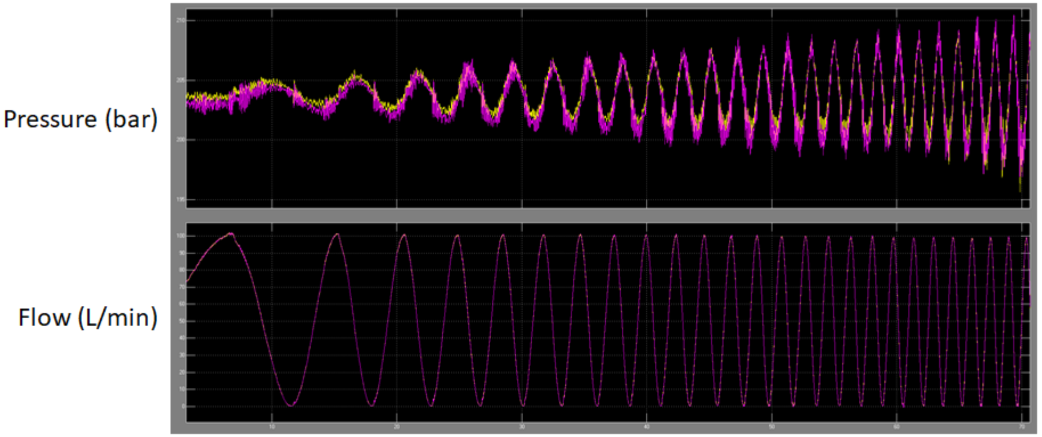
Frequency increasing…

Comparison with the measured Data

Sinusoidal Chirp: 0 to 0.7Hz (0 to 70s)

In yellow is the measured data

In purple is the simulation



Limiting frequency:

Swashplate	0.77Hz
DDP	2.5Hz

Noise vs displacement – 200 bar, 1800rpm

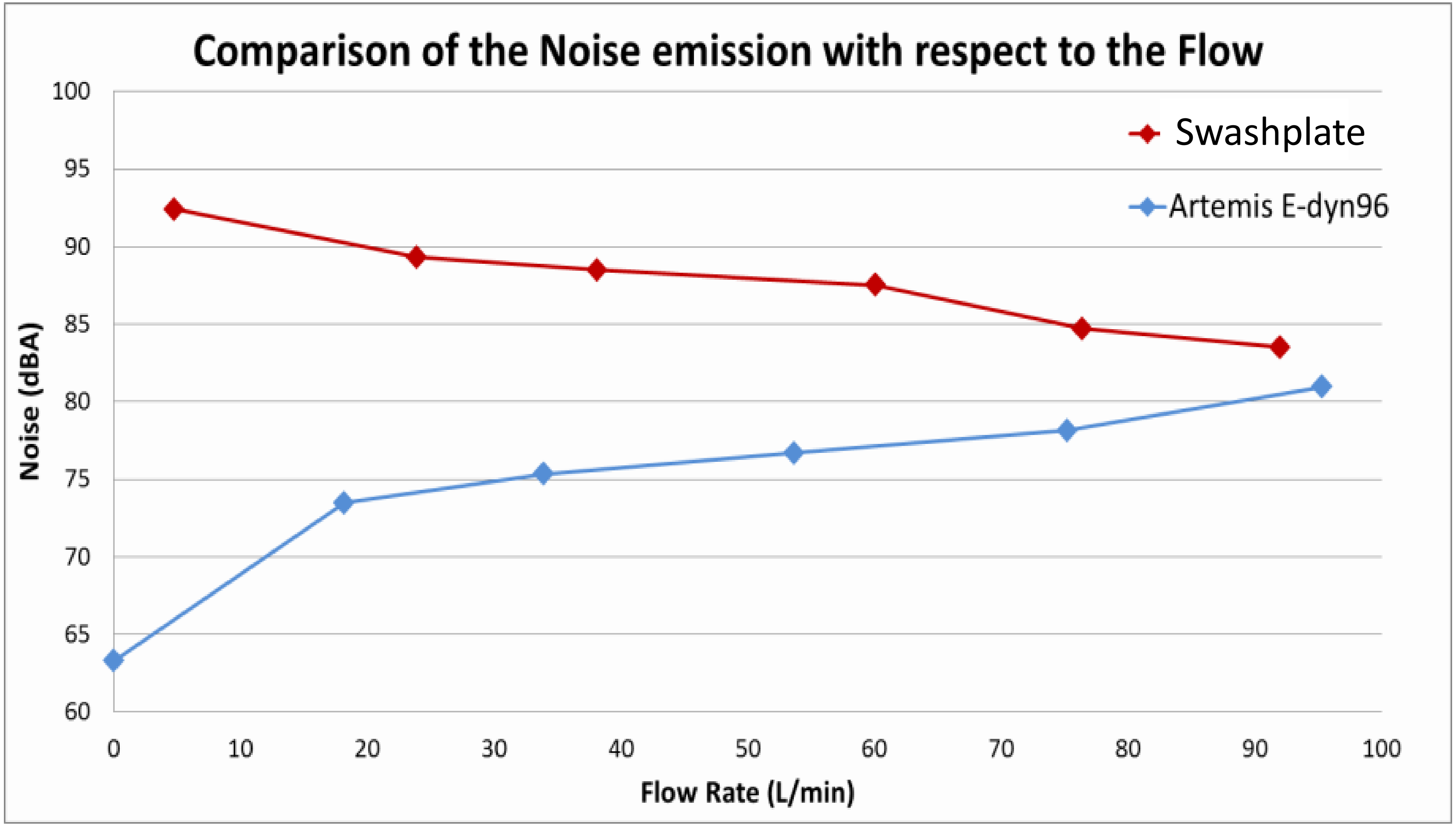
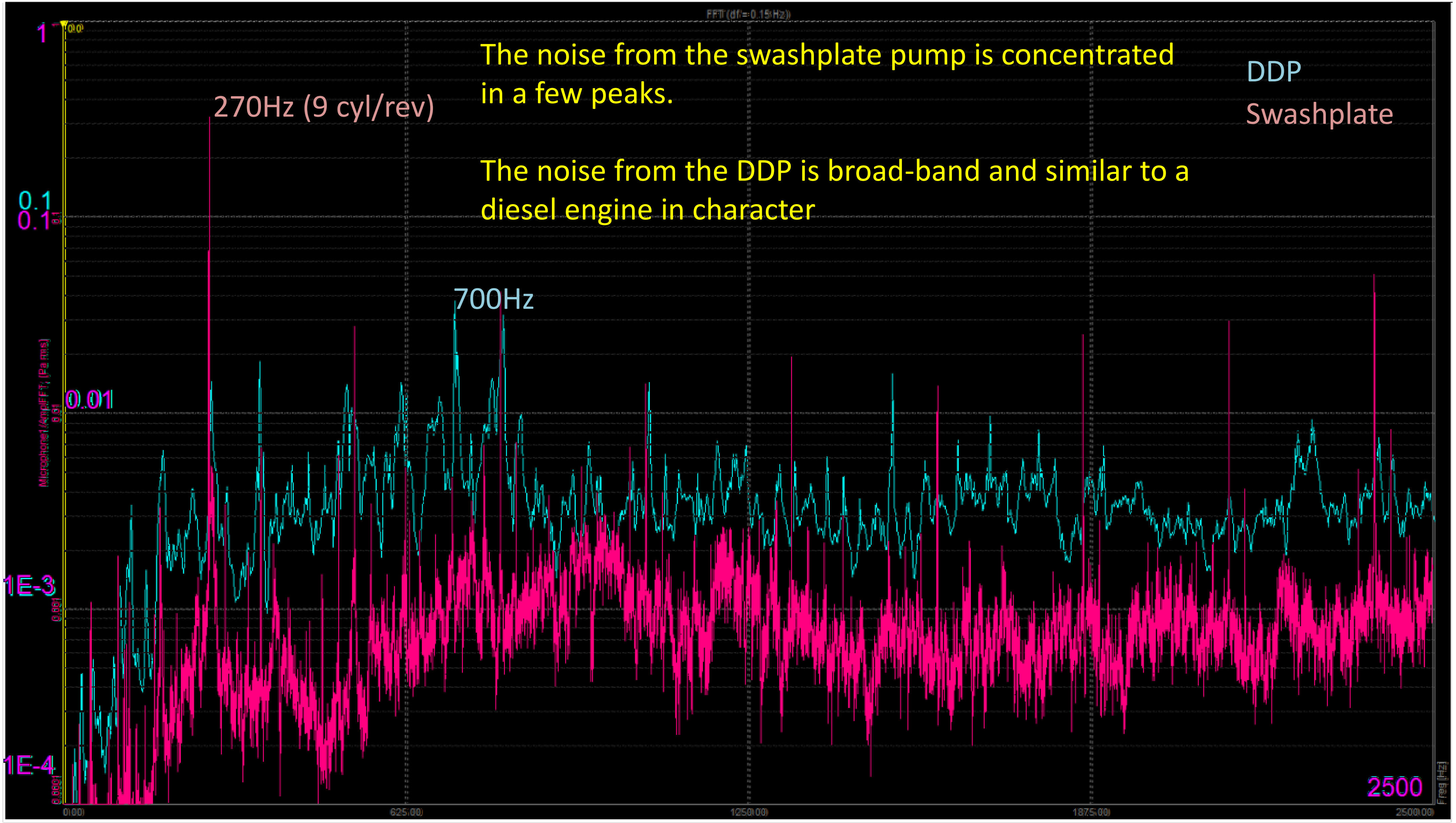


Figure 3-3: Noise emission versus Displacement

Noise: Frequency content

Microphone signal (A wieghted), 1m on axis, semi-anechoic
20 GPM, 200 bar, 1800rpm



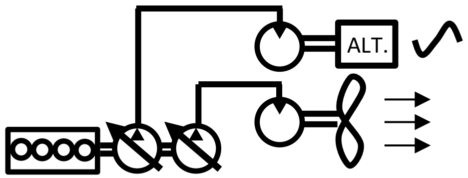
The noise from the swashplate pump is concentrated in a few peaks.

The noise from the DDP is broad-band and similar to a diesel engine in character

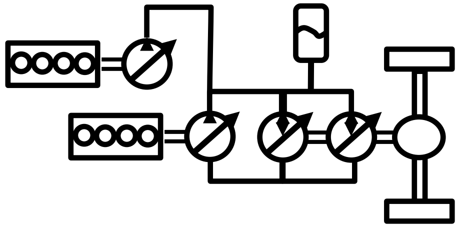
Heavy vehicle applications

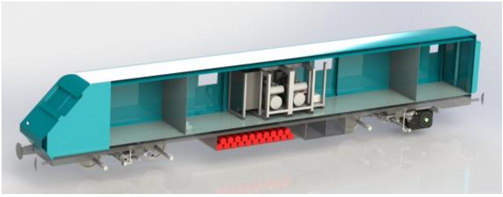
Rail

Accessory drive



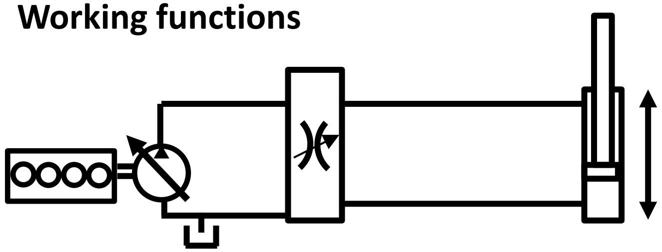
Series hybrid



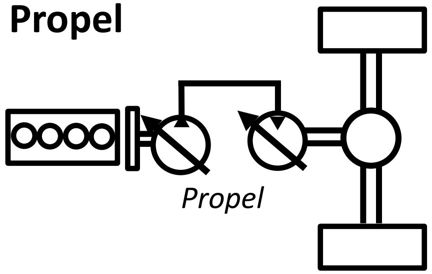


Off-highway

Working functions

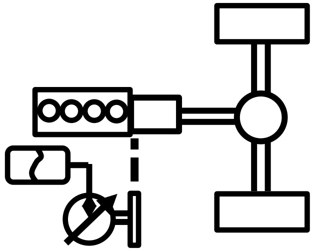


Propel



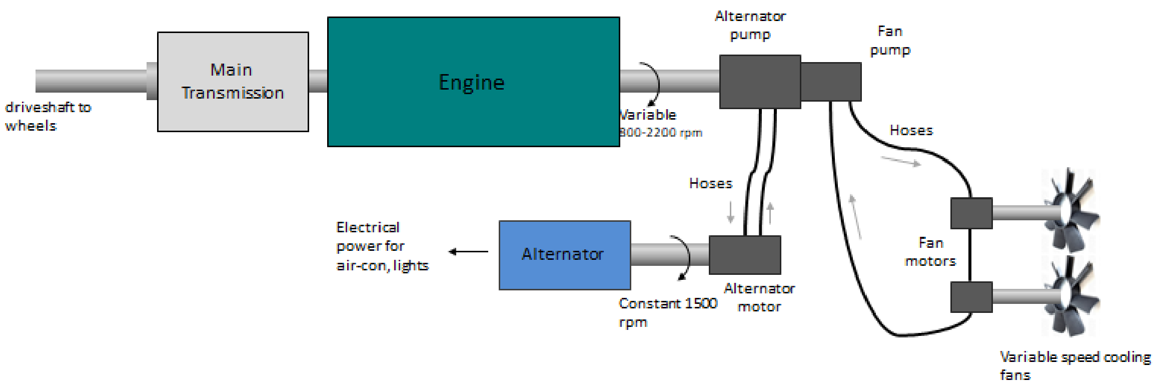
On-highway

Parallel hybrid

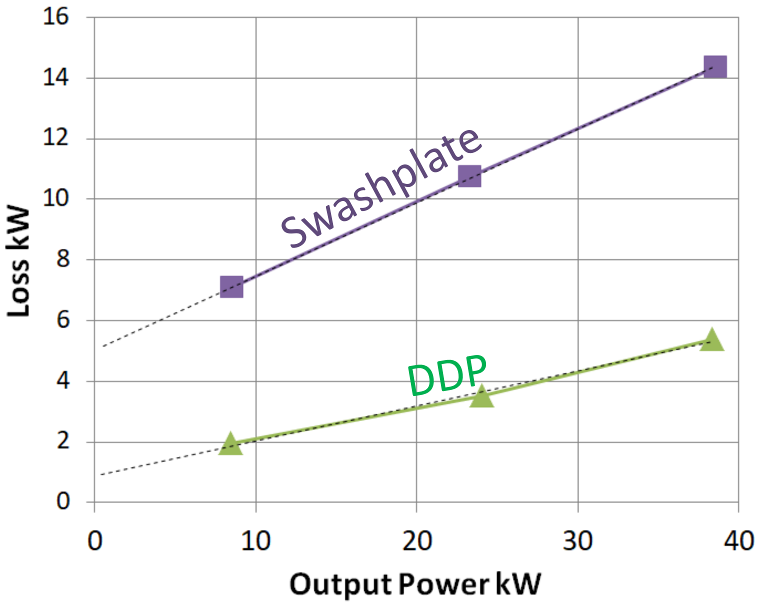


Rail: accessory drive

Accessory drive for diesel rail car (Oct 2017)



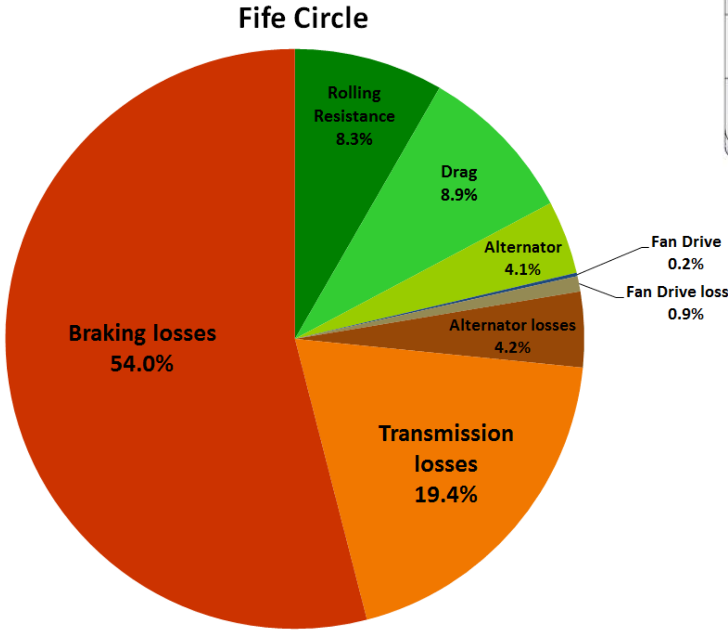
	Swashplate	DDP
Average Power Out	23.72	23.68 kW
Average Power In	33.35	26.84 kW
Average Losses	9.63	3.16 kW
Average Efficiency	71.1%	88.2%

