Transport Energy Network

What does the future hold for thermal propulsion systems and fuels?

Philippa Oldham, Gloria Esposito, Penny Atkins

25 April 2019

ADVANCED PROPULSION CENTRE UK | FUNDING. EXPERTISE. COLLABORATION.

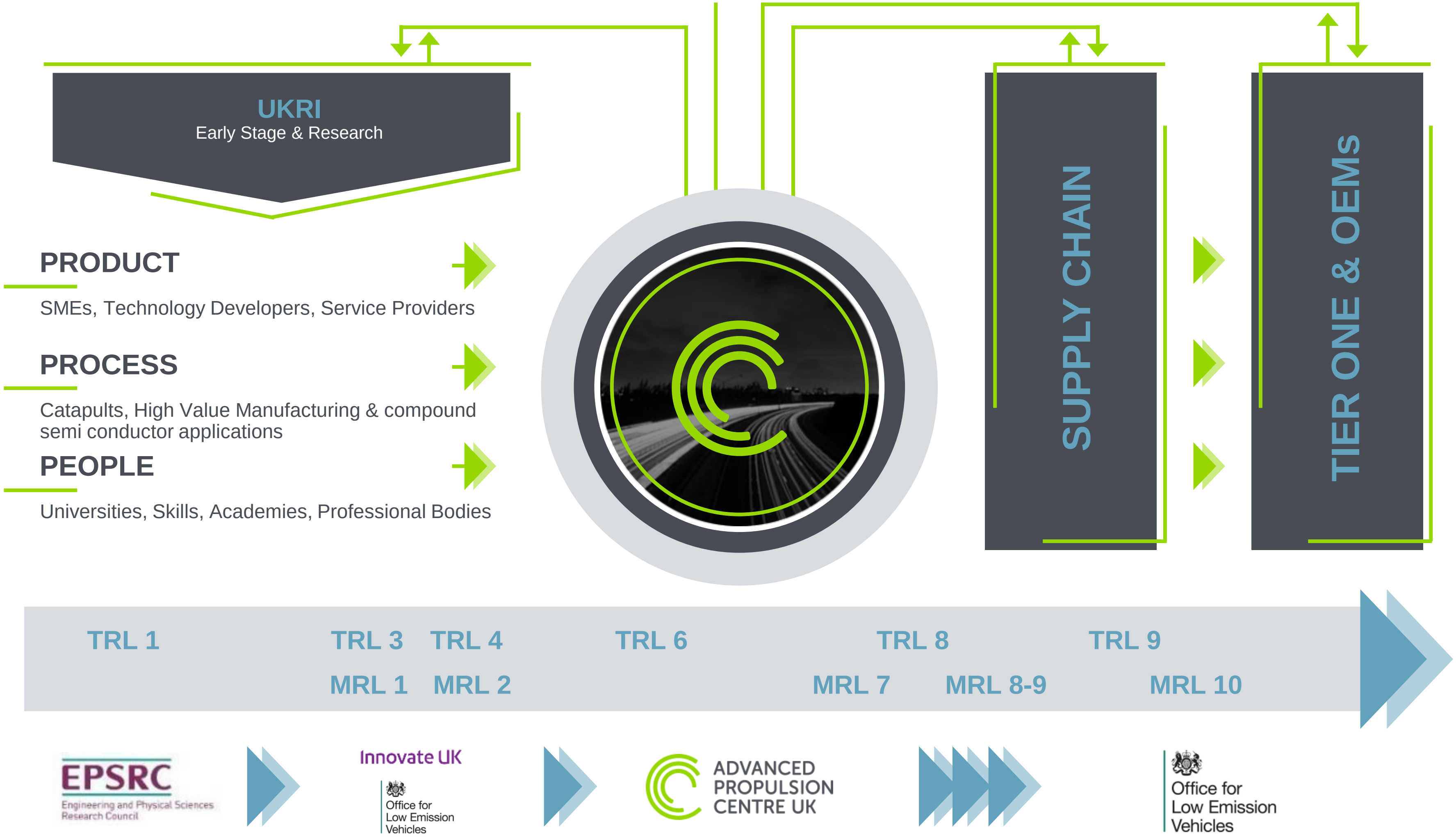
LowCVP Low Carbon Vehicle Partnership | Connect Collaborate Influence

University of Brighton | Advanced Engineering Centre

Workshop agenda

- 10.00 - 10.15 Arrival & breakfast
- 10.15 - 10.25 Introduction
- 10.25 - 10.45 Future transport overview (Neville Jackson, Ricardo)
- 10.45 - 11.05 Transport in the future energy system (Matthew Joss, ETI)
- 11.05 - 11.25 Biofuels of the future (Patricia Thornley, Aston University)
- 11.25 - 11.30 Break
- 11.30 - 11.50 Synthetic fuels (Ausilio Bauen, E4tech)
- 11.50 - 12.10 Engine evolution in the medium term (Adrian Cooper, Mahle)
- 12.10 - 12.30 The long term future for engine technology (Andrew Smallbone, Newcastle University)
- 12.30 - 12.45 Q&A
- 12.45 - 13.15 Lunch
- 13.15 - 14.45 Workshop sessions
- 14.45 - 15.00 Wrap up and close