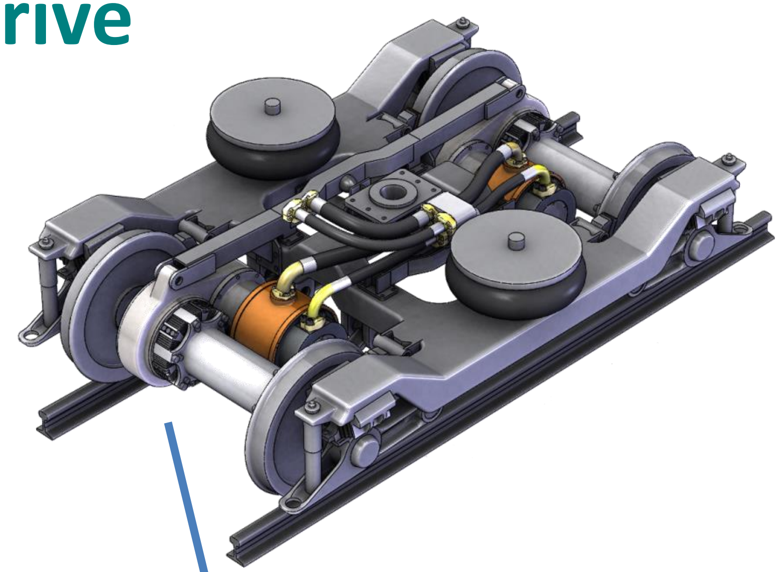


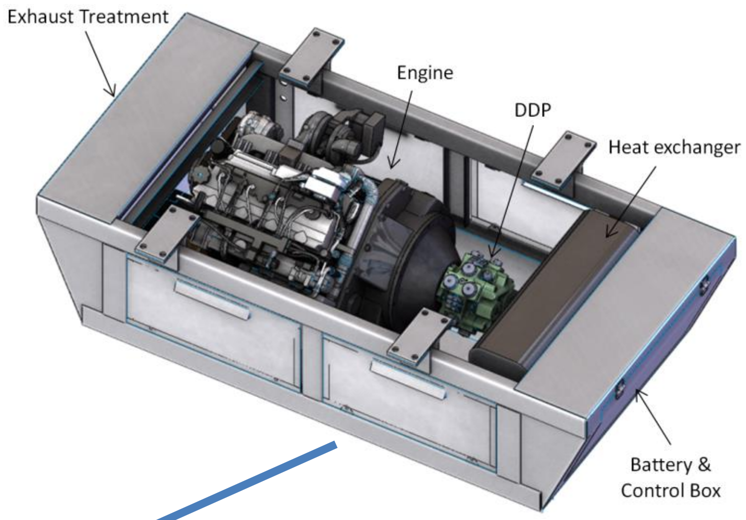
1/3rd of the losses = **6.5kW** less on average
19% reduction of engine power consumed
Saving: **10,000L** diesel per year, per car.
Expected payback period measured in months

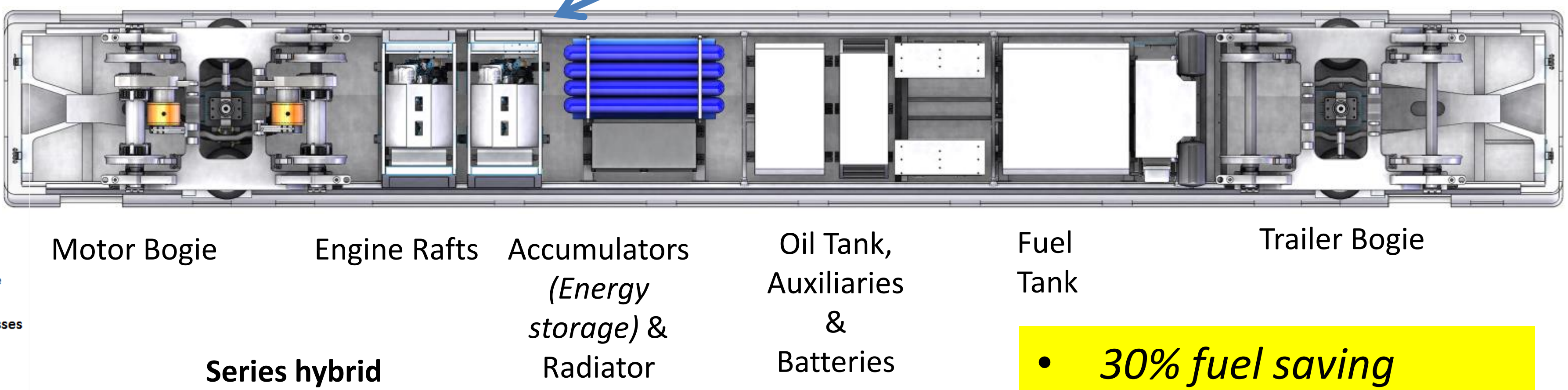
19h/day * 365 days = 6935hrs/year
6.5kW @200g/kwhr = 1.3kg/hr = 1.5L/h
=>Save 10,400 L/year

Rail: series hybrid drive

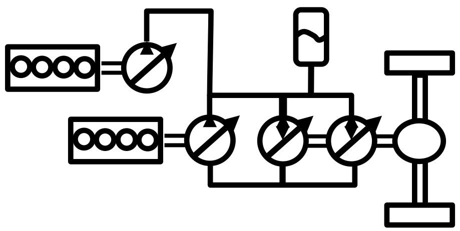




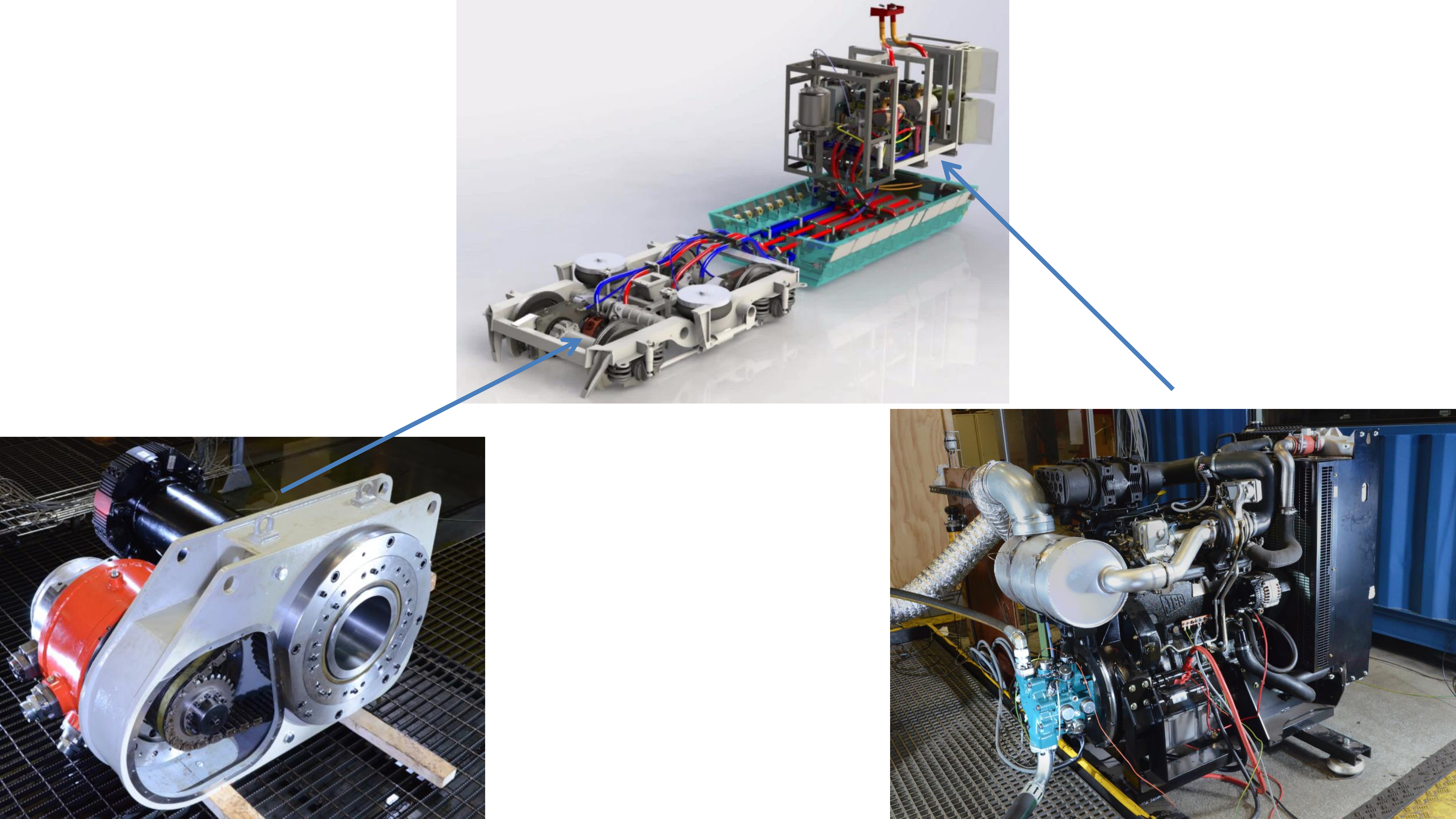




Series hybrid

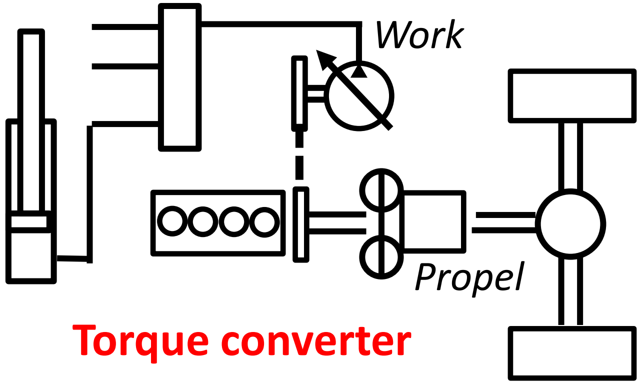


- *30% fuel saving*
- *Better acceleration*
- *Less noise*
- *Lower emissions*



Digital Displacement offers a cost-effective and achievable route to decarbonise our rail sector

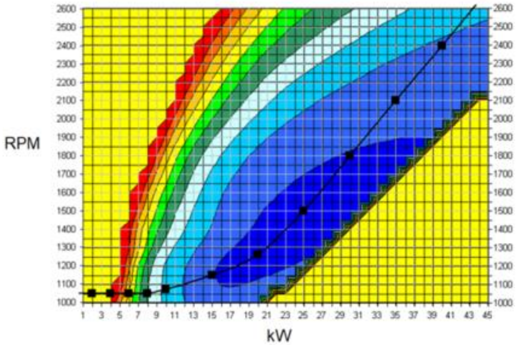
Diesel Forklift



Torque converter

- Poor transmission efficiency
- Poor engine utilisation
- Driving behaviour is “sloppy”

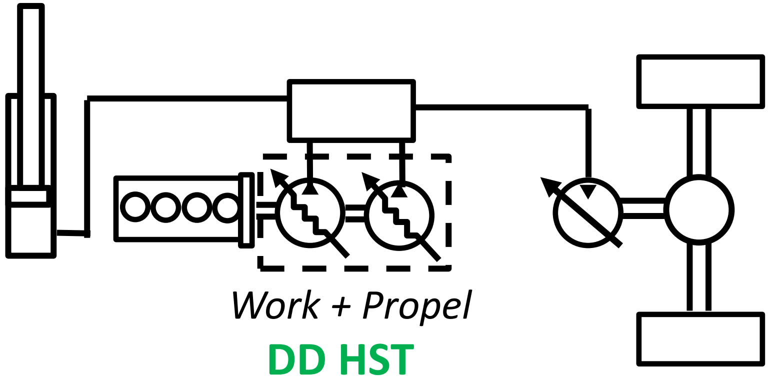
7.3 l/h



-40%

- Best transmission efficiency
- Can optimise engine speed perfectly
  - by coordination of propel and work load
- Driving behaviour is fully adjustable

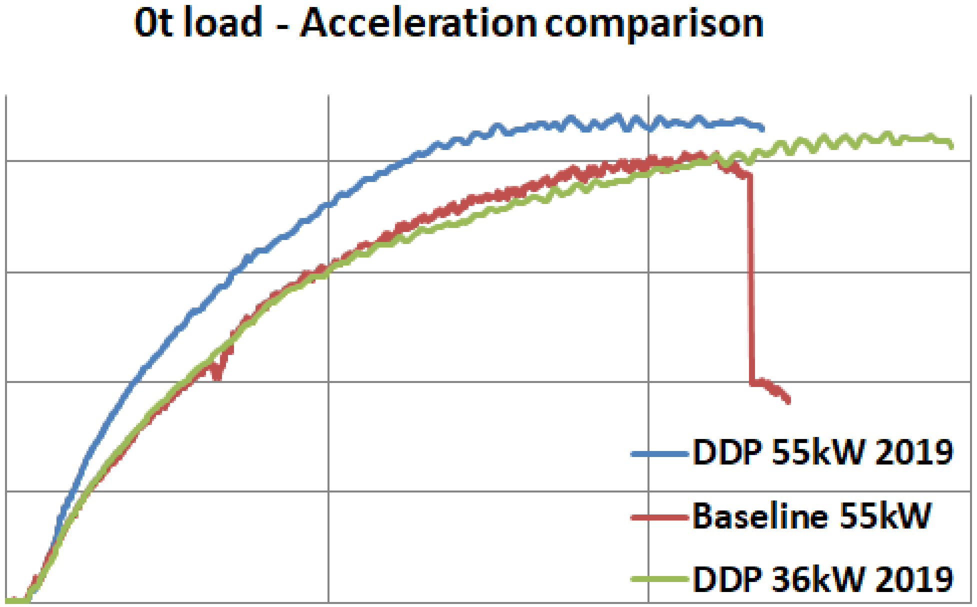
Fuel/hr :4.4l/h

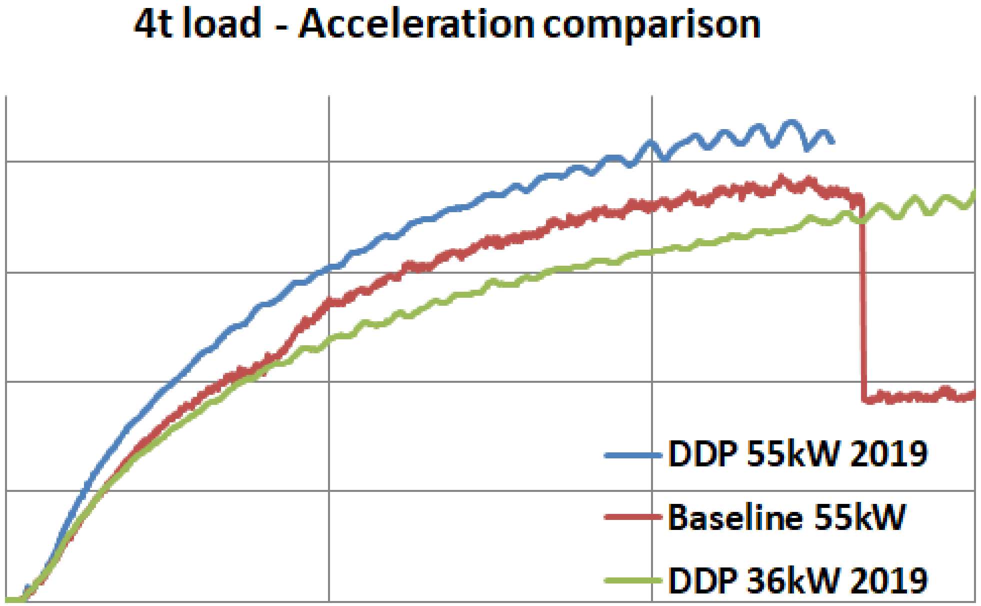


DD HST

With DDPM & accumulator there is a pathway to > 50% reductions

Demo vehicle



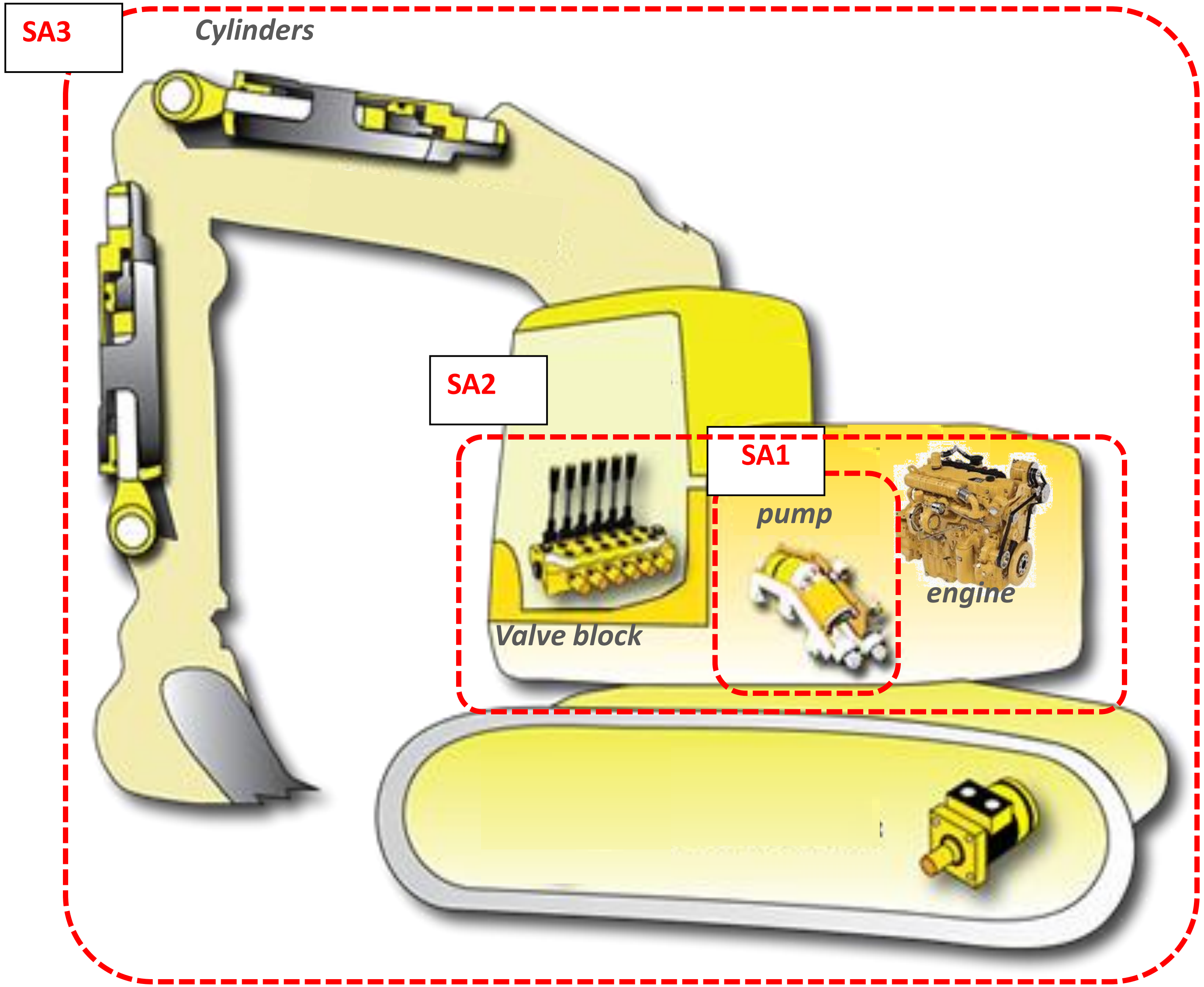


Better performance from the same engine vs hydrodynamic

OR

Engine downsizing by 30% is possible

Excavator: System Architecture Levels



Excavator: DEXTER1 project (SA1)

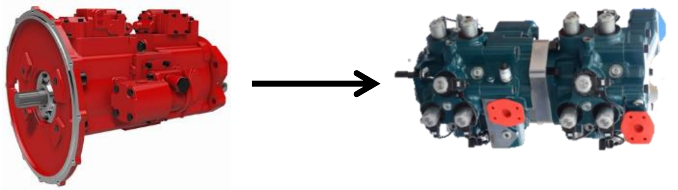
Demonstration of DDP in a 16T excavator
Concept: minimal intervention "pump swap"

Supported by…

Scottish Enterprise

Project summary:

- Baseline machine instrumented to determine where energy is lost.
- Tandem DDP fitted as direct replacement for swashplate
- Engine and hydraulic circuit left completely standard
- Controls developed using model-based design
- Demonstrated at dedicated test facility for two weeks: 100% uptime



Baseline Tests
August 2016

DDP fitted
Nov 2016

DDP Tests Complete
March 2017

	Swashplate	E-dyn DDP
Capacity	80cc x 2	96cc x 2
Rated pressure	350 bar	350 bar
Control	Hydro-mechanical	Software-Electronic
Interface	Hydraulic pressure	CANbus / analog / digital
Response speed	300ms	30ms

DEXTER is more efficient, more productive and quieter than the baseline machine

Results

Bulk Dig results:

DDP Eco Mode:

21% fuel saving + **10%** productivity increase

DDP Power Mode:

10% fuel saving + **28%** productivity increase

Expectation over typical annual usage:

20% reduction in operating expenses

Cycle	Base - line RPM	DDP RPM	Fuel/cycle saving	Cycles/hour increase
Trenching	2050	1450	21.2%	10.4%
Bulk Dig - ECO MODE	2050	1450	21.2%	10.6%
- POWER MODE	2050	2050	10.0%	28.0%
Bulk Dig - slow (20% reduced work rate)	2050	1450	37%	-
Lorry load 90 degrees	2050	1450	18.4%	-0.4%
Lorry load 180 degrees	2050	1450	16.1%	1.9%
Tracking (up and down-hill)	2050	1650	16.1%	-
Idling	950	950	27.1%	-

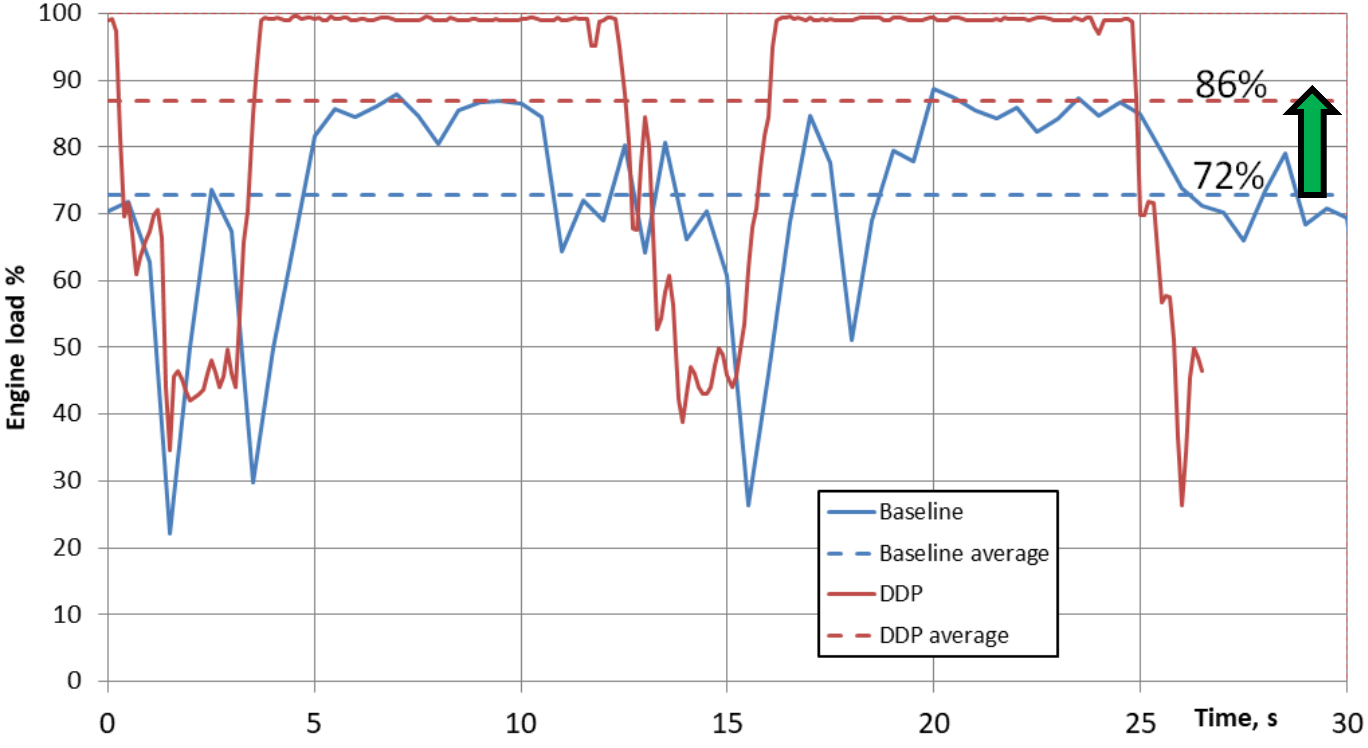
How did we achieve 28% productivity increase?

1. DDP has unprecedented control

⇒DDP takes over the job of speed governor

⇒Engine reaches maximum torque for most of the time, without risk of stalling

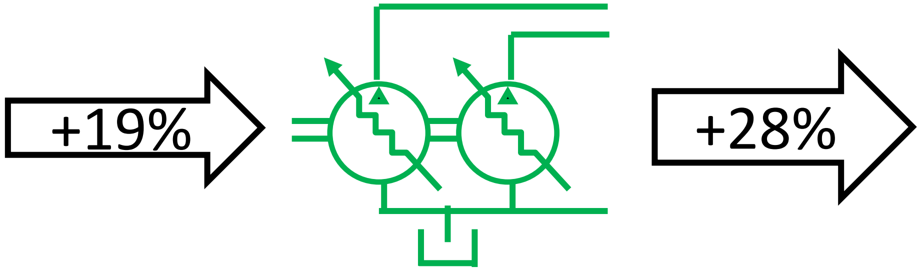
⇒**19%** more engine power delivered than the analogue pump



Comparison of engine load conditions during trenching

2. DDP is much more efficient

⇒Further **9%** increase in fluid power delivered



Danfoss DDP Excavator Demonstrator

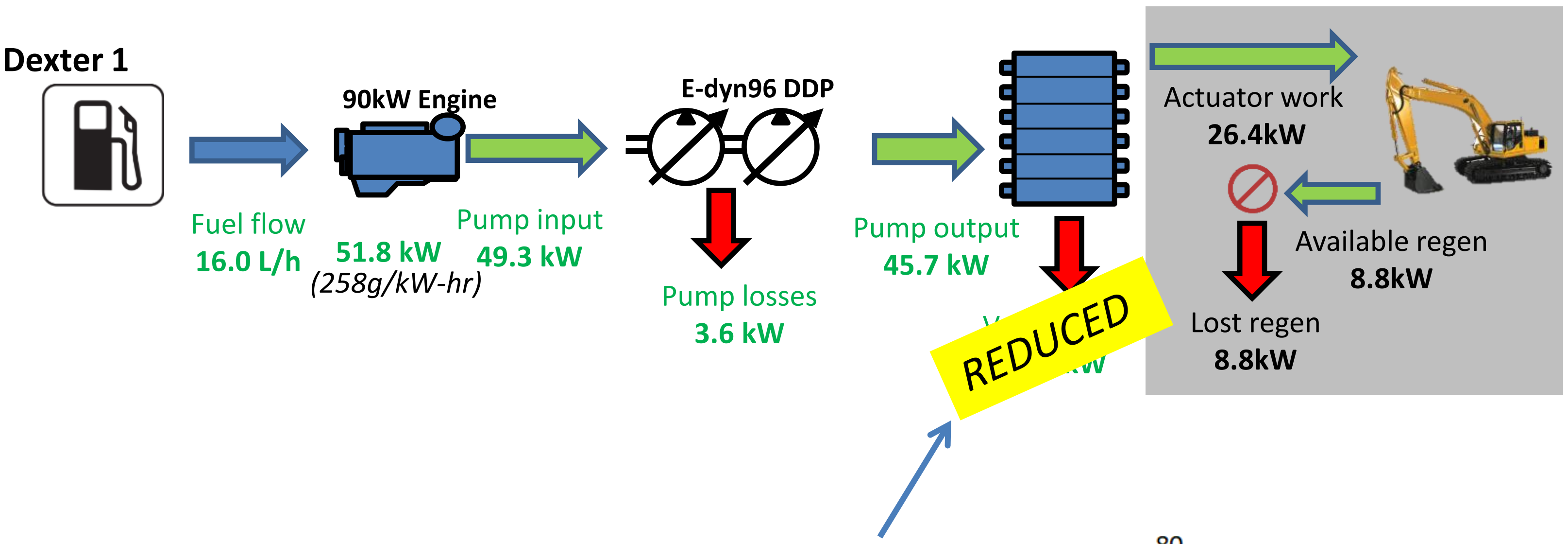
Based on CAT 320

SA1 (pump swap) system

Tandem E96 x 2 with gear-up

Led by Chris Williamson of Danfoss (Monika’s student)

Dexter 2 (SA2)



Dexter 1

90kW Engine

E-dyn96 DDP

Fuel flow
16.0 L/h

51.8 kW
(258g/kW-hr)

Pump input
49.3 kW

Pump losses
3.6 kW

Pump output
45.7 kW

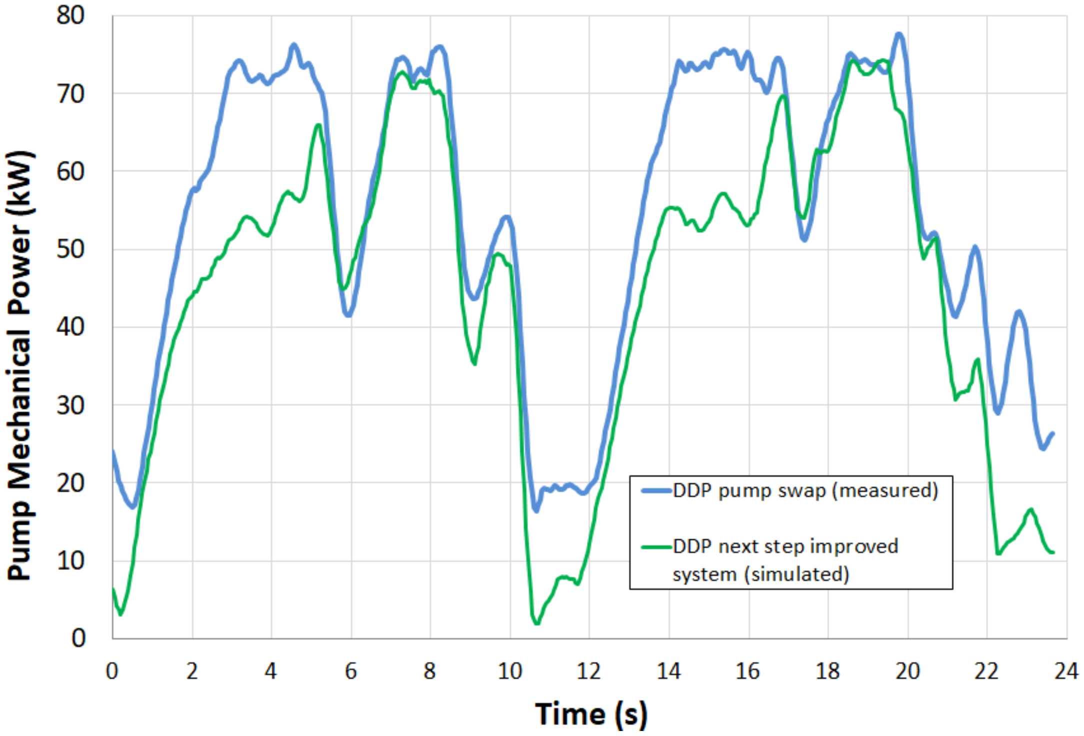
REDUCED

Actuator work
26.4kW

Available regen
8.8kW

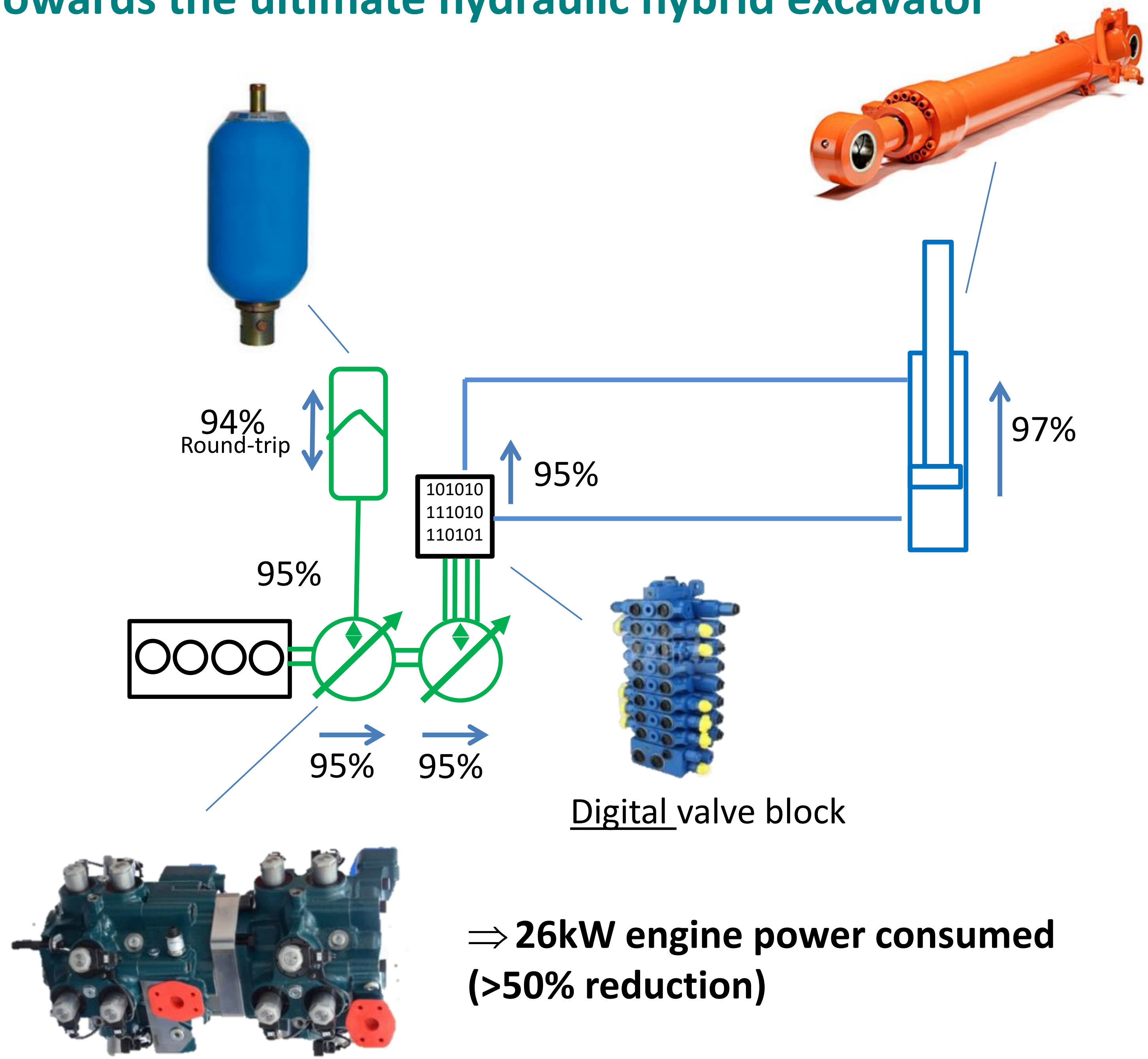
Lost regen
8.8kW

Modifications to valve block + Optimisation of DDP control strategy = Reduction of throttling losses