FUNDING LANDSCAPE - WHERE THE APC FITS IN



ADVANCED PROPULSION CENTRE
THE JOURNEY SO FAR…

£770M
INVESTMENT

44
PROJECTS

154
ORGANISATIONS

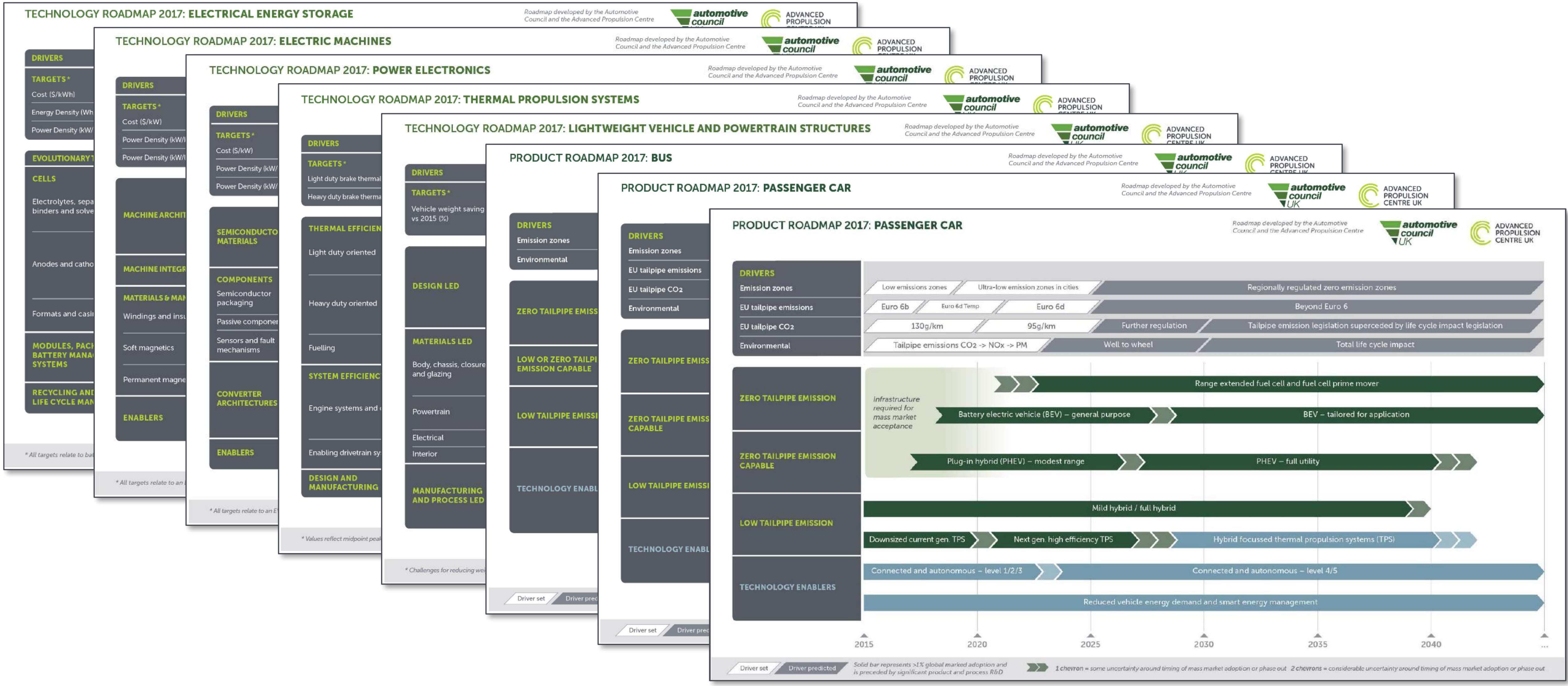
ADVANCED PROPULSION CENTRE
THE JOURNEY SO FAR…

25,596
JOBS

42.7m
TONNES OF CO_2 SAVED

2.4m
CARS OFF THE ROAD

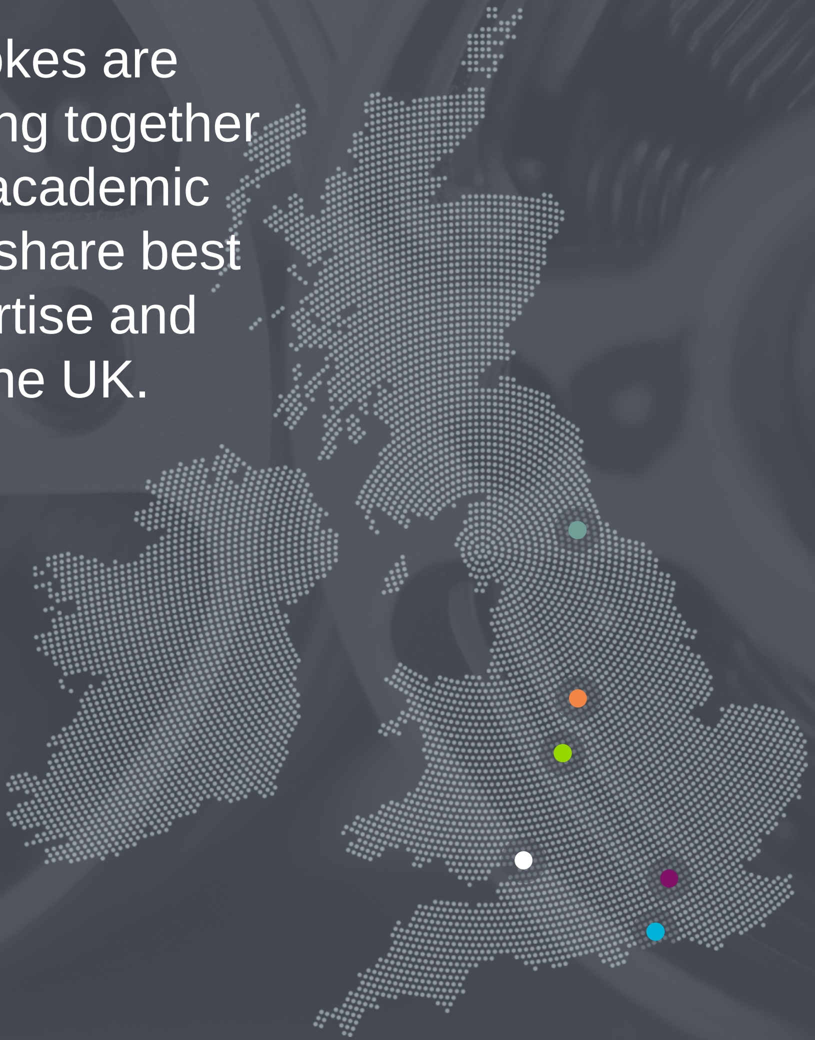
TECHNOLOGY & PRODUCT ROADMAPS



ADVANCED PROPULSION CENTRE UK

DEVELOPING AND LINKING **INDUSTRIAL AND ACADEMIC COMMUNITIES**

The APC Spokes are networks that bring together industrial and academic communities to share best practice, expertise and facilities in the UK.

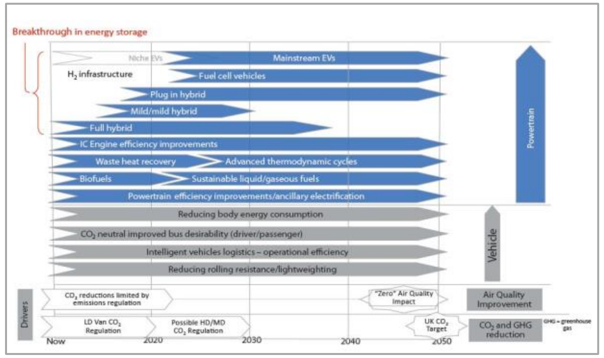


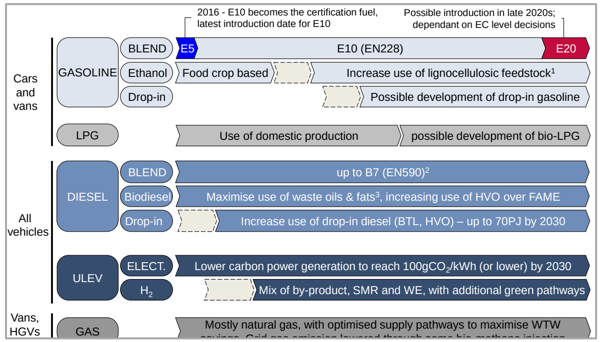
- ELECTRIC MACHINES SPOKE
  Newcastle University
- POWER ELECTRONICS SPOKE
  University of Nottingham
- ELECTRICAL ENERGY STORAGE SPOKE
  University of Warwick
- TPS SYSTEM EFFICIENCY
  University of Bath
- DIGITAL ENGINEERING AND TEST SPOKE
  Loughborough University (London)
- TPS THERMAL EFFICIENCY
  University of Brighton

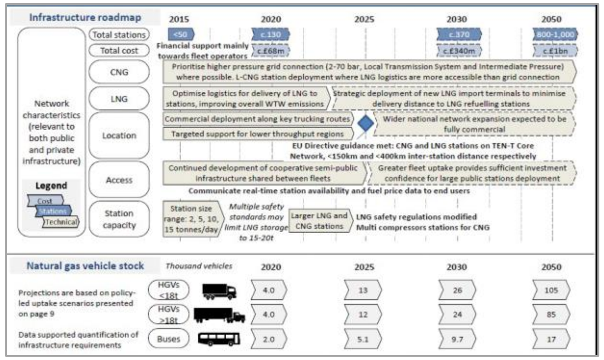
ADVANCED PROPULSION CENTRE UK

LowCVP's mission is to accelerate a sustainable shift to low carbon, clean vehicles and fuels, whilst creating opportunities for UK businesses

- 200 members across the automotive, fuels and energy sectors – bring different stakeholder together.
- Work streams - passenger cars, commercial vehicles, buses, fuels, electricity and innovation.
- Led the creation of vehicle, infrastructure and fuels roadmaps for the UK.
- Transport Energy Network sits in our Fuels Working Group – critically important for advancing future low carbon fuels and strengthening UK supply chains. Aligning vehicle and fuels roadmaps.







LowCVP
Low Carbon Vehicle Partnership
Connect
Collaborate
Influence

The Transport Energy Network aims to accelerate decarbonisation through targeted collaboration between fuels, powertrain and energy systems communities

- **Objectives**
  - Understand long term R&D priorities for low carbon fuels and clean efficient thermal powertrains
  - Enhance collaboration between fuel and thermal powertrain developers
  - Develop links to energy systems work and R&D community

- **Scope**
  - Timescale: Now to 2050, Transport Modes: on road, off highway, marine, rail (consider synergies with aero)
  - Liquid and gaseous fuels
  - UK focus, but recognising global supply chain

- **Work programme 2019/20**
  - Four workshops (April, June (x2), November)
  - Deliverable report – cross discipline roadmaps

Transport Energy Network work programme

2019/20 work programme

Workshop 1	Today – Background for roadmaps
Workshops 2 & 3	June 19 – Roadmap detail
Workshop 4	November 19 – Stakeholder review
Report	March 20 – Roadmap publication and dissemination

2020/21 work programme

Assess R&D priorities based on roadmaps
Dissemination
Feasibility studies (funding dependent)

Workshop sessions this afternoon will pose three questions to gather background for the roadmaps

1. **Landscape** - Barriers and enablers for low carbon fuel/powertrain development (short, medium and long term, legislative, organisational, supply chain...), links to wider energy system *Neville, Gloria, Matt*

2. **Collaboration** - where is collaboration needed (technology areas, organisations) what projects/collaborations are currently underway/planned, what could it achieve, who should be involved in the process *Penny, Philippa*

3. **Technology** - Scenarios for co-development of low carbon fuels and powertrains (eg highly optimised powertrain, tight fuel specification or wide fuel spec to include many different types of fuel and tolerant engine), cross sector synergies (marine, aero, rail), technology focus areas for cross sectoral roadmaps (fuel and powertrain) *Patricia, Ausilio, Adrian, Andy*

Delivering Excellence Through Innovation & Technology

Future Transport Challenges & Opportunities

Prof. Neville Jackson
Chief Technology & Innovation Officer
Ricardo plc

www.ricardo.com

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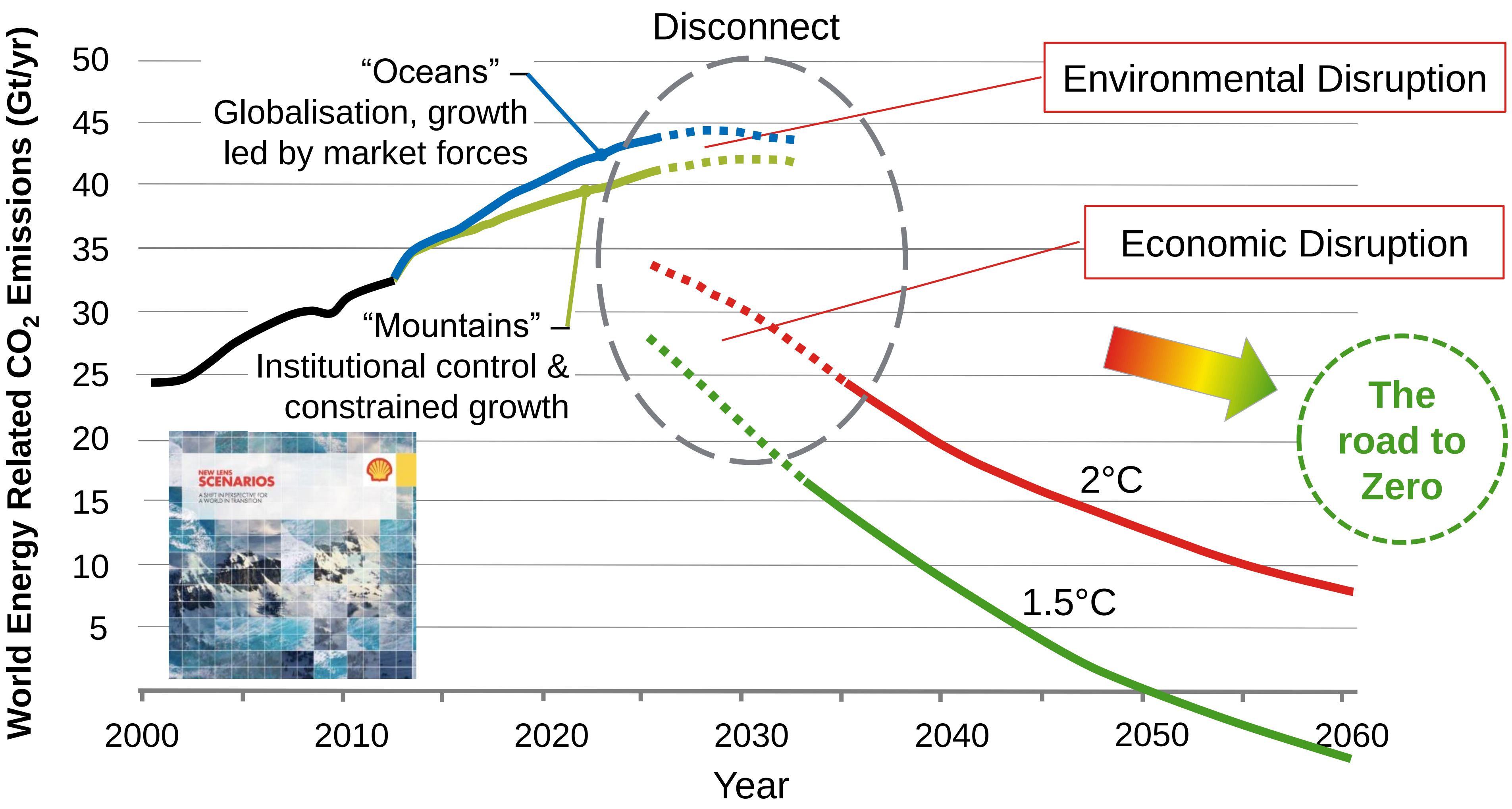
The Energy/Climate challenge and projected future energy scenarios reveal a significant discontinuity – disruption the likely outcome