⇒ 30% reduction over baseline

Towards the ultimate hydraulic hybrid excavator



⇒ **26kW engine power consumed (>50% reduction)**

Retain the existing hydraulic actuators

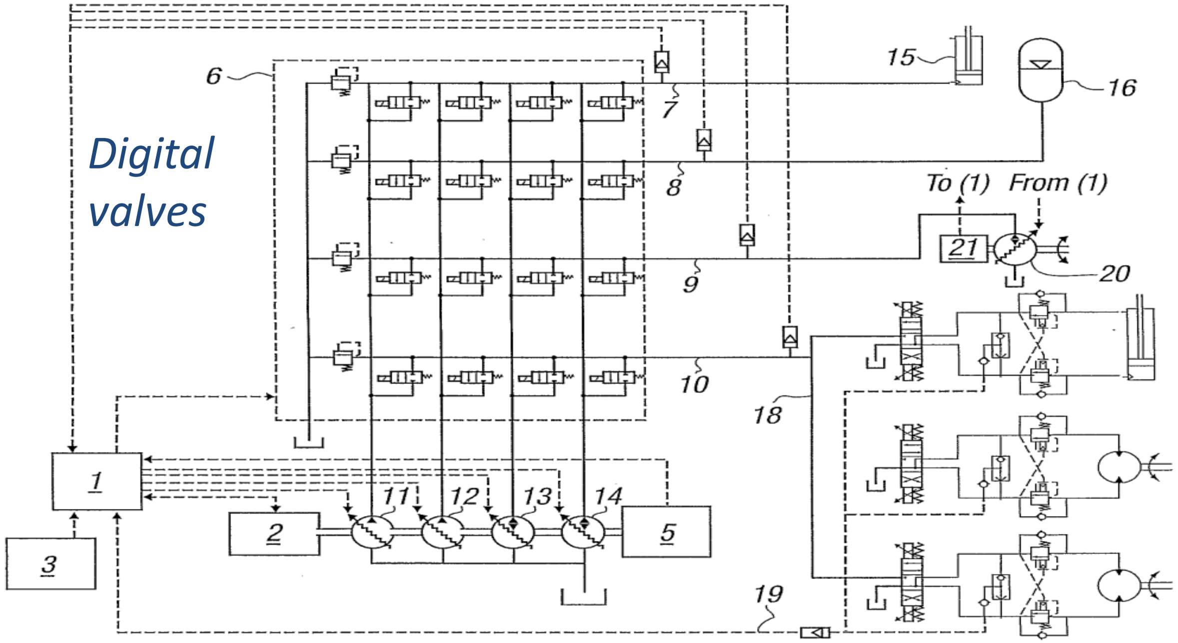
Instead of throttling, all control comes from displacement of multiple separate pump services, digitally switched into each load

Energy storage by gas accumulator

Fluid and mechanical power are transformed by Digital Displacement pump/motors.

- Efficient power transmission
- Mechanical energy recovery
- Low cost, but high efficiency

Direct displacement control of multiple actuators - without proportional valves



Digital valves

One pump…
Multiple outputs

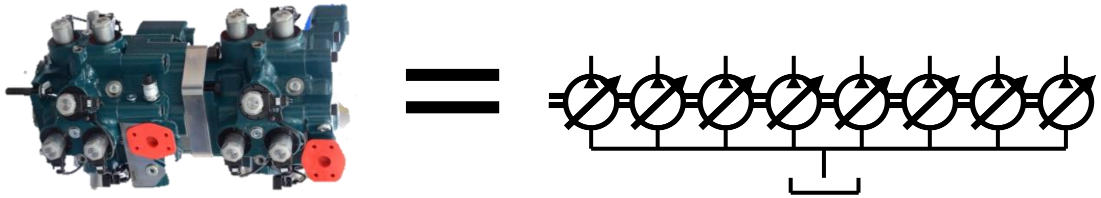
FIG. 1

Multiple actuators

Concept

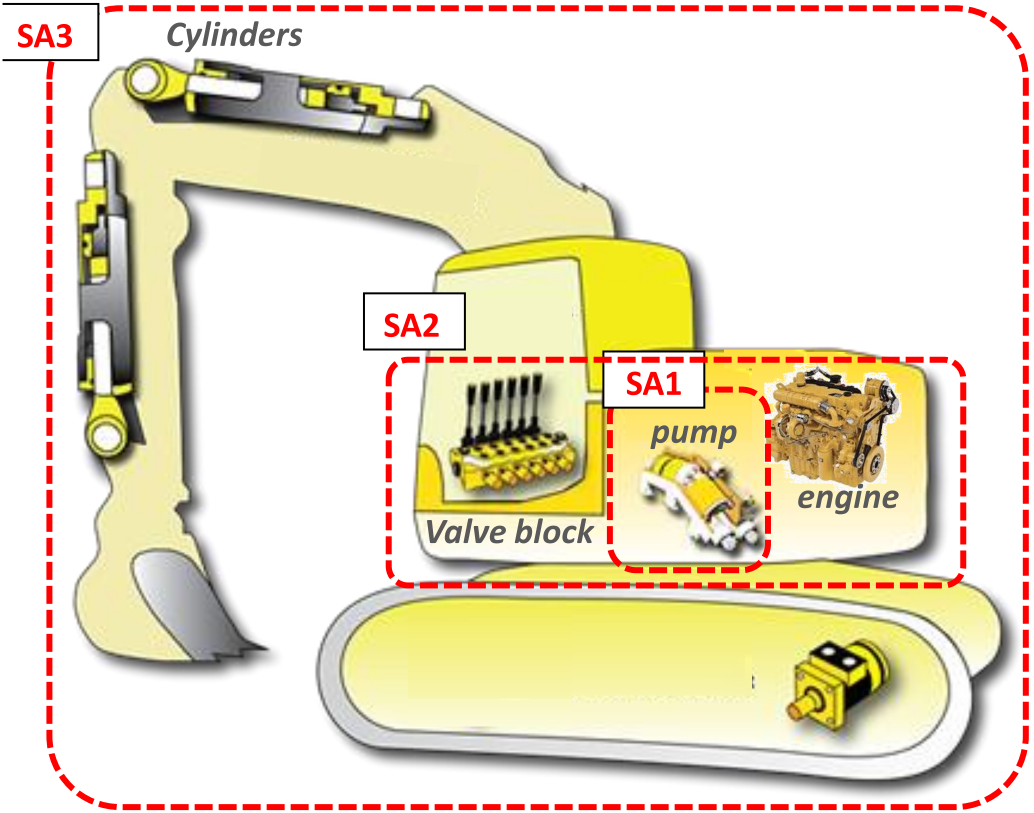
- “The Workbus”: multiple DDPM services are connected to loads in real time as demand varies by digital valves.
- Energy is regenerated onto the shaft, for immediate reuse or storage in accumulator
- Engine can be downsized, and operate at constant load
- Proportional valve throttle loss is eliminated
- Digital open-loop position control comes direct from the pump

VIDEO: Direct digital control of hydraulic actuator from DDP (without proportional valve)



Diesel Excavator Results - and Future Potential

Concept	System impact	Benefits	Predicted fuel reduction (trenching)	Proven fuel reduction (trenching)	Next steps
SA1 "Pump swap"	**Minimal** A simple pump retrofit	Reduced pump losses. **Much higher productivity (+28%)**	16% (IVT 2016)	21% (IVT 2017)	Danfoss: Go to market!
SA2 "Smarter system"	**Medium** Electronic joysticks, some valve block changes	As SA2, plus Reduced valve losses	30% (IVT 2017)	32% *NEW!*	Artemis: Demonstrate to OEMs. Partner to develop
SA3 "Ultimate system"	**Major** Replace proportional valves with digital. Add accumulator.	As SA3, plus minimised throttling losses. Kinetic energy recovery on major axes. Engine load levelling.	>50%	*Watch this space!*	Artemis: Prove elements in lab. Demonstrate in excavator.



Outlook to Battery-Electric DD System for a 20T excavator…

System	Energy reduction	Battery Capacity	Life Cycle CO2 kg/h (diesel)	Life Cycle CO2 kg/h (UK electricity)
Baseline	-	651 kWh	54.9	41.2
DD SA1	21%	514 kWh	44.9	34.0
DD SA2	32%	442 kWh	39.6	30.3
DD SA3	50%	325 kWh	31.1	24.2

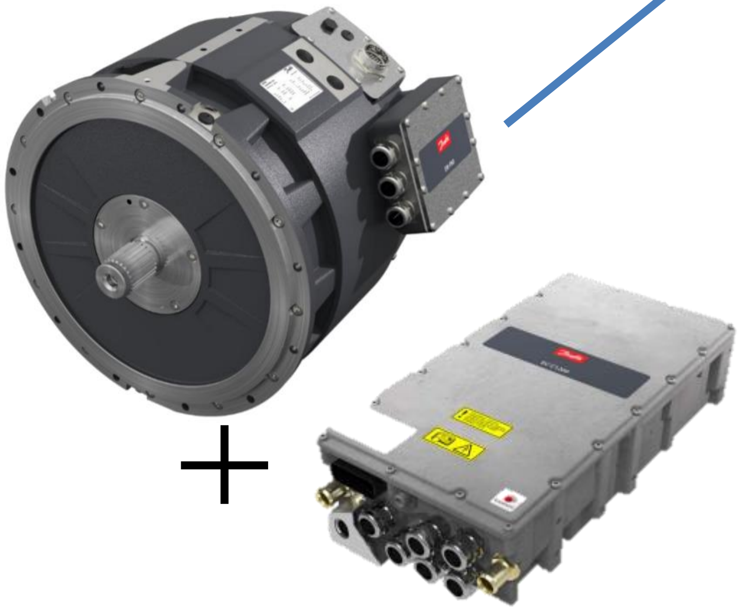
Effects of improved system efficiency

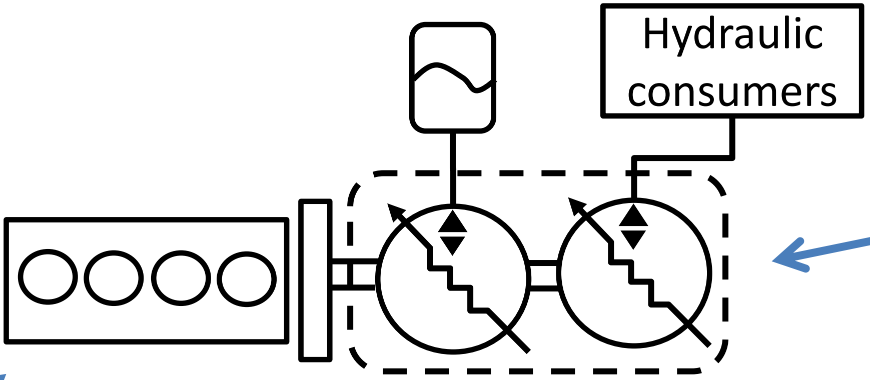
Reduced battery size => less cost
Reduced motor & inverter capacity => less cost
Reduced input energy => less cost
Reduced charging supply rating => less cost

Towards a universal solution for Diesel and Battery Electric

93kW diesel engine

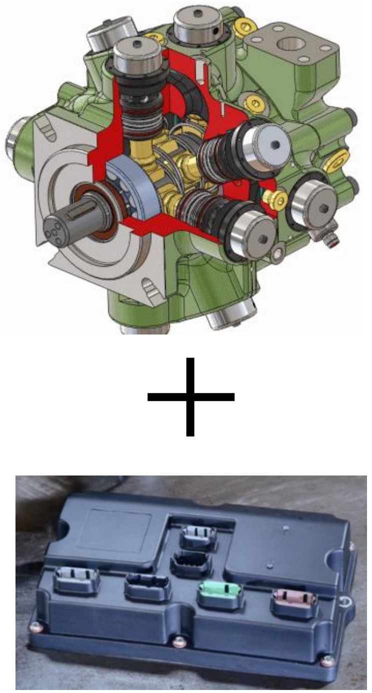
Danfoss Editron





Multi-service DDM

DD Pump/Motor



Diesel engine benefits:
Save fuel
Downsize engine
Improve productivity

Save $$$

Battery-electric benefits:
Reduce battery capacity
Reduce electric machine rating
Reduce charging requirements

Save $$$

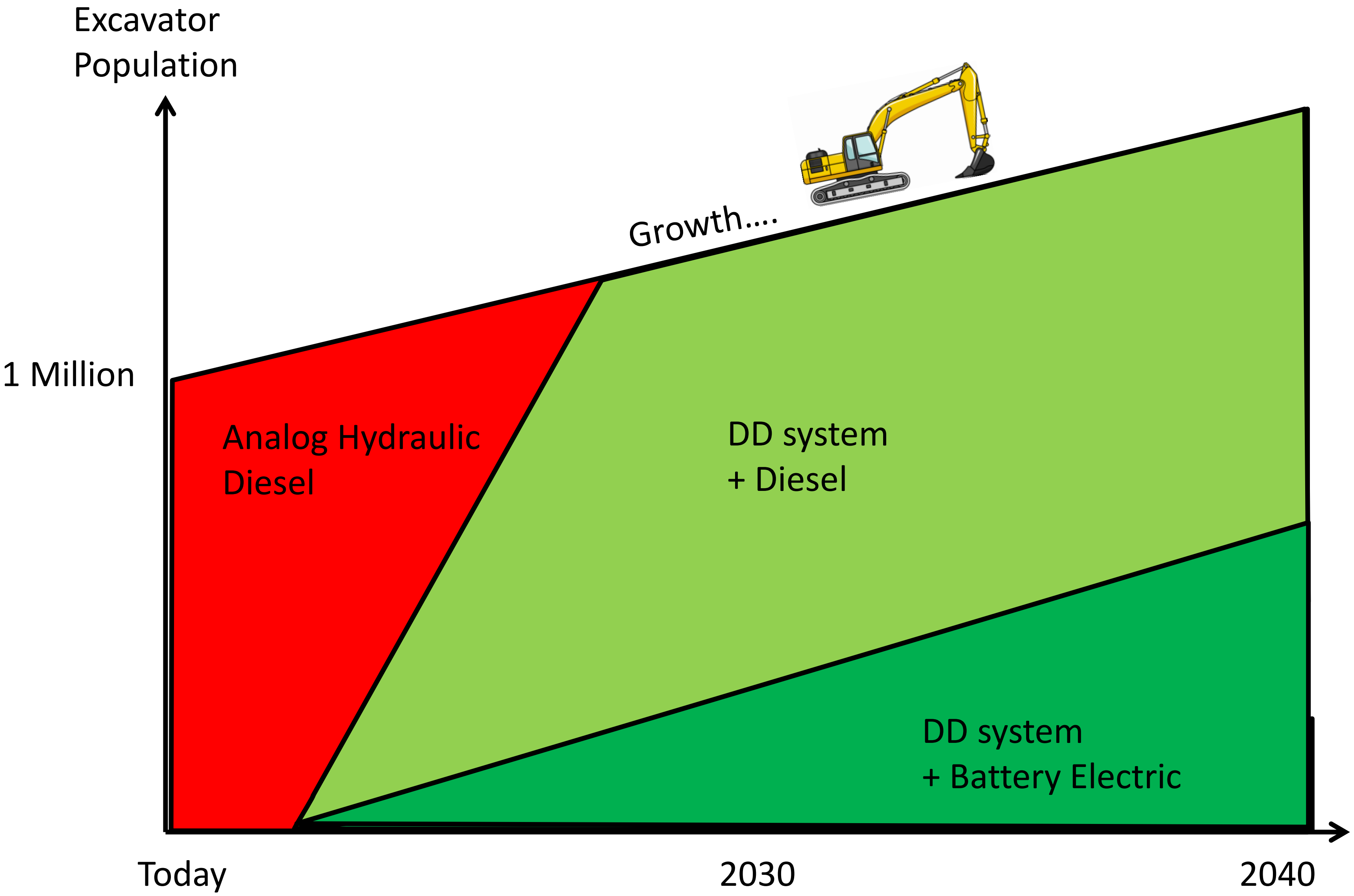
Alternative futures...

Analog Diesel continues to grow…
Battery Electric grows slowly from niche markets

OR

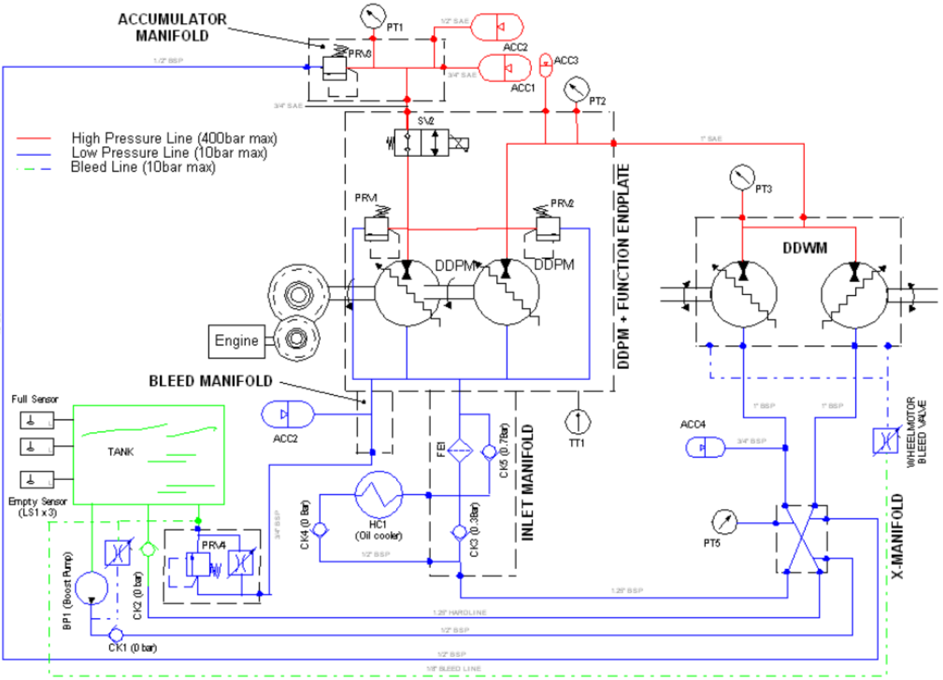
High efficiency systems grow: driven by positive business case based on fuel saving and productivity increase

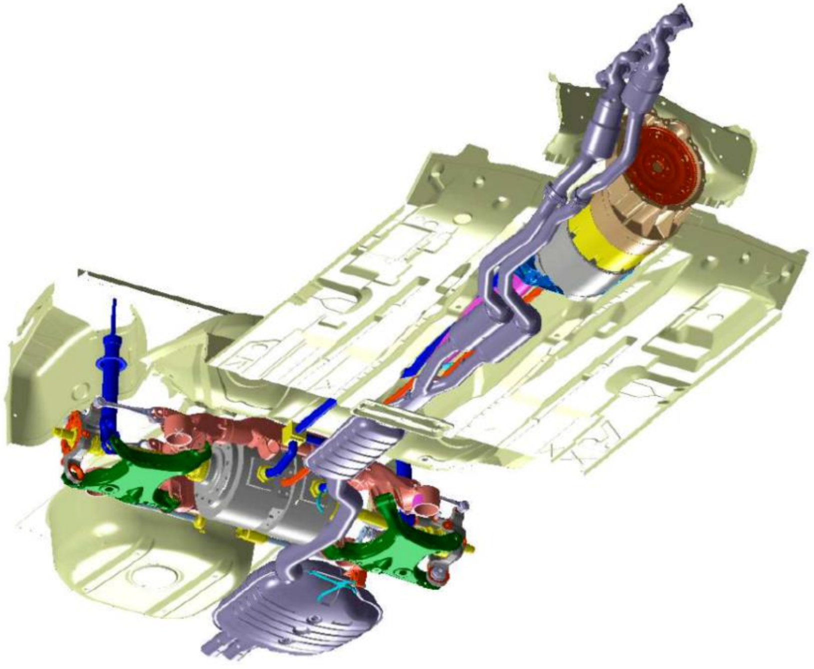
Battery-Electric becomes more favourable due to lower energy requirements and cost .
⇒ More commonality between Diesel and Battery variants
⇒ Faster market penetration of batteries

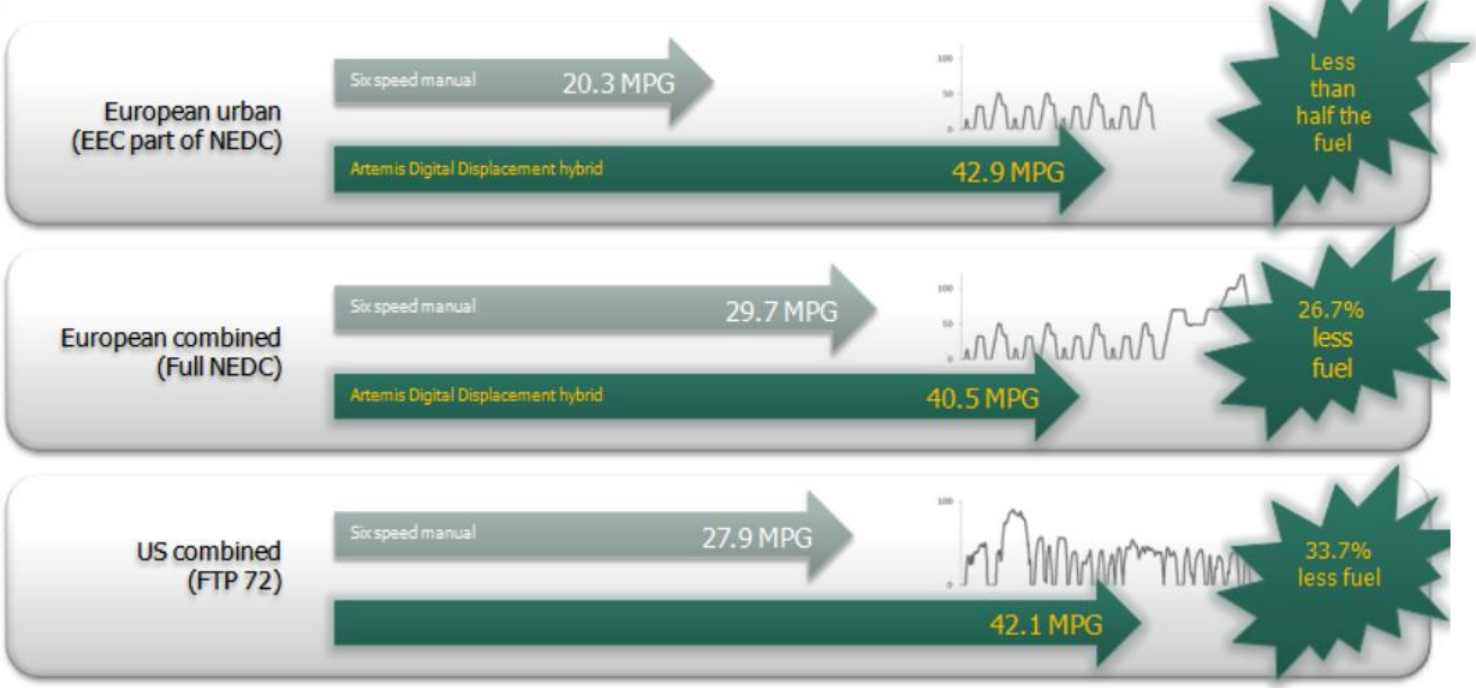


Maybe we have finally found a Green Solution… which is also a Business Solution!

On road vehicles







European urban (EEC part of NEDC)

Six speed manual 20.3 MPG

Artemis Digital Displacement hybrid 42.9 MPG

Less than half the fuel

European combined (Full NEDC)

Six speed manual 29.7 MPG

Artemis Digital Displacement hybrid 40.5 MPG

26.7% less fuel

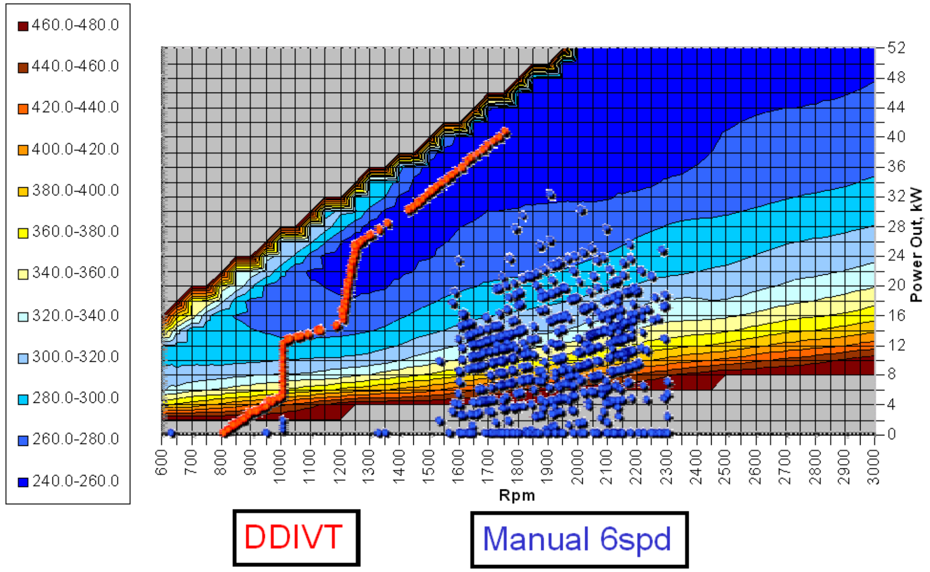
US combined (FTP 72)