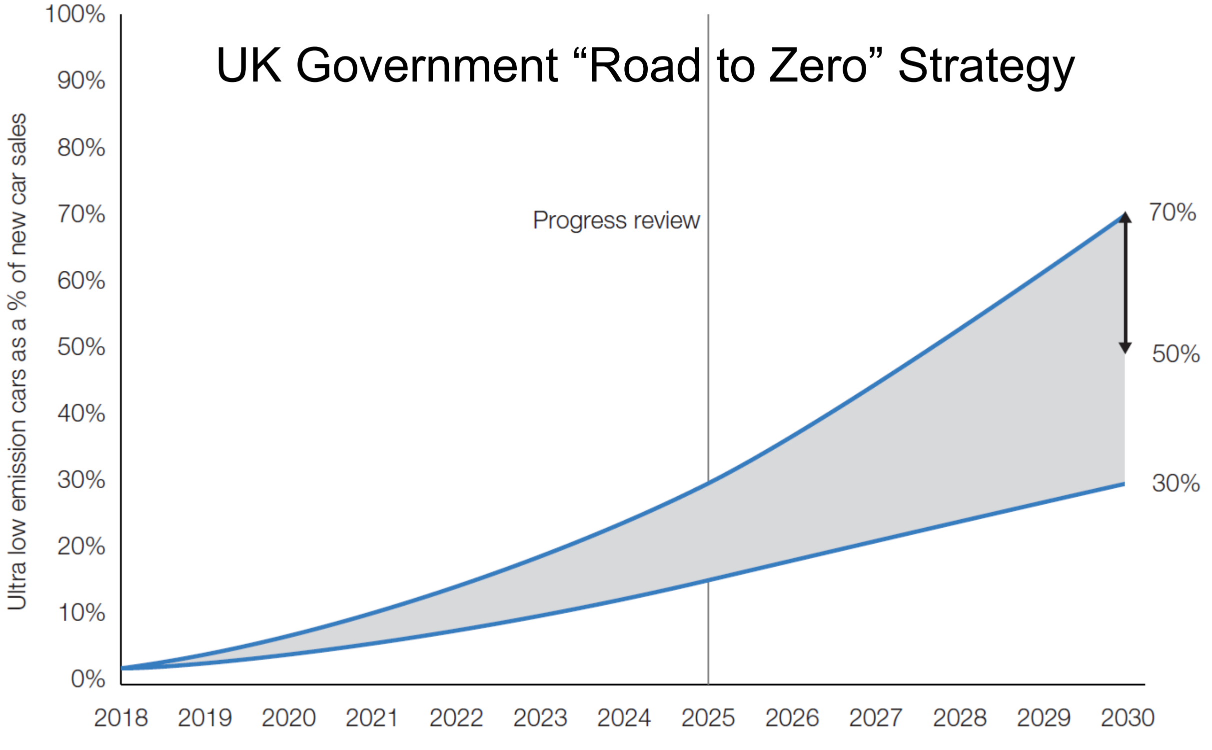
- Policymakers in Europe increasingly focused on “Zero” emissions for road transport
- Reducing carbon intensity in other sectors perceived to be more difficult

Source: Shell New Lens Scenarios; Gert Jan Kramer, Utrecht University

EU GHG reduction to 2030 for Cars & Trucks - Commission, Environment Committee & Parliament have proposed aggressive targets

EU Position

*Ref 2021 ^Ref 2019	CO_2 Reduction 2025	CO_2 Reduction 2030	EV/PHEV Target 2030
Cars*	15%	35%	35%
Vans*	15%	30%	
Trucks^	15% - 20%	35%	20%
Buses			75%



- EU Council has agreed to a 35% cut in CO_2 emissions from cars by 2030
- EU Parliament Environment Committee have voted for a 35% reduction in Truck CO_2 emissions by 2030
- UK Clean Growth Strategy:
  - At least 50%, and ideally 70%, of new car sales ultra low emission (EV/PHEV) by 2030
- Potential Challenges: consumer surveys indicate concerns:
  - higher upfront costs of the vehicles
  - infrastructure provision and recharging availability

Source: EU & UK Government

What do we need where?

- Cars and vans
  - Batteries will meet almost all requirements
  - Hydrogen fuel cells for particularly high mileage requirements
- HGVs, buses
  - Batteries
  - Motorway overhead electrification
  - Inductive charging
  - Hydrogen fuel cells
- Trains
  - Electrification
- Shipping
  - Hydrogen and ammonia
- Aviation
  - Biofuels?
  - …

Fuel	Flash Point	Auto Ignition Temperature
Gasoline	-43°C	280°C
Diesel	>52°C	210°C
Ammonia	Flammable gas	651°C

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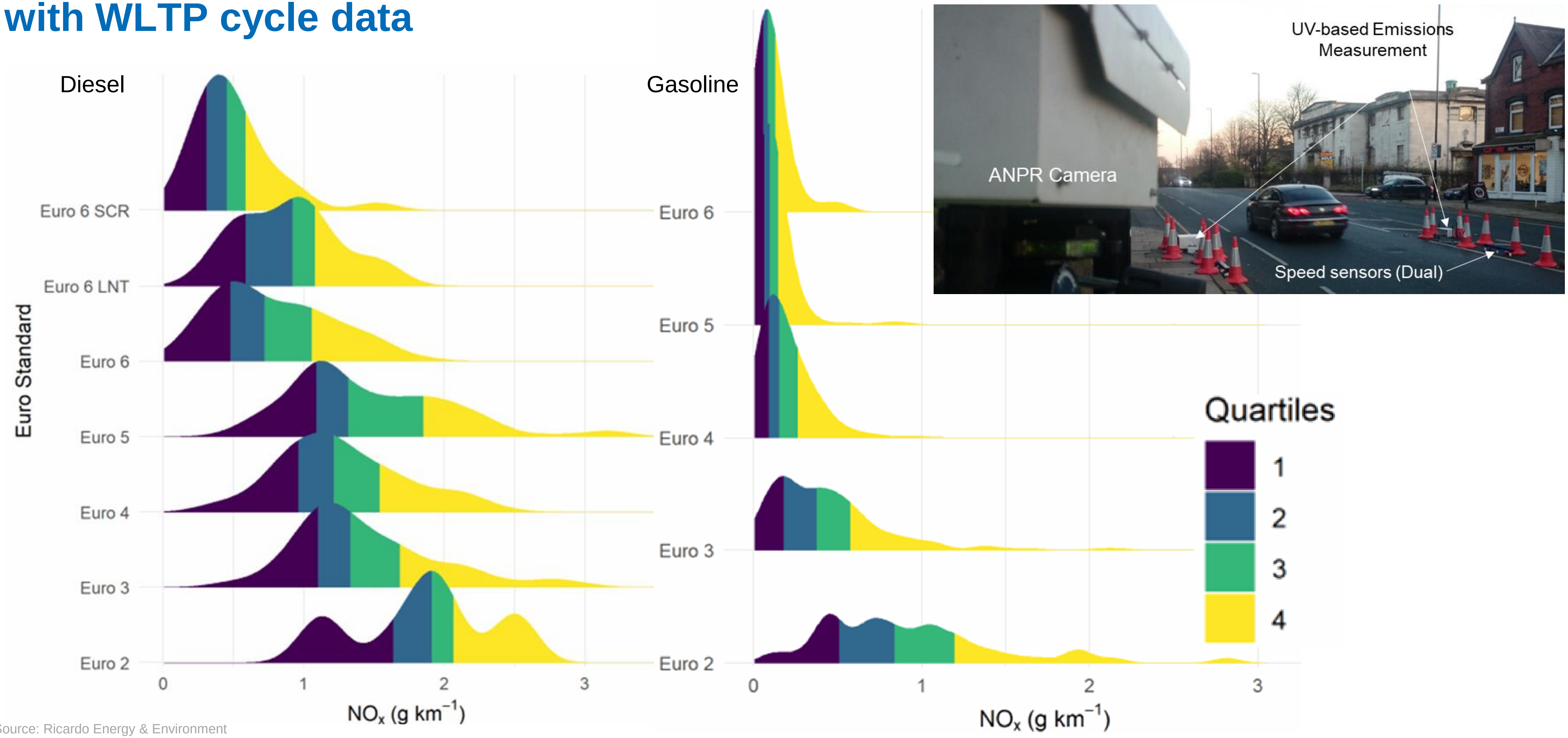
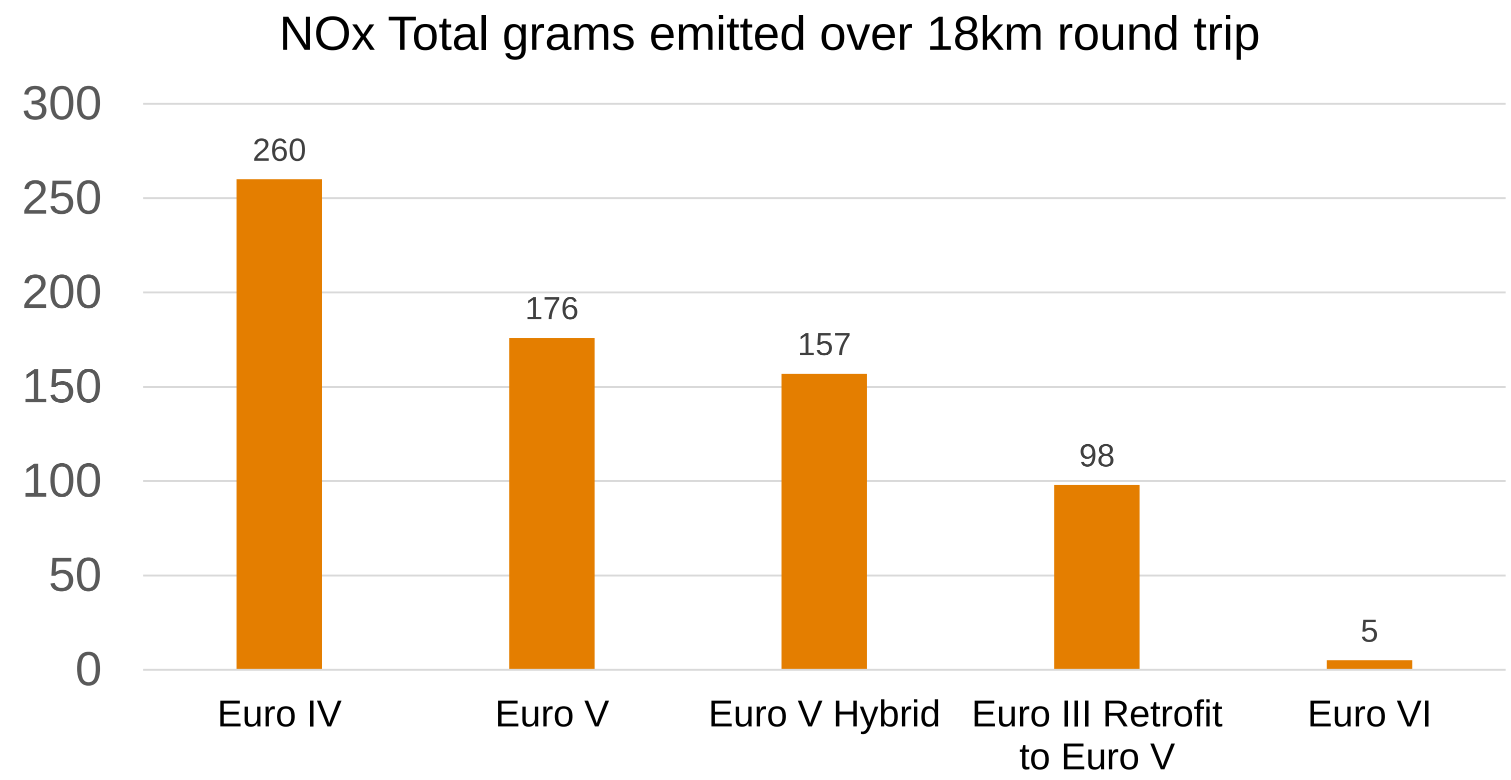
Ricardo remote roadside monitoring system – light duty passenger car data indicates past regulatory issues - not directly comparable with WLTP cycle data



Source: Ricardo Energy & Environment

Real-World Bus Emissions measurements by Portable Emissions Measurement Systems (PEMS)

PEMS measurements of emissions of buses running on Route 7, Brighton & Hove Buses



CF	1.85	2.3	2.0	1.28	0.52

For Euro VI HD vehicles, we see good conformity in the real world

Source: Ricardo

Gasoline & Diesel vehicle emissions will not impact air quality in the medium term – Particulates & Road/Tyre/Brake wear next challenge?

Tighter control of NOx emissions

- NOx limits for petrol and diesel converge post Euro 6
- Emphasis on real-world emissions performance

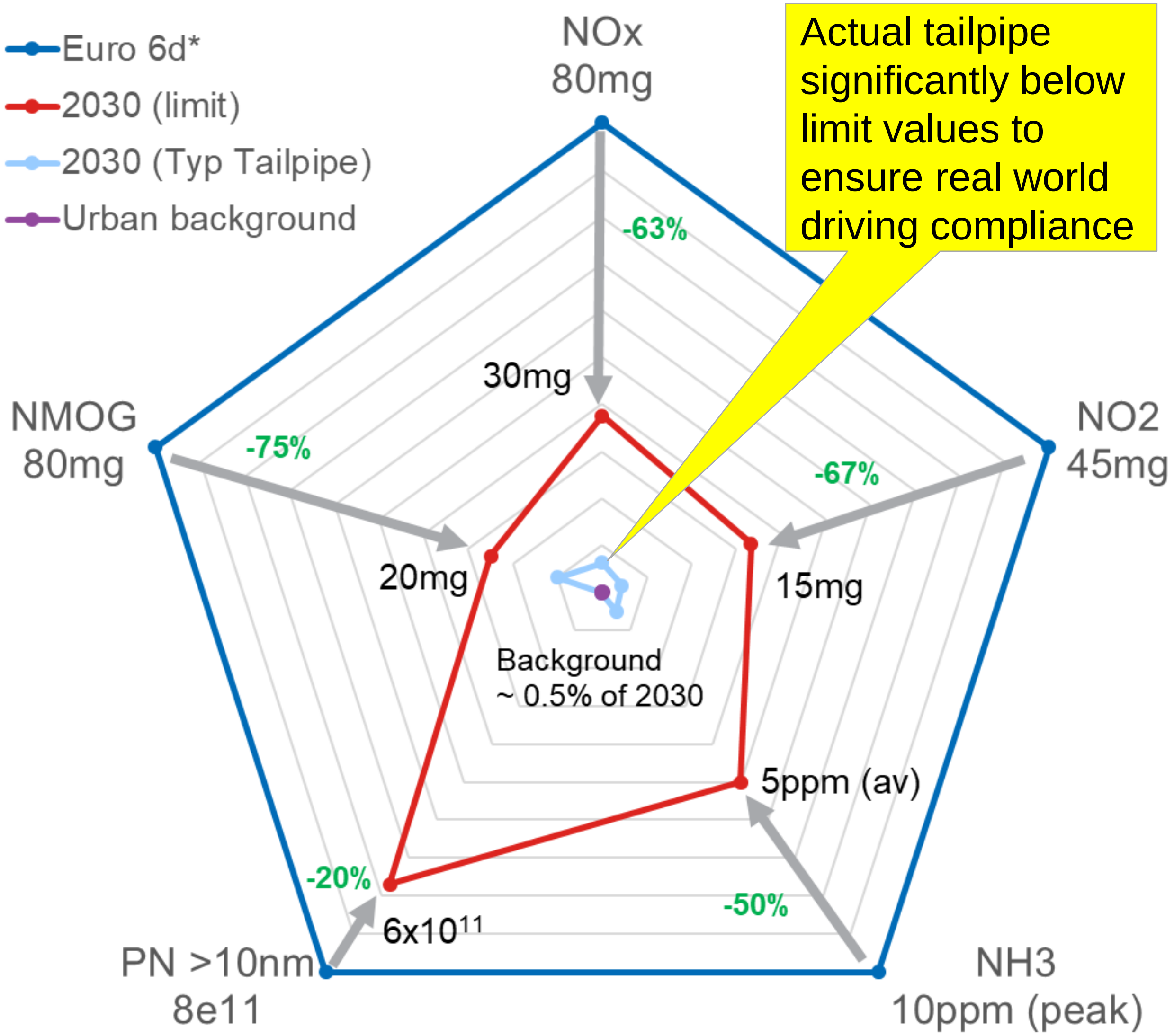
Ultrafine particle emissions

- GDI engines emit high levels of ultrafine particles
- Smaller particles thought to be greater health risk
- Gasoline particulate filters required to control ultrafine particles
- GDI with GPF has higher PN emissions than Diesel & DPF

Other emitted nitrogen compounds

- **Ammonia (NH3)**
  - Eutrophication – enrichment of environment with nutrients, big issue in Europe
  - NH_3 slip from SCR systems – potentially increasing in importance
- **Nitrous oxide (N_2O)**
  - Very powerful **greenhouse gas** (~300 x CO_2)
  - Some exhaust after-treatment technologies

Possible Reductions in Passenger Car Emissions EU6 to 2030



Source: Internal combustions engines – what does the future hold in a post-dieselgate world? - Ricardo – Vienna Motor Symposium 2017

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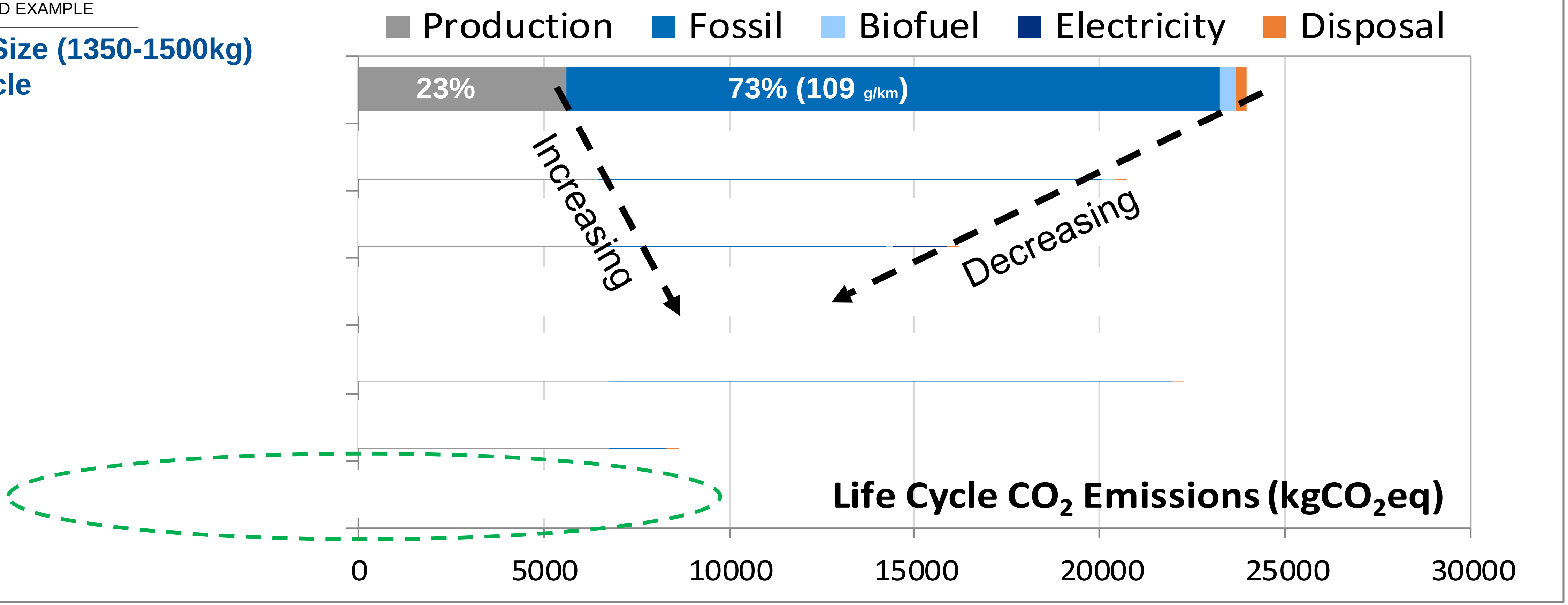
Light Duty Vehicle - Ricardo analysis - hybrids & EVs have lower life cycle CO_2, higher embedded emissions – bio/e-fuels also attractive?