Six speed manual 27.9 MPG

42.1 MPG

33.7% less fuel

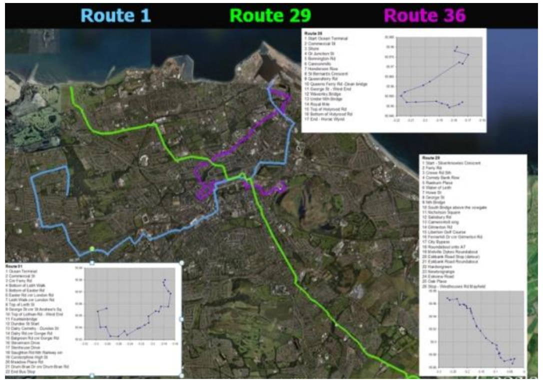
Scatter of operating points on NEDC

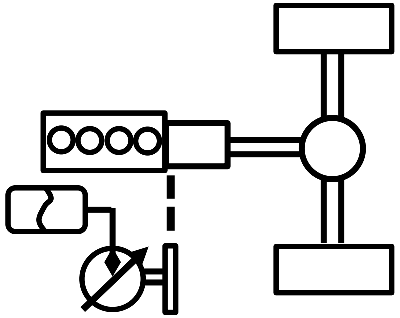


Torque Vectoring Demonstration

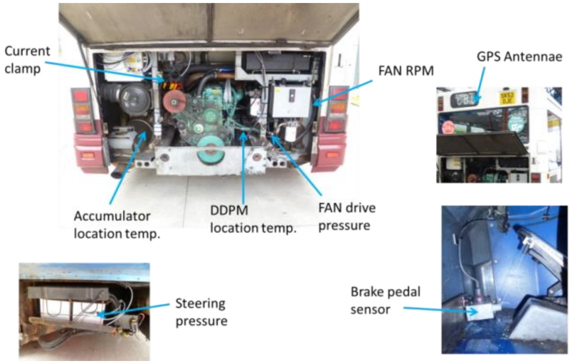
Parallel hybrid – on-road

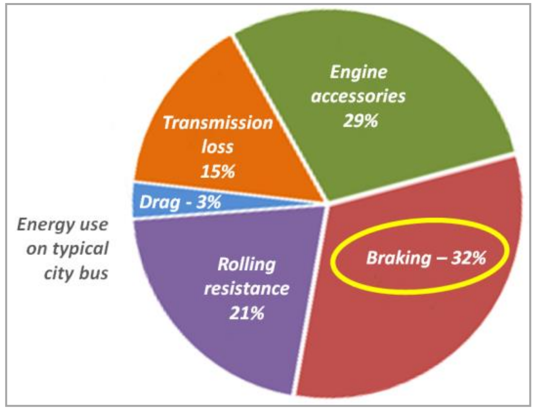
Supported by…
Innovate UK

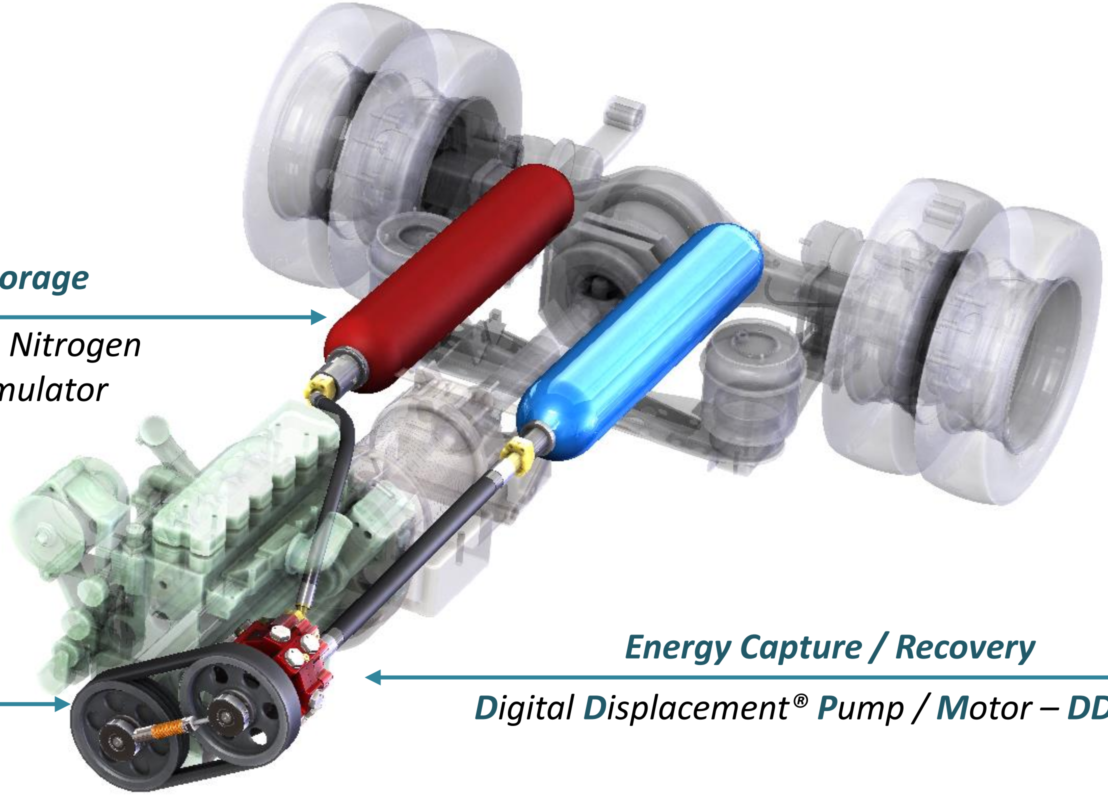




Proven 20-30% fuel saving







Energy Storage

High pressure Nitrogen filled accumulator

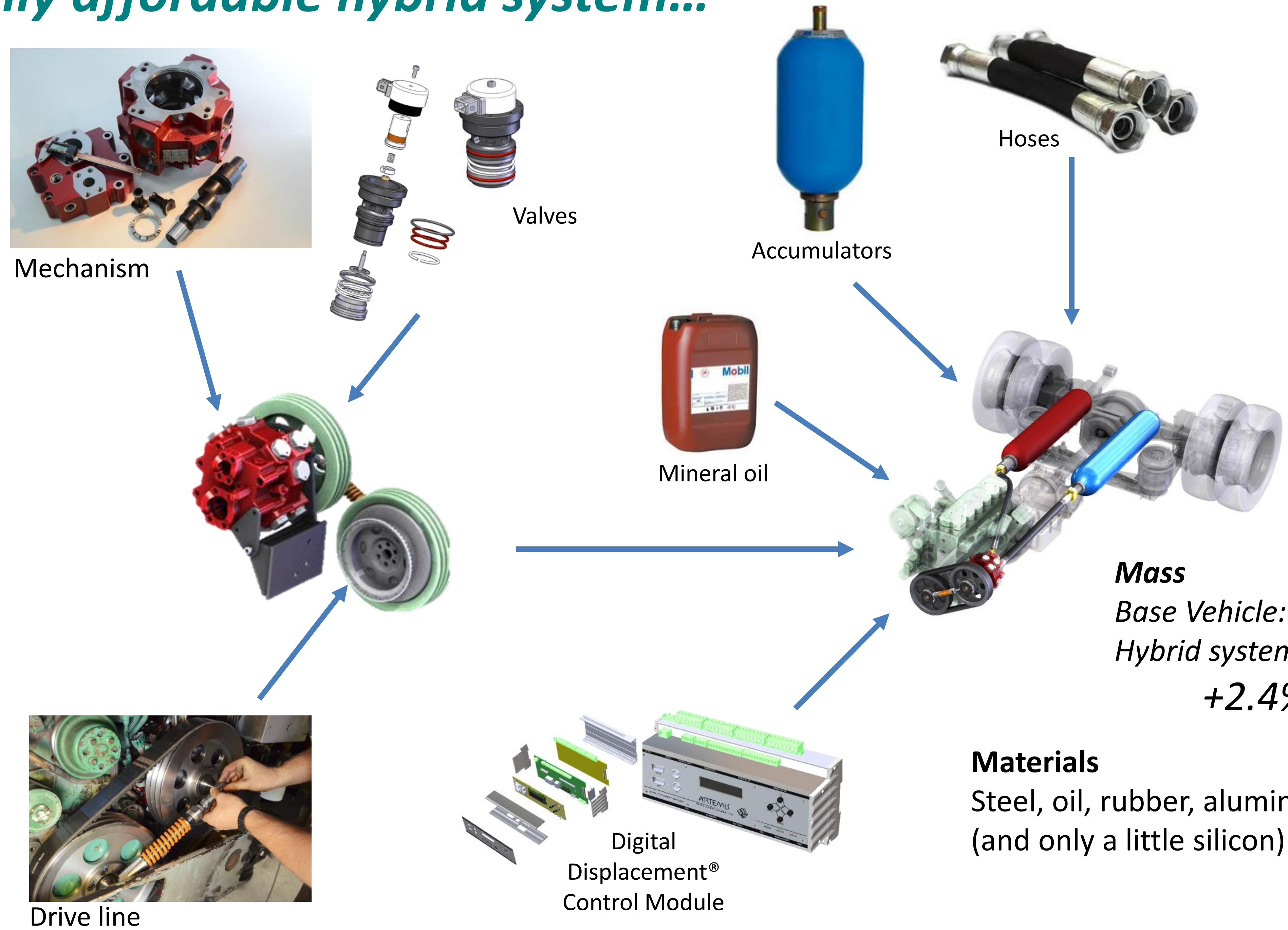
Drive line

High power, low cost belt drive.

Energy Capture / Recovery

*Digital Displacement® Pump / Motor – **DDPM®***

A globally affordable hybrid system…



Mechanism

Valves

Accumulators

Hoses

Mineral oil

Drive line

Digital Displacement® Control Module

Mass

Base Vehicle: 8140kg

Hybrid system: 200kg

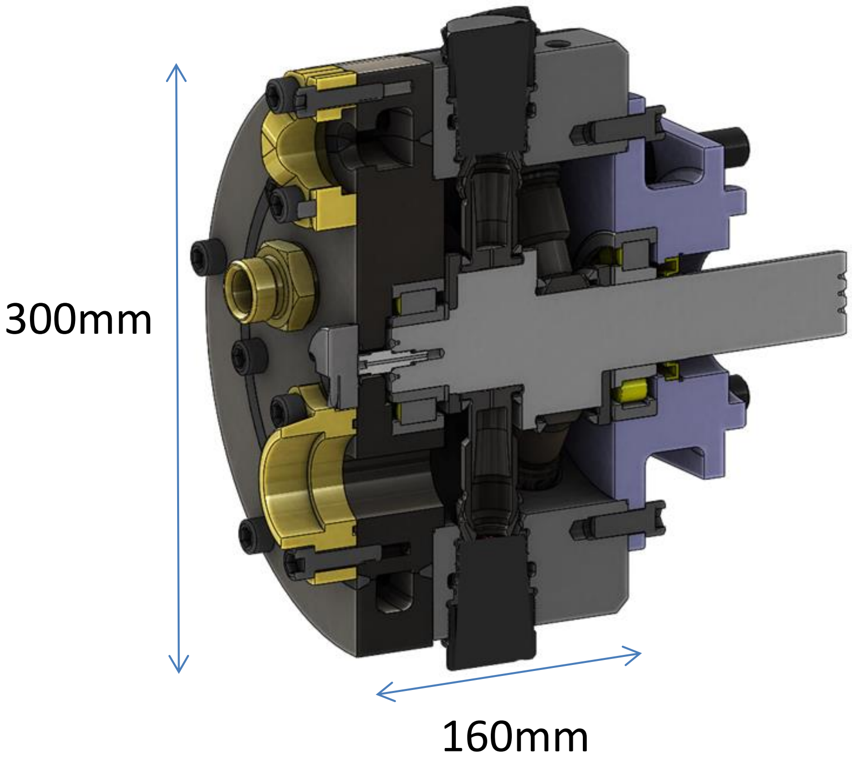
+2.4%

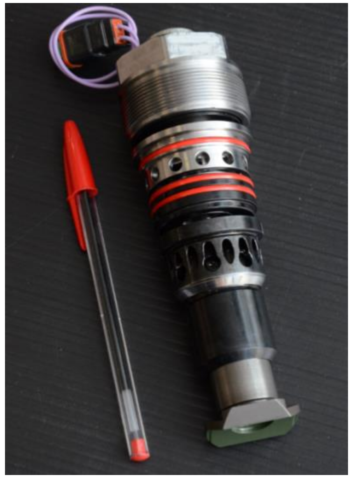
Materials

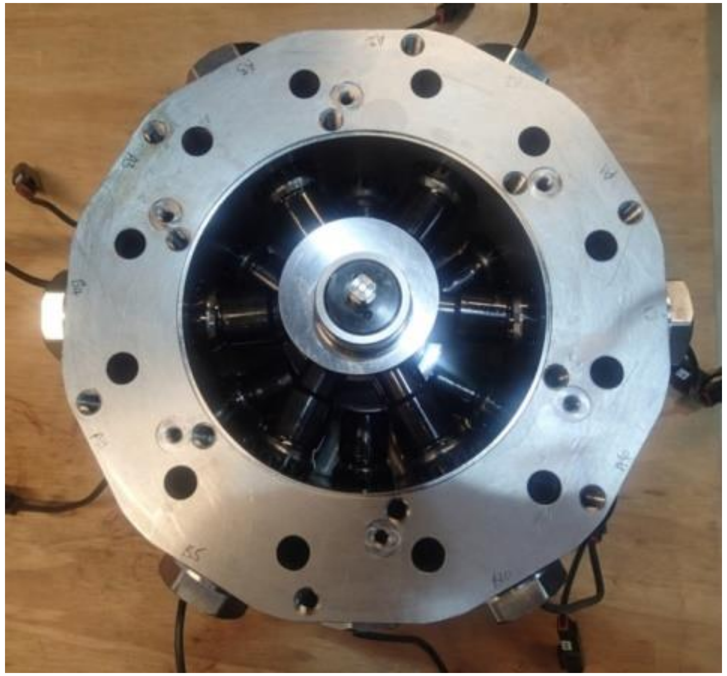
Steel, oil, rubber, aluminium….

(and only a little silicon)

The enabling machine: M96



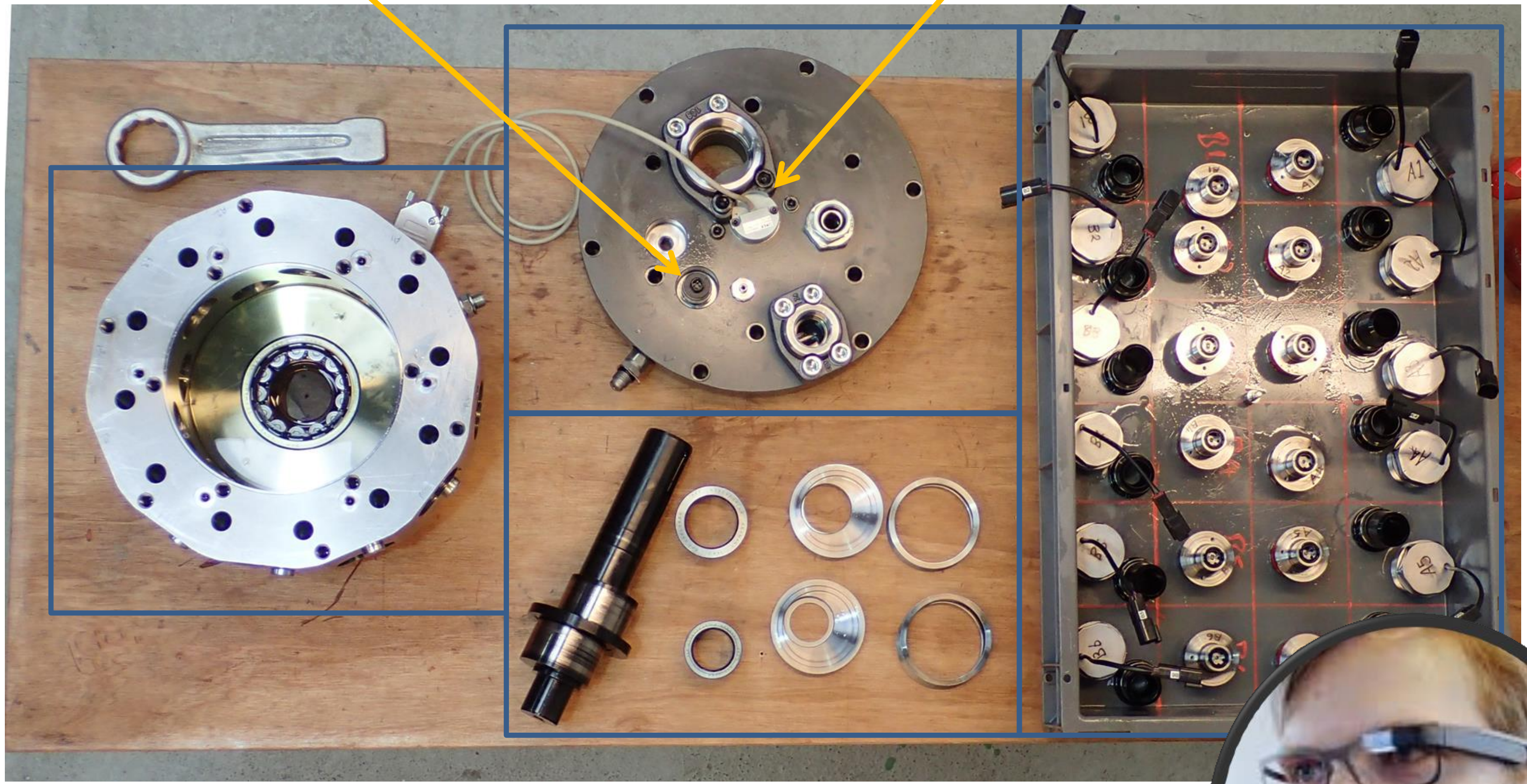




Continuous torque	500Nm @ 350 bar
Continuous power	125kW @ 2500rpm
Mass	45kg
Control interface	CAN bus
Response speed	12ms @2500rpm
Typical efficiency	95%

M96 DDM assembly

- Simple design
- Low cost materials
- Standard production processes



Pressure Transducer

Manifold endplate with ring gallery

Shaft Encoder

Valves & Cylinders

Machine Ring & drive side endplate

Crankshaft & Piston retention

Electronic controller

No nano-materials?
No graphene?
It's not very futuristic, is it?

Research Horizons

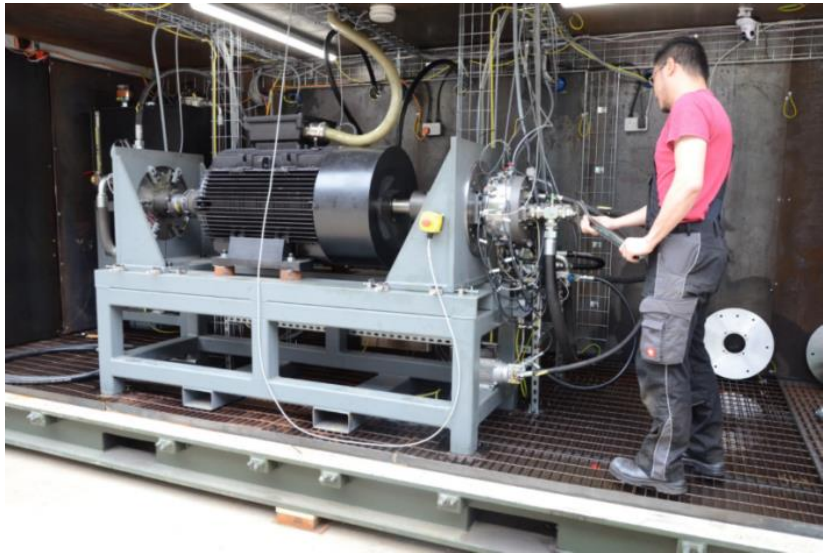
ADVANCED PROPULSION CENTRE

DDISPLACE

Digital **D**isplacement **I**ntelligent **S**ystem and **P**ump for **L**ifting **A**nd **C**onstruction **E**quipment