SELECTED EXAMPLE

Mid Size (1350-1500kg) Vehicle



Source: Based on "Preparing for a Life Cycle CO_2 Measure", Low Carbon Vehicle Partnership

Assumptions:

Vehicle specifications based on real world 2020 values
Assumed lifetime mileage 150,000 km.
Gasoline fuel E10. Diesel fuel B7
Fischer-Tropsch diesel from farmed wood (WTW = 6 gCO2eq/MJ)
Hydrogen carbon intensity 99.7 gCO_2e/MJ (NG Steam Reforming)

Electricity carbon intensity 200 gCO_2/kWh (~2025 best case)
Hybrid Battery 1.8 kW.hr NiMH, 56 kW Motor
EV Battery 32 kW.hr Li-ion ~ 150 km range
PHEV Battery 5 kW.hr ~ 20 km range
FCEV Battery 1.8 kW.hr

Source: Ricardo

Some initial global dialogue on LCA implementation – EU may be first mover – voluntary monitoring 2025 & potential "framework" by 2026

- Of key US/China/European regulatory areas, EU probably most interested in LCA
- EU Commission proposal for post 2021 regulations does not include WTW or LCA
  - Legislative framework considered too complex at this stage
- However, EU Parliament proposes that the Commission develops methodology by 2023*
  - To support this, Vehicle OEM's to "voluntarily" report LCA GHG emissions in 2025
  - EU Commission to propose regulatory GHG framework by end 2026
    - Potential options: Focused LCA, Credits for LCA reductions, Robustness v Accuracy
- Ricardo is currently conducting a major LCA project for DG Climate Action…

"Pilot study on determining the environmental impacts of conventional and alternatively fuelled vehicles through Life Cycle Assessment"

*Agreed by European Parliament and Council on 17 December 2018

Source: Ricardo

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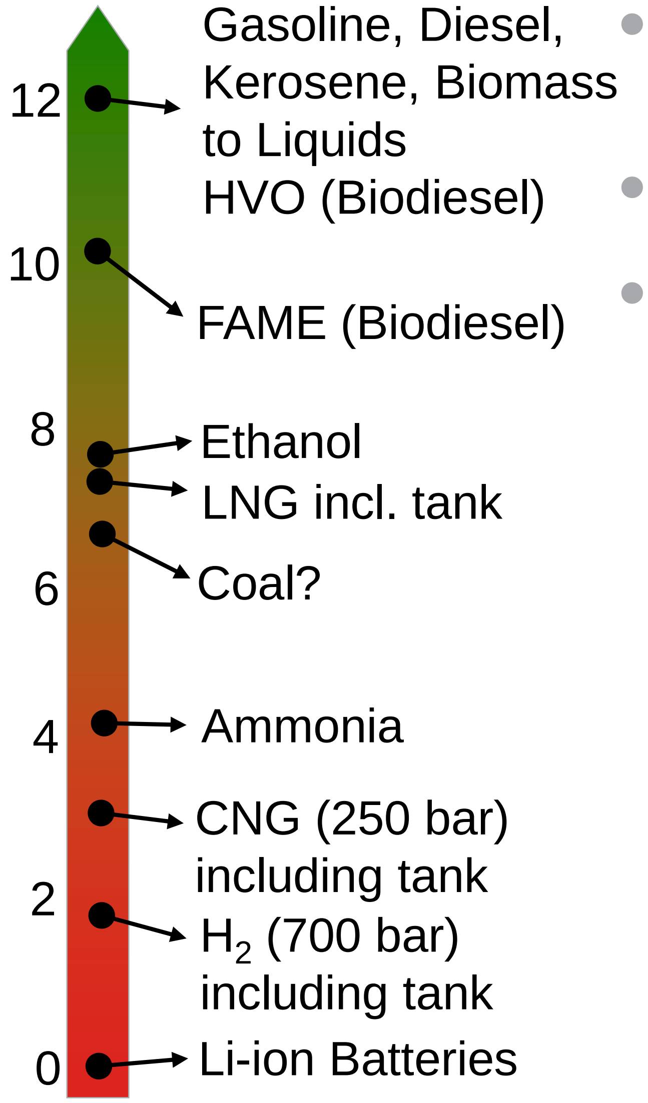
Long haul / heavy duty applications will require low carbon liquid fuels – light duty applications more suited to battery/electric systems



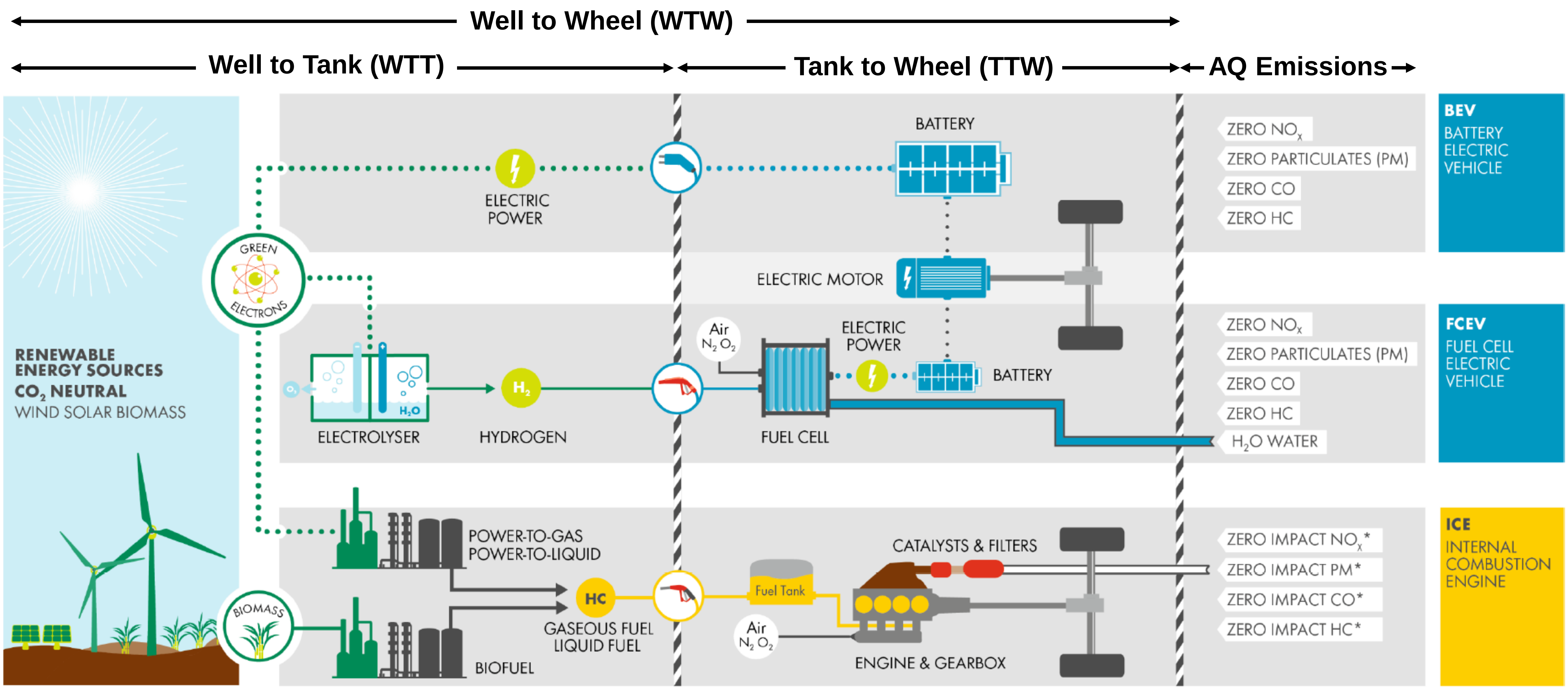
- **HGV 36 ton, 500 mile range** – 1 MWh battery (2.0 kW.hr/mile) **>5.5 tons**, cost over $125,000 assuming $125/kWh pack. Charge time at least 12 hours @120 kW*
- **Airbus A320 Neo** - equivalent range battery pack ~**1480 tons** – 19x take off weight*
- **Container ship (**Benjamin Franklin) - 4.5 million gallons of fuel ~ 170 million kWh. Battery pack for same range over **300,000 tons** – twice the dead weight tonnage*

Long Distance/Heavy Duty → Short Distance/Light Duty

Low Carbon Liquid Fuels	Liquid Fuel / Battery Hybrid	Battery Electric
Long distance/ heavy duty vehicles need space/weight efficient energy storage	Use of both liquid/gaseous fuel and grid re-charged battery offers more flexibility and utility	EV's suited to short distance/light duty applications to minimise cost
Technology/Cost & Availability →		← Technology/Cost Innovations

Source: Ricardo research; Is it really the end of internal combustion engines and petroleum in transport? G. Kalghati; Applied Energy, Volume 225, 1 September 2018, Pages 965-974