£11M from UK government


Vehicle applications

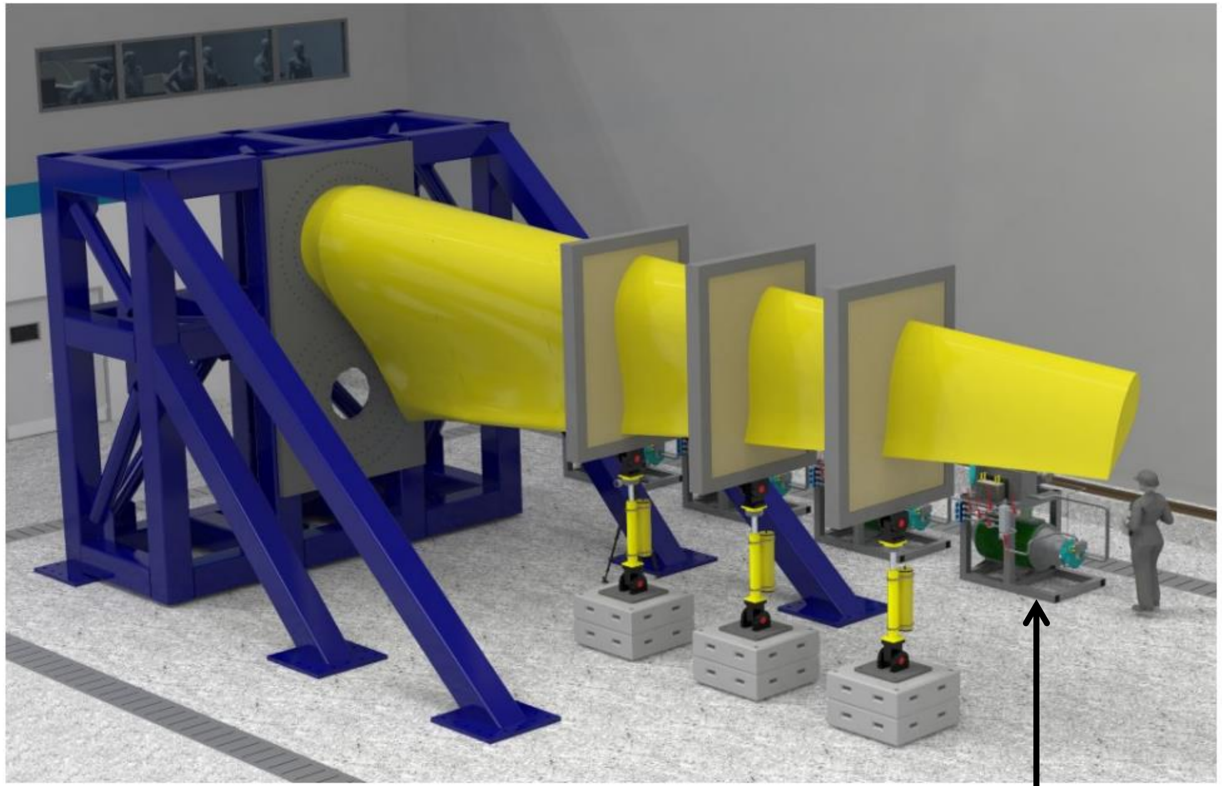

Durability Testing


Work function R&D rig

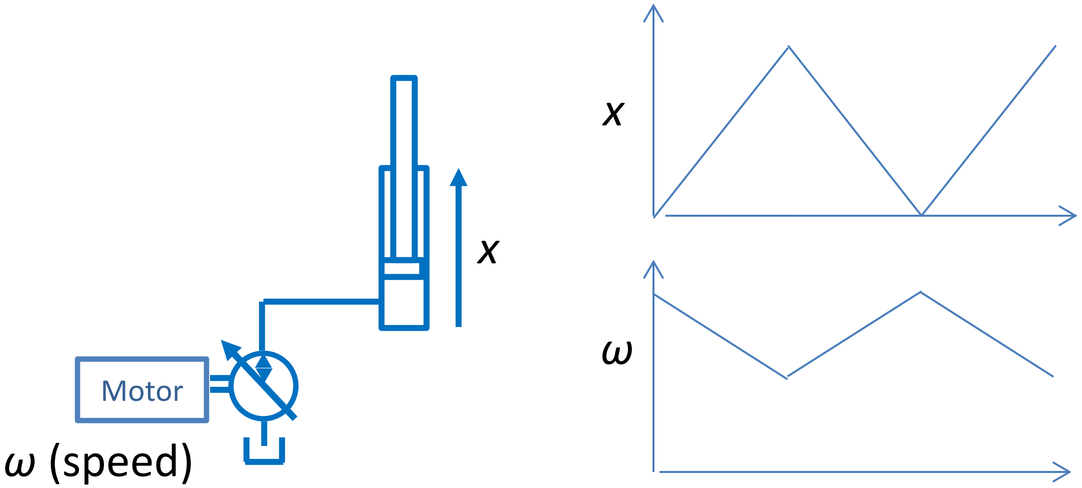

Next generation DDPM development

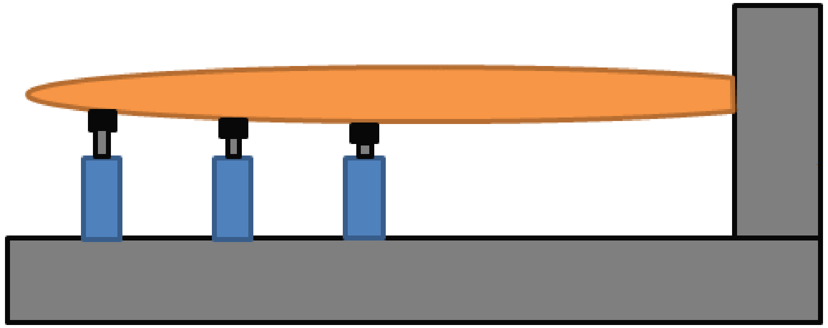

Electronics & Software

Regenerative fatigue test rig



The FASTBLADE facility https://www.fastblade.eng.ed.ac.uk



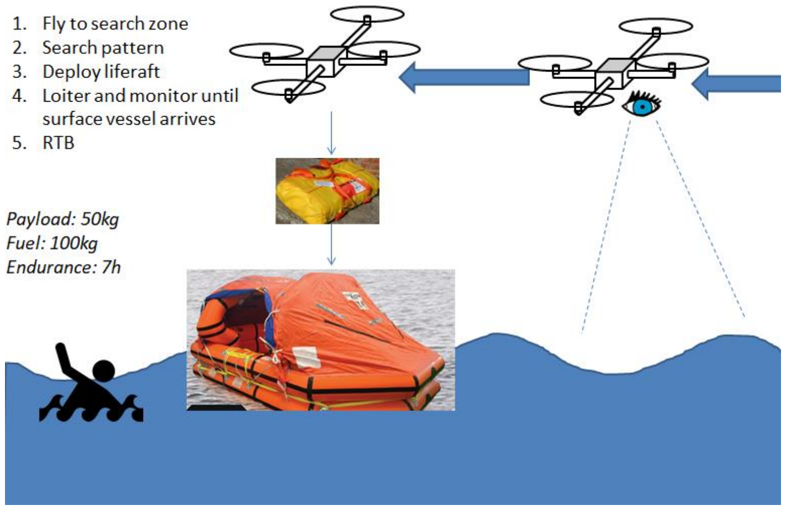


Regenerative fatigue testing facility for tidal turbine blades

- Pump-controlled motion with flywheel energy storage
- Valve losses are eliminated
- Regenerates strain energy (80% round-trip efficiency)
- Less than a quarter of the electrical consumption of servo-valve control
- First commercial system application of M96

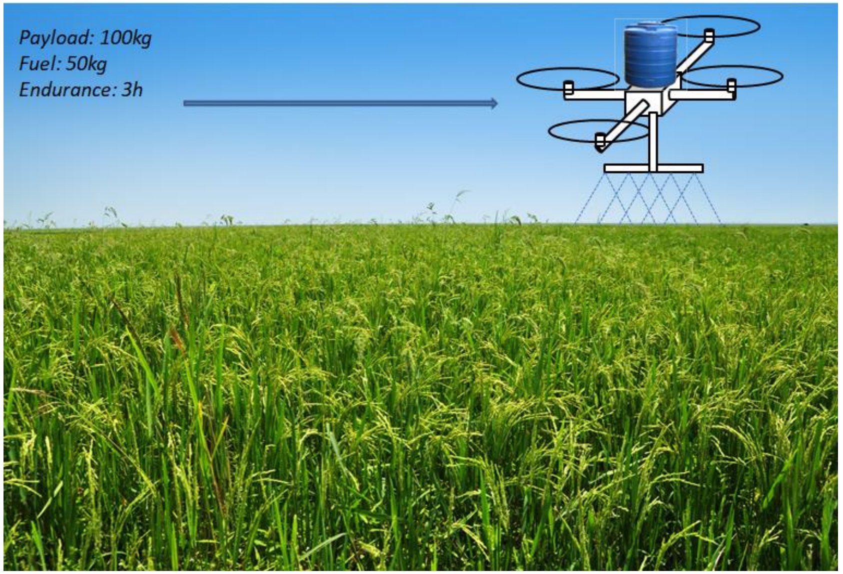
How can DD make drones better?

- **Search and Rescue**
- **Logistics**
- **Marine logistics**
- **Inspection/surveying**
- **Crop spraying/Agriculture**
- **Forestry**
- **..**



1. Fly to search zone
2. Search pattern
3. Deploy liferaft
4. Loiter and monitor until surface vessel arrives
5. RTB

Payload: 50kg
Fuel: 100kg
Endurance: 7h



Payload: 100kg
Fuel: 50kg
Endurance: 3h

Payload: 25kg
Fuel: 125kg
Endurance: 9h

1. Fly to Turbine 1
2. Execute inspection cycle
3. Fly to Turbine 2
4. Execute inspection cycle
5. ....
30. RTB

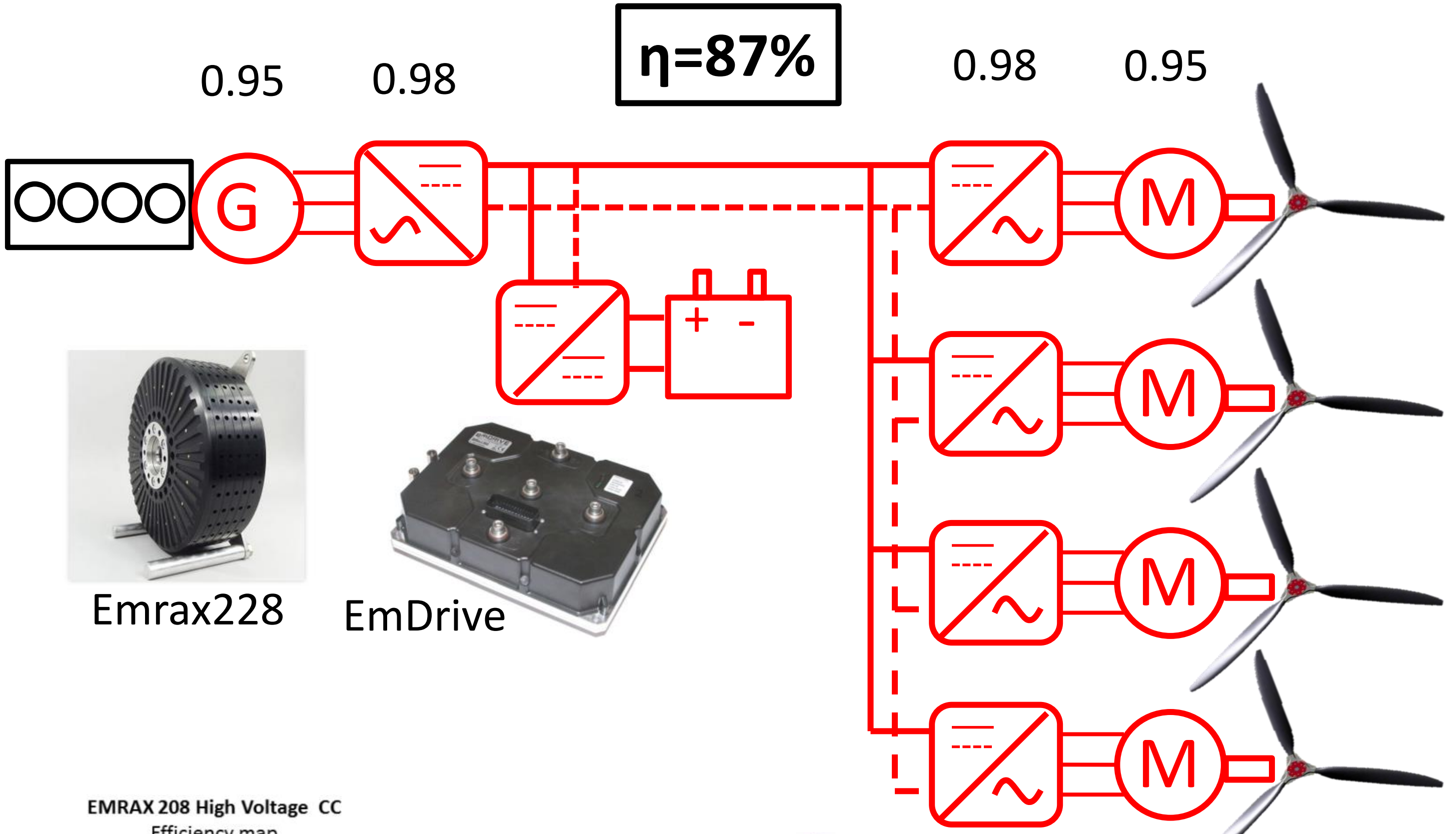
WANTS

- More range & payload
  - Batteries not included!
- No people – less liability – less weight
- Low cost
- All weather
- Easy maintenance in the field – no high voltages
- Take-off and land anywhere
- Continuous hover and positioning – like today’s multirotor – not a transitioning eVTOL with limited hover time
- => Continuous power required
- Significant payload 50kg: FLIR gimbal, life-raft
- Fill from a jerry can in 5 minutes. No mains (or diesel genset) required!
- Fuel = fossil, bio or e-fuel

Replace helicopters…
⇒ Burn 1/10 fuel
⇒ 1/10 operating cost
⇒ Reduce risk to humans

Hybrid electric transmission?

Fuel



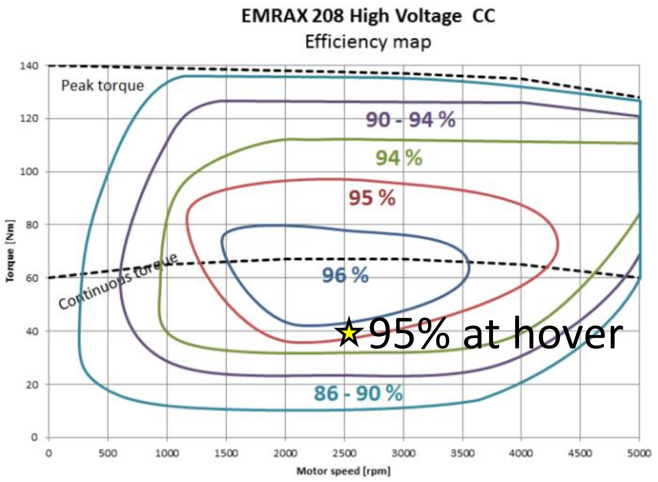
Efficiency
87% - seems OK

Controllability
Zero hysteresis
Perfect linearity
Zero deadband
Fast reponse
…perfect!

Battery
If continuous hover is required, what is it for? The optimum size is ZERO

Isn't this just a continuously variable transmission?

?



EmDrive

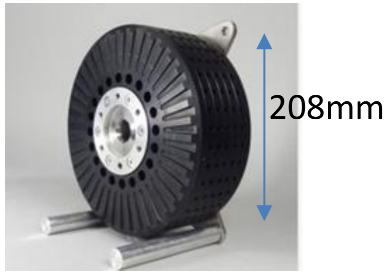
Emrax208

Could we do it with hydraulics?

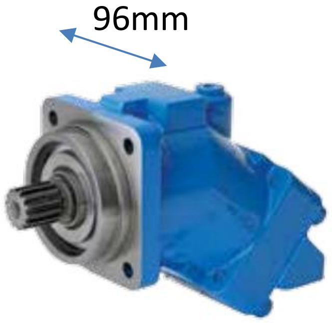
Motors compared

(Liquid cooled)

+



vs

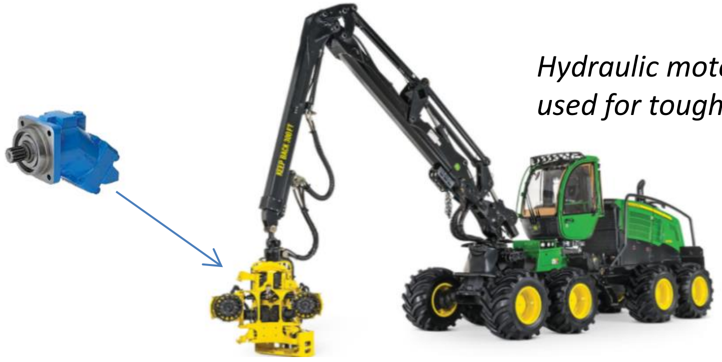


	Electric			Hydraulic	
	Emrax 188	Emrax 208	Emrax 228	Hydroleduc M12	Hydroleduc M18
Type	Axial Flux Motor	Axial Flux Motor	Axial Flux Motor	Bent Axis Motor	Bent Axis Motor
Power Continuous kW	30	32	42	61	92
Max RPM	7000	6000	5500	8000	8000
Motor mass	7kg	9.4kg	12.3kg	5.5kg	5.5kg
Torque Continuous Nm	50	80	125	73	110
Controller mass	5kg	5kg	5kg	None	None
Total Mass inc controller	12 kg	14.4kg	17.3 kg	5.5kg	5.5kg
Efficiency inc controller	93-94%	93-94%	93-94%	93-94%	93-94%
Nm/kg	4.2 Nm/kg	5.6Nm/kg	7.2 Nm/kg	13.3 Nm/kg	20Nm/kg
kW/kg Continuous	2.5kW/kg	2.2 kW/kg	2.4 kW/kg	11 kW/kg	16.7 kW/kg
Cost + controller	€2,190 + €1800	€2,390 + €1,800	€2,490 + €1800	<€1000	<€1000

Includes controller

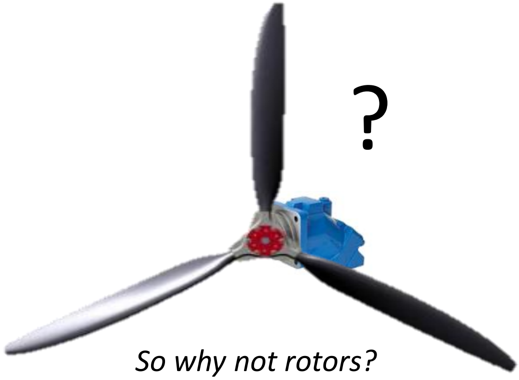
Hydraulic motors are…

- Lighter
  - X2-3 Torque to weight ratio
- Continuous rating
- More compact
- Waterpoof
- Much lower cost
- Just as efficient
- Much more robust