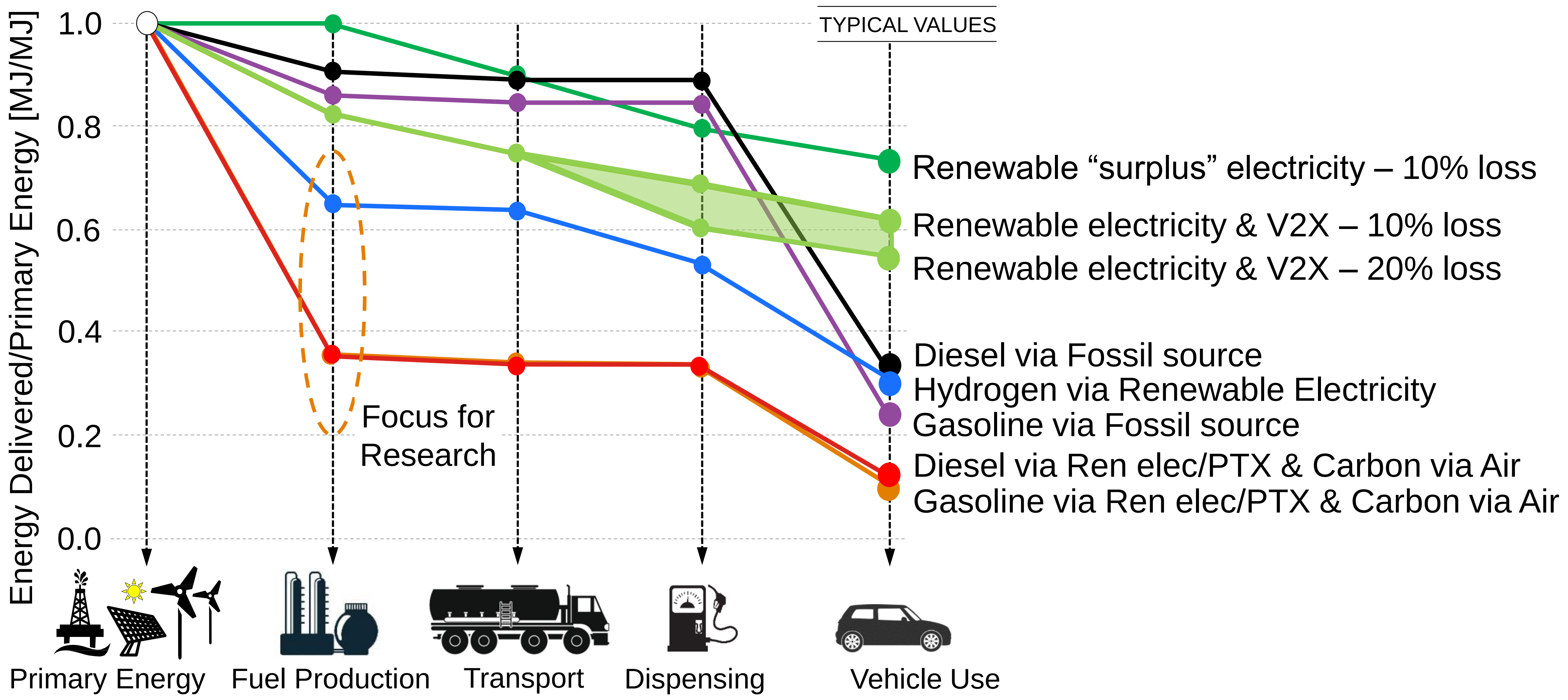
Potential routes to clean vehicle powertrains – alternative pathways to use renewable & sustainable energy sources in transport



*SULEV or equivalent technology – post Euro 6/IV

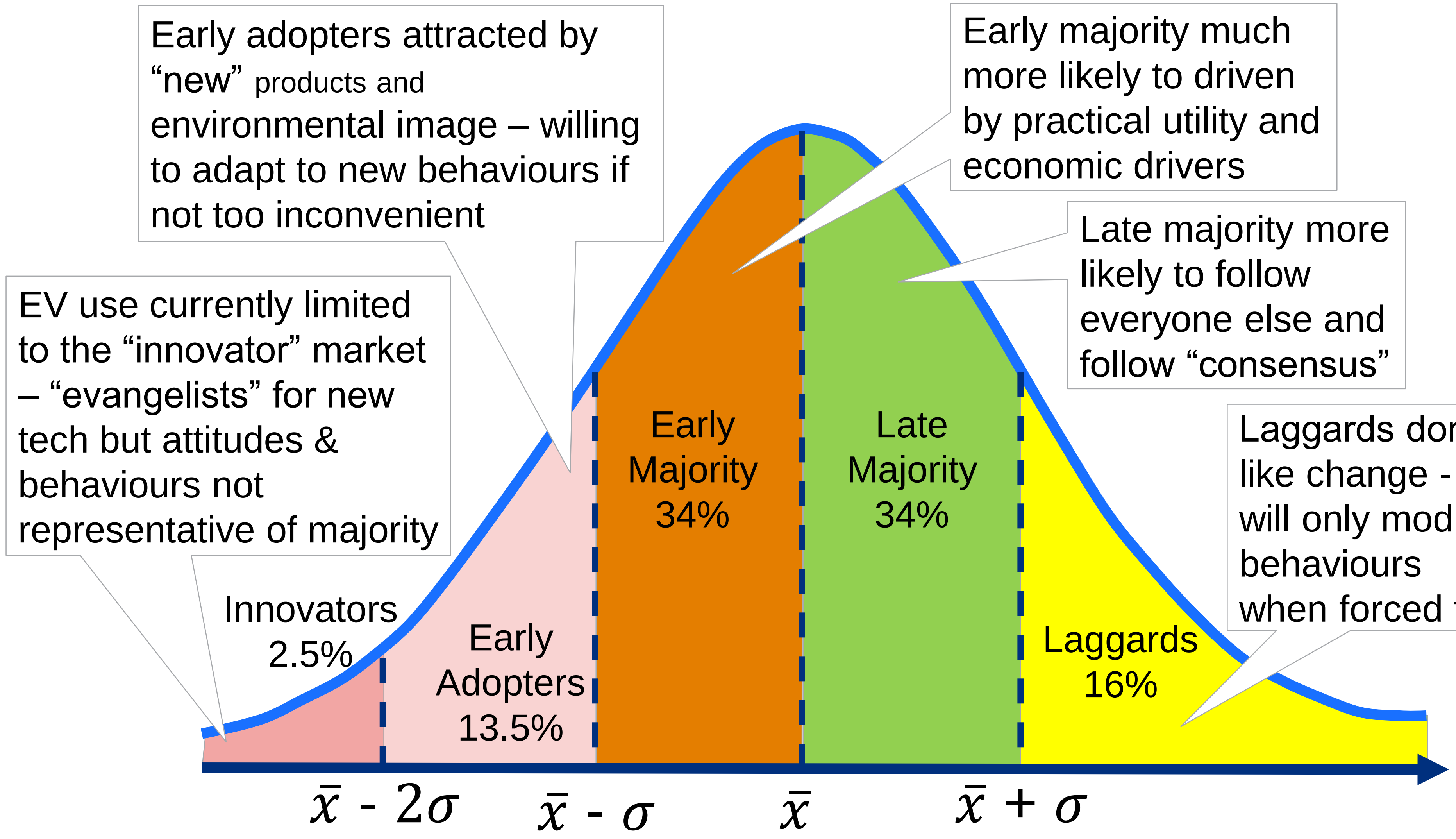
Source: The Road to Sustainable Fuels for Zero Emissions Mobility – Shell/OVK

"Well to Wheels" - EV's offer efficient use of renewable energy – H_2 less efficient – Power to Liq/Gas inefficient but uses existing infrastructures



Source: The Road to Sustainable Fuels for Zero Emissions Mobility – Shell/OVK

To accelerate EV/PHEV penetration and move beyond the innovator/early adopter market, focus on "User Centric" attributes and requirements?

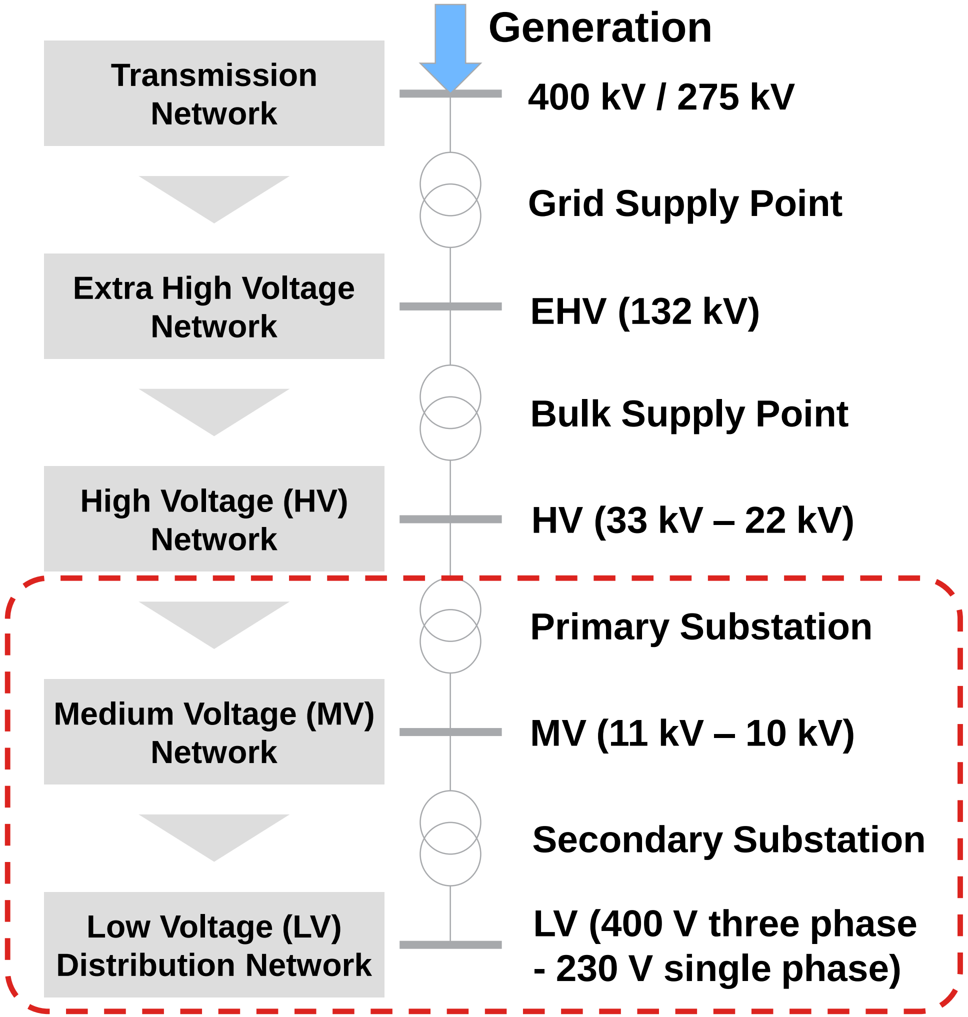


Reaching the early and late majority market:

- Focus on "User Centric" approach
- A more attractive EV/PHEV experience for consumers:
  - Ease of charging – wireless?
  - Improving charge availability?
  - More connected?
  - Preferential usage – HOV lanes/ Parking etc.
  - New ownership models?