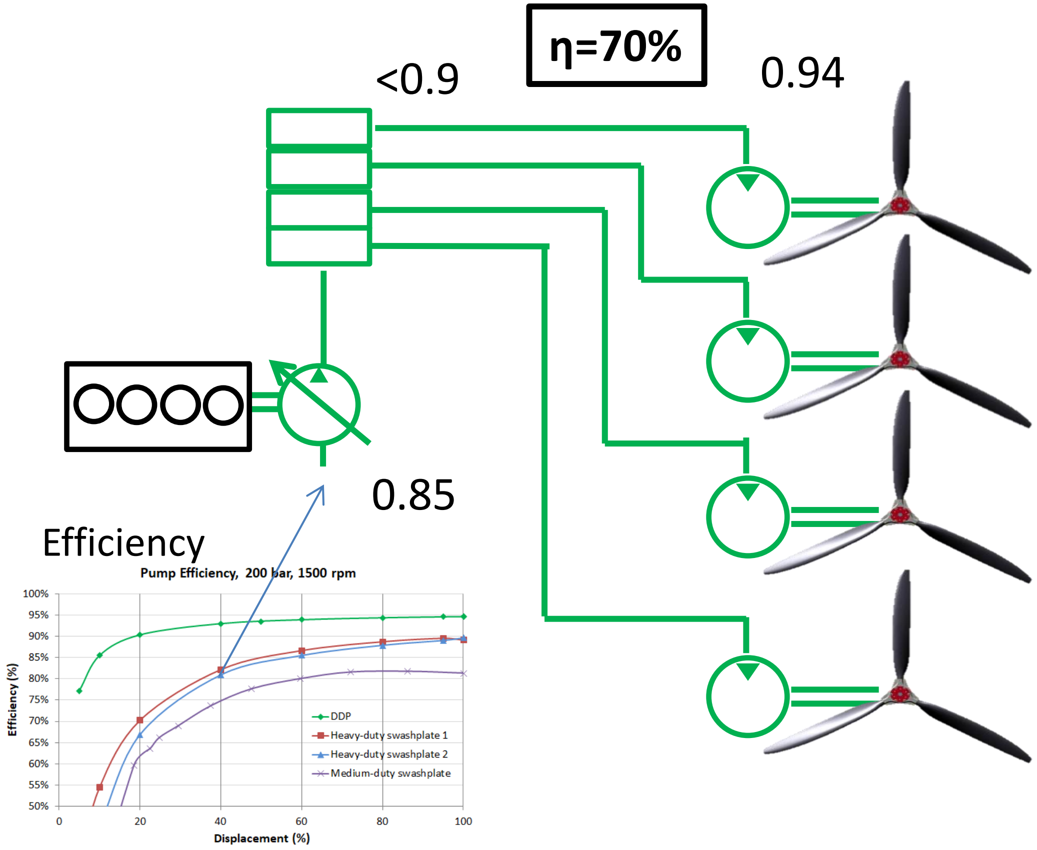
Hydraulic motors are used for tough jobs…

Hydraulic motors are often used to drive fans



So why not rotors?

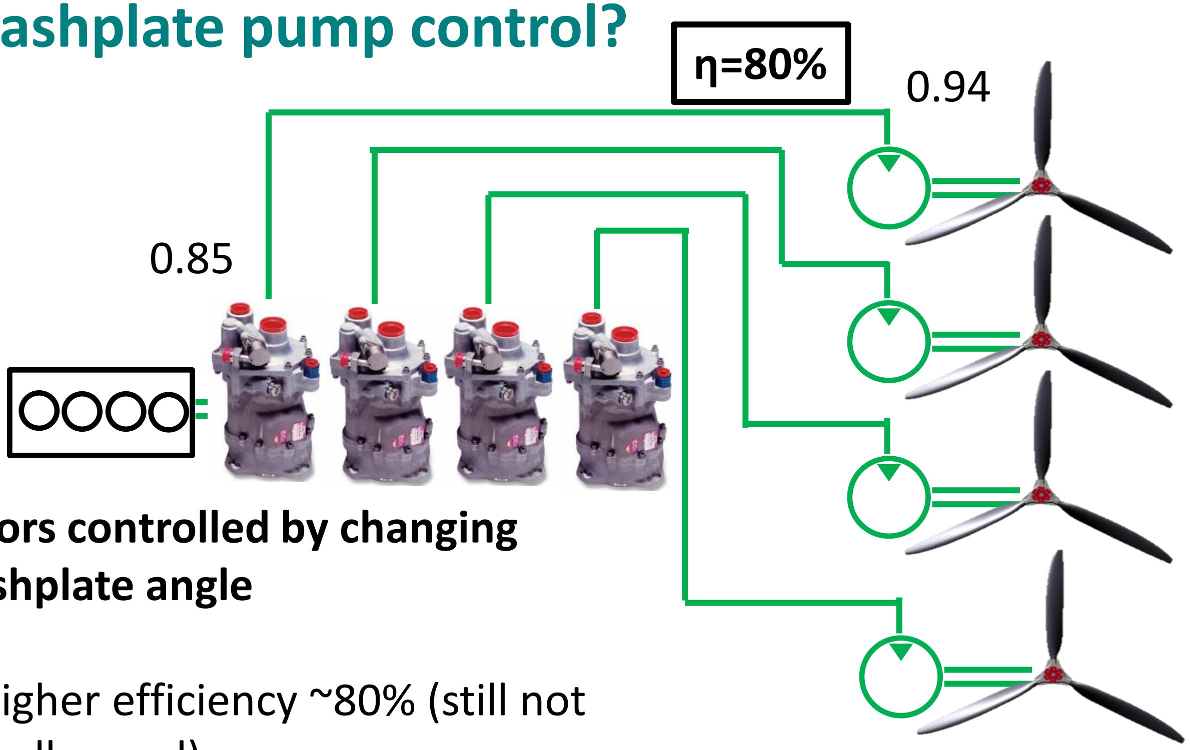
Proportional valve control?



Motors controlled by proportional valves

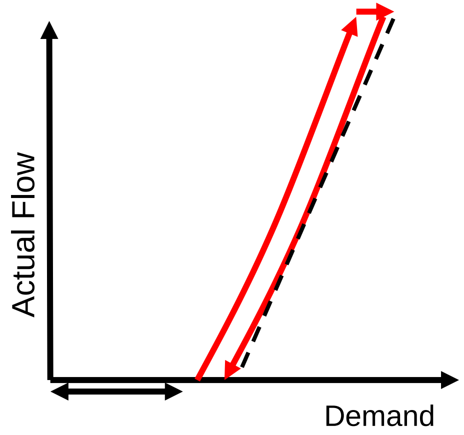
⇒ Large pressure drop in valves = energy loss
⇒ Pump works at part load
⇒ Result: <70% efficiency … unacceptable!

Swashplate pump control?



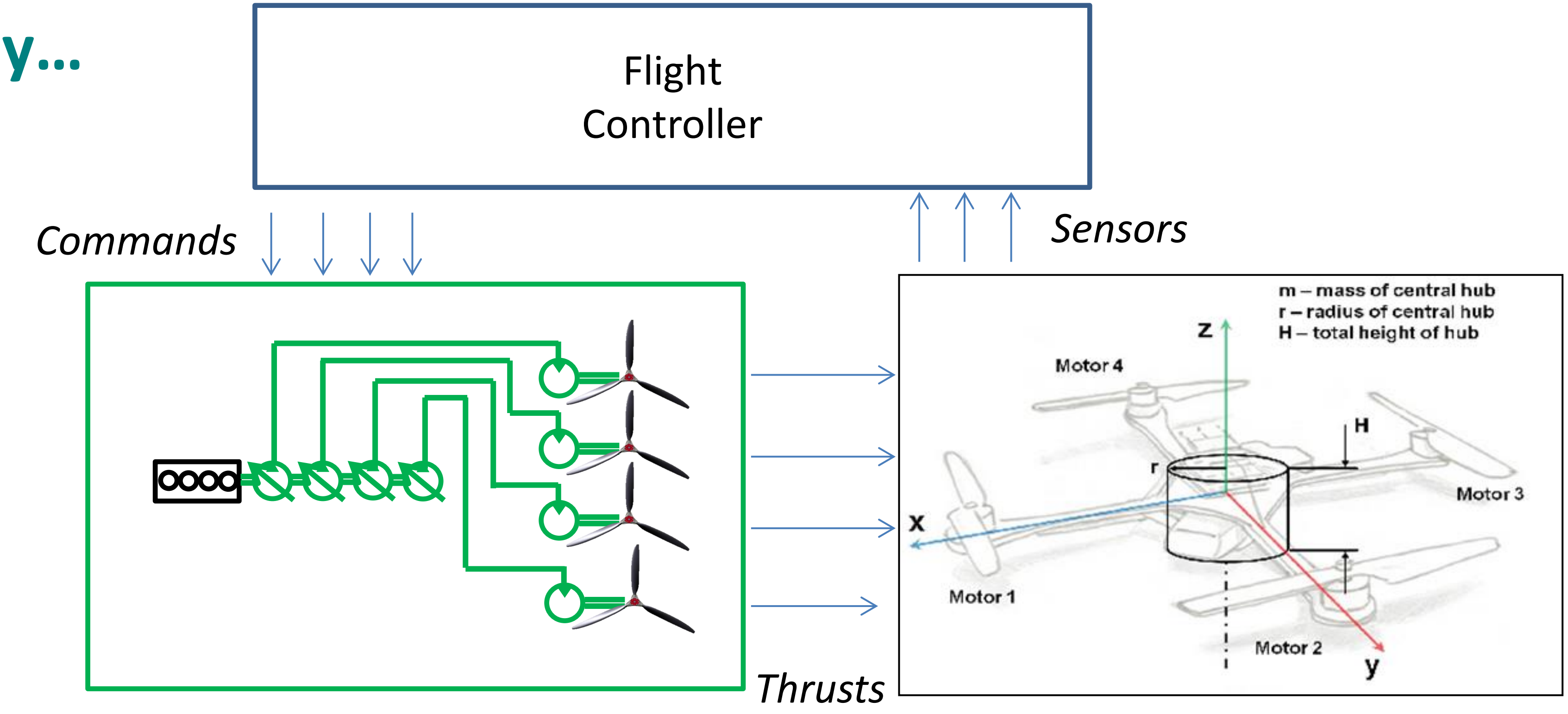
Motors controlled by changing swashplate angle

- Higher efficiency ~80% (still not really good)
- Need 4 separate pumps & splitter gearbox!
- Is control from swashplate actuator good enough?
    - delay
    - hysteresis
    - non-linearity
    - deadband



Effect of poor controllability…

Simulation of quadcopter rigid body dynamics, coupled to hydraulic circuit dynamics, in Matlab Simulink

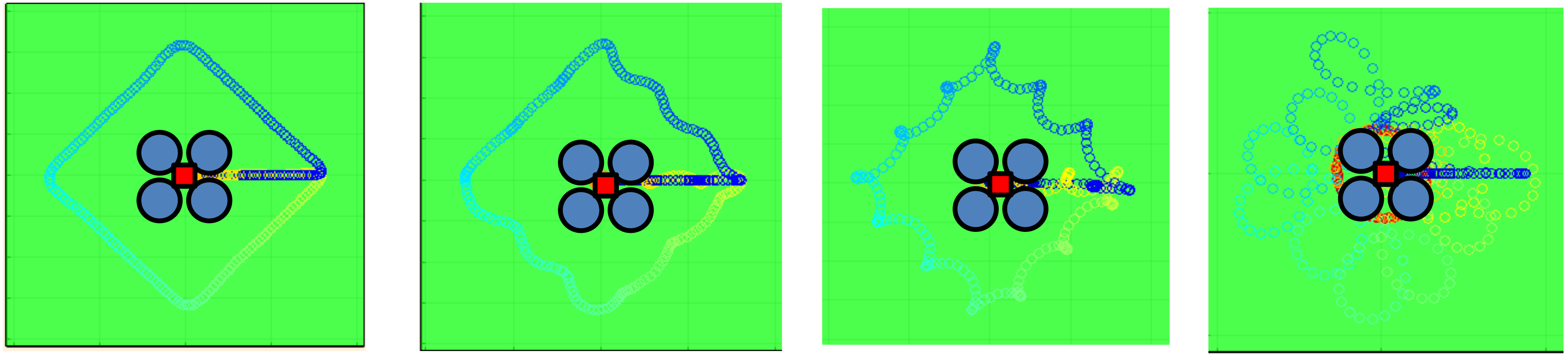


Flight Controller

Commands

Sensors

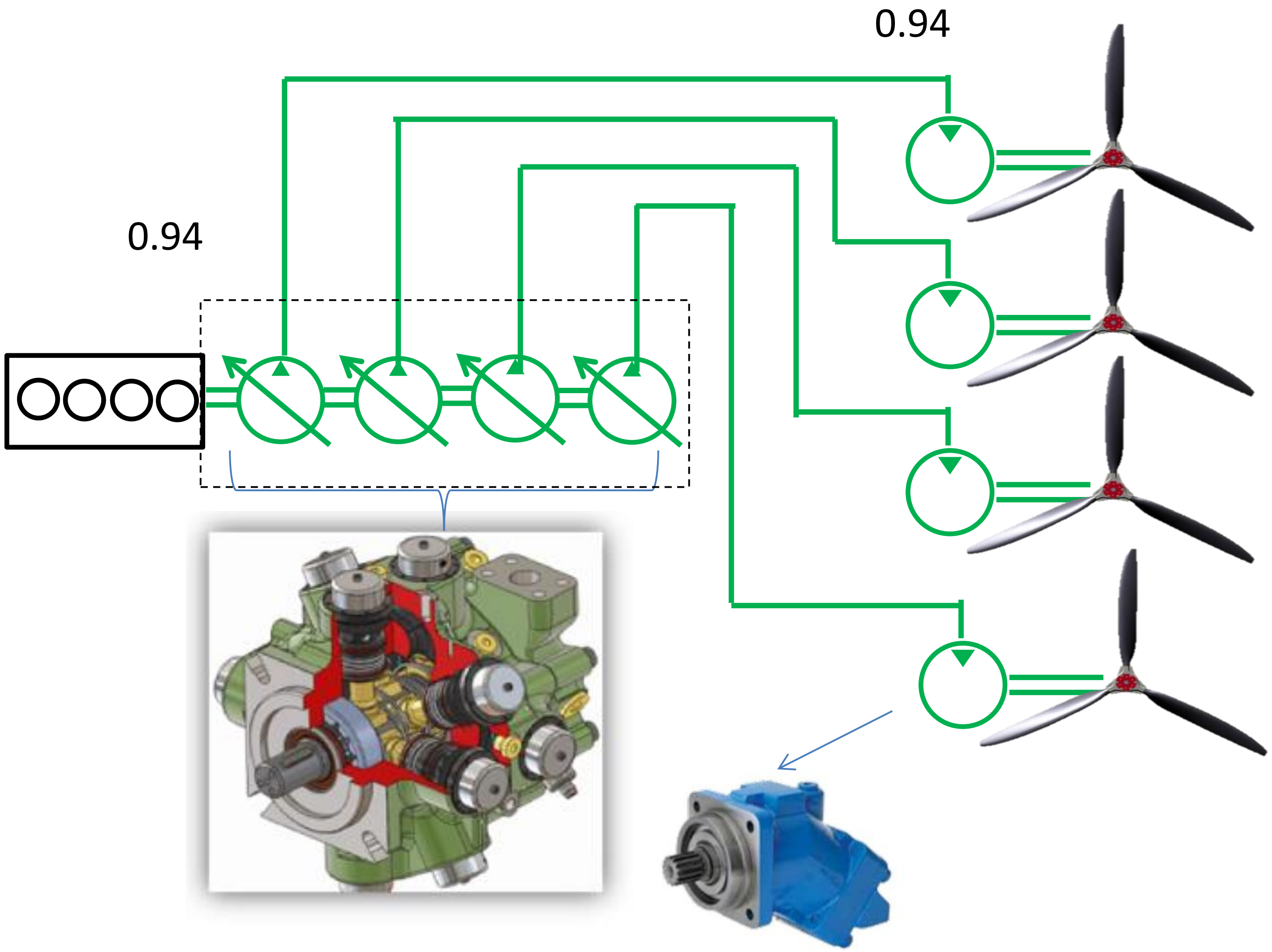
Thrusts



Hysteresis: 0% 0.1% 0.25% 1%

=> *We need very high precision!*

DDP multirotor



Lighter components
=> More payload

One machine, four outputs
=> No splitter gearbox

Efficiency = 88%
=> As good as electric

Controllability is no problem

- Hysteresis = 0%
- Non-linearity = 0%
- Dead-band = 0%
- Response speed = 20ms
- CANbus interface

Let’s try it!

Small-scale demonstration showed good hover control

Video of full-size rotor test rig (1.5m diameter) – capable of 100kg thrust

Final thoughts

Climate change is an existential challenge

Fluid power is part of the solution…
… not part of the problem.

We need to work together to find “green solutions” that are also “business solutions”

Let’s start with a coffee…

Or maybe a red wine?

Thank you!