Source: Everett Rogers; Diffusion of Innovations, 1962

Local network reinforcement required beyond 15-20% EV penetration to deliver adequate EV re-charge capacity will be significant*



Significant Re-enforcement Required

- Capital costs for re-enforcing EU EV charging infrastructure & charge facilities for predominantly EV passenger cars & van parc:
  - **€630 billion assuming primarily "home" charging**
  - **€830 billion assuming "grazing" frequent top-up**
- Based on "Smart" network with charge periods selected to minimise local network loads

Only a small part of total road transport costs including vehicles and energy but who pays for this?

Ref: Impact Analysis of Mass EV Adoption – Ricardo
Defossilizing the transportation sector - FVV

Source: Ricardo

Ultra Low or Zero carbon HD trucks – probably a choice between H_2 Fuel cells with renewable hydrogen or Bio-Waste/Power to Liquid/Gas Fuels

H_2 FC Trucks – e.g. Toyota/Nikola Motors

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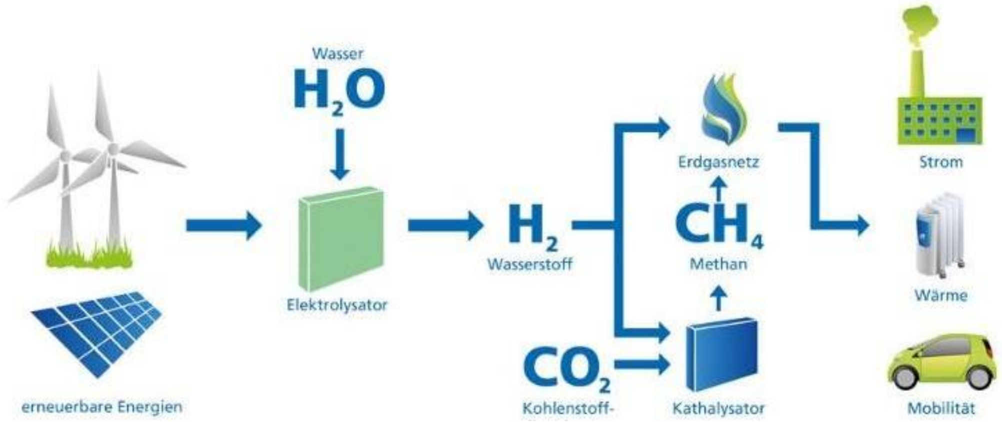
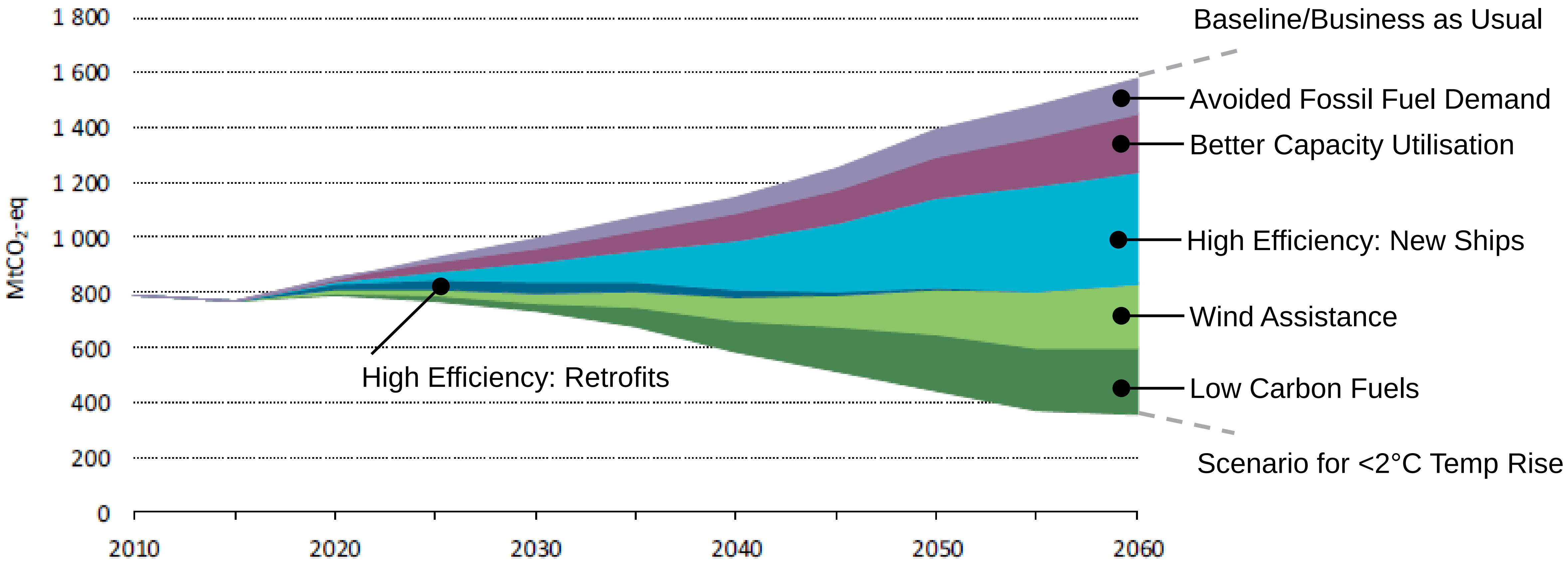


Renewable Electricity to Liquid Fuels

Renewable “Synthetic” Fuels

IEA Well-to-Motion GHG emission reduction in international shipping proposed via logistics, efficiency improvements & low carbon fuels



- EU Commission committed to reduce CO_2 maritime transport in EU waters by 40% - 50% vs 1990
- EU requirement for Monitoring, reporting and verification of CO_2 emissions from large ships using EU ports came into effect in January 2018

Source. IEA Energy Technology Perspectives 2017

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COP21 GHG targets in transport not straightforward – Need efficiency improvements, new energy vectors & carbon intensity reductions

Future Demands:

-80% GHG
Zero Impact
Customer Needs
Business Case

Efficiency Improvements

Vehicle (energy per vehicle mile)

Passenger, Goods
(energy per person mile or ton mile)

Mobility Supply & Services

Ride Share, Mobility as a Service, Autonomy, Logistics/Load Optimisation

Energy/Fuel Carbon Intensity

Gas/Diesel - Increasingly renewables
NG - Increasing H_2 content, RNG, e-gas
Electricity – Reducing GHG intensity
Hydrogen – From renewable sources

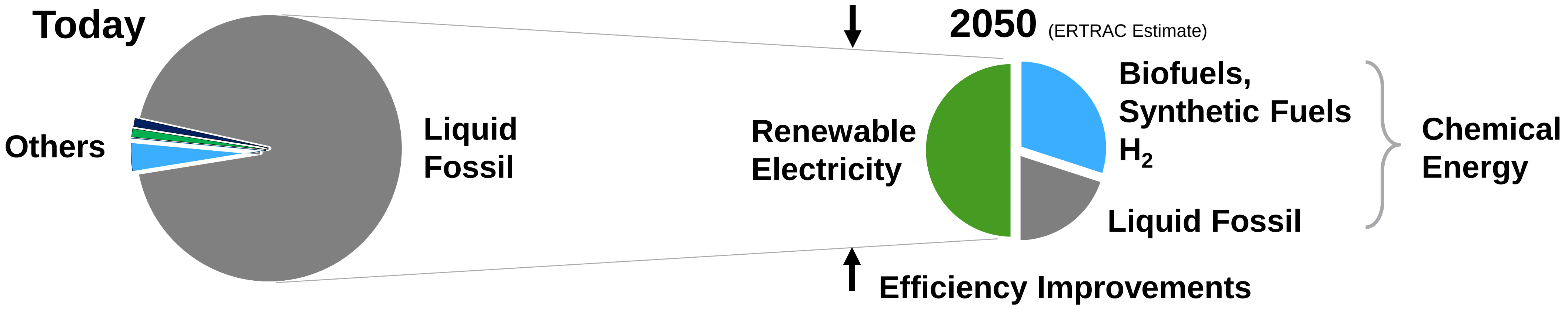
Significant Interactions

Multiple options for renewable H_2:
- Heat (via NG networks)
- Transport
- Displacing fossil H_2 in oil refineries

Increasing requirement for intermittent renewable energy storage – H_2 may be lowest cost approach?

Source: Ricardo

ERTRAC analysis for 80% reduction in road transport GHG - half of energy from electricity by 2050 – remainder from Bio, Waste & e-Fuels

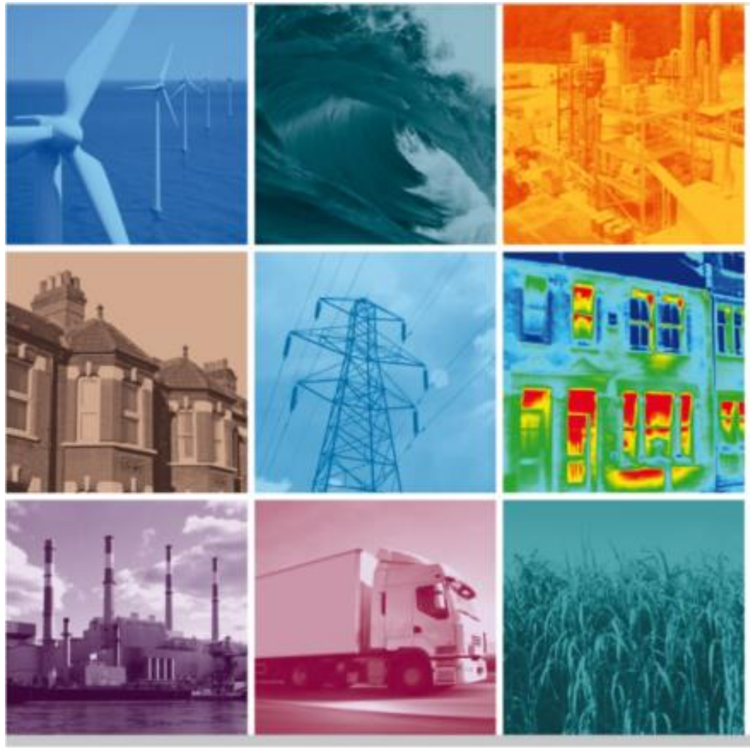


- By 2050, ~50% of all road transport energy from electricity. The remainder comes from chemical energy
  - Chemical energy (including H_2) for energy intensive transport (HGV & high speed journeys / intercity)
- Choice will be between decarbonising legacy (diesel/gasoline) fuels or investing in new infrastructures for H_2 generation & supply for transport – largely defined by economics and national fiscal policies
- Fuel Cell propulsion system cost challenges will be overcome - renewable H_2 supply driven by need for "storage" of intermittent renewable electricity and to reduce carbon intensity of domestic heating
- Increasing focus on "total environmental impact" will drive more holistic balance between use of critical materials, embedded and emitted emissions and recycling/re-use

Source: Automotive Council, *ERTRAC, E4tech, Element Energy, Ricardo analysis

Summary & final comments…

- In the real world, **economics rules**
- De-fossilising **transport** is only the **appetiser,** de-fossilising **heat** will be the **main course**
- It's not always about the extra cost, but who is able and **willing to pay** for it
- There is **no single technology** that will viably address our low carbon energy/transport challenges
- **Battery electric** vehicles are the **most efficient** route to use of renewable electricity but:
  - **Significant issues** with **battery** manufacture at scale (**cost/embedded energy/environment**)
  - **Electricity distribution** networks not designed to support mass EV re-charging & electric heating
- To meet climate goals:
  - Need to address **rate of adoption/implementation** – **not** some **unobtainable theoretical solution**
  - **Electrify as much as possible** – but focus on sustainable battery design/manufacture (**materials/recycling**)
  - Develop **solutions** for low/zero carbon **longer distance/heavy duty** transport applications:
    - Zero carbon **Hydrogen** and supply network **initially for B2B/commercial** applications
    - Further **cost reductions** and efficiencies for "**PTX" liquid and gaseous fuels** as "drop-in" solutions compatible with **existing infrastructures** and vehicles
    - Continue to **invest in efficient combustion engines** – both **evolutionary** & **disruptive**
    - **Fiscal policies** to encourage **low/zero carbon sustainable** fuels in road transport market



www.eti.co.uk

2050 Energy System Overview and Challenges

Matthew Joss

What is the ETI?

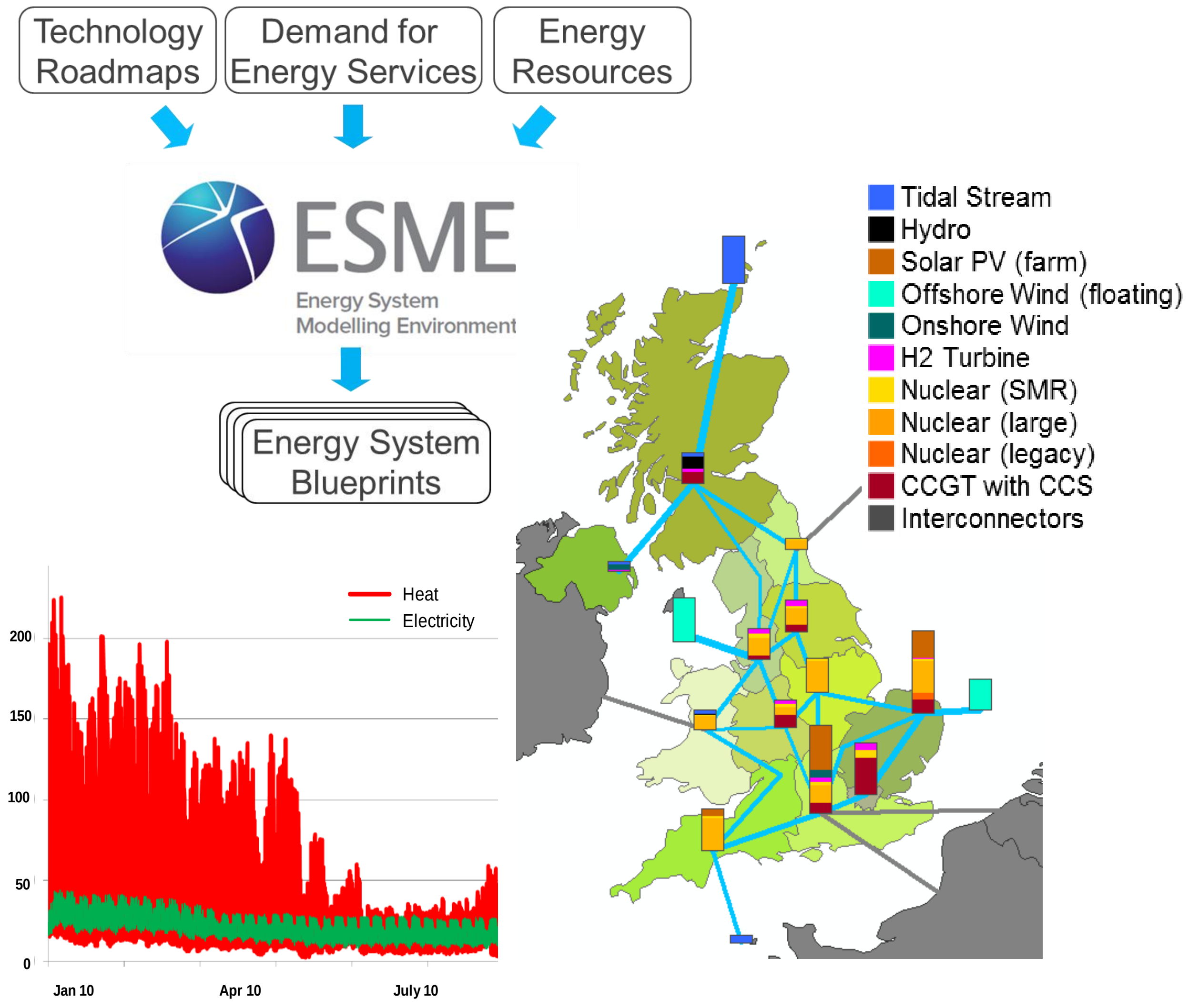
- The ETI is a public-private partnership between global energy and engineering companies and the UK Government.
- Targeted development, demonstration and de-risking of new technologies for affordable and secure energy
- Shared risk

ETI members

bp	CATERPILLAR®	EDF ENERGY
Rolls-Royce	Shell	EPSRC Pioneering research and skills
Department of Energy & Climate Change	Department for Business Innovation & Skills	Innovate UK

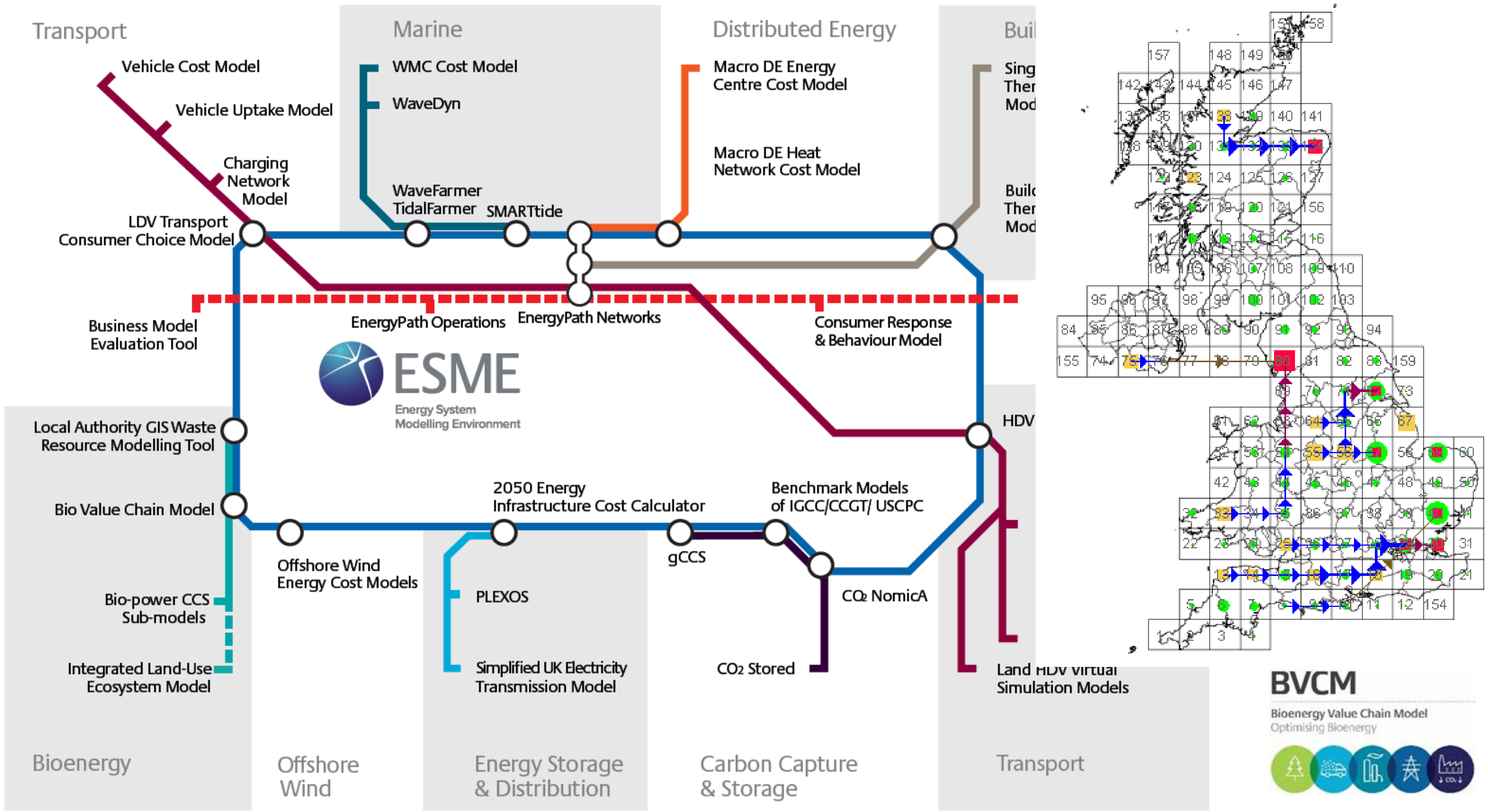
Background - ESME

- Whole-system approach: power, heat, transport, industry and energy infrastructure
- Least cost optimisation, policy neutral
- Deployment & utilisation of 300+ technologies
- Probabilistic treatment of key uncertainties
- Pathway and supply chain constraints to 2050
- Spatial and temporal resolution sufficient for system engineering



More details in *Modelling Low-Carbon Energy System Designs the ETI ESME Model* available on the web:
http://www.eti.co.uk/project/esme/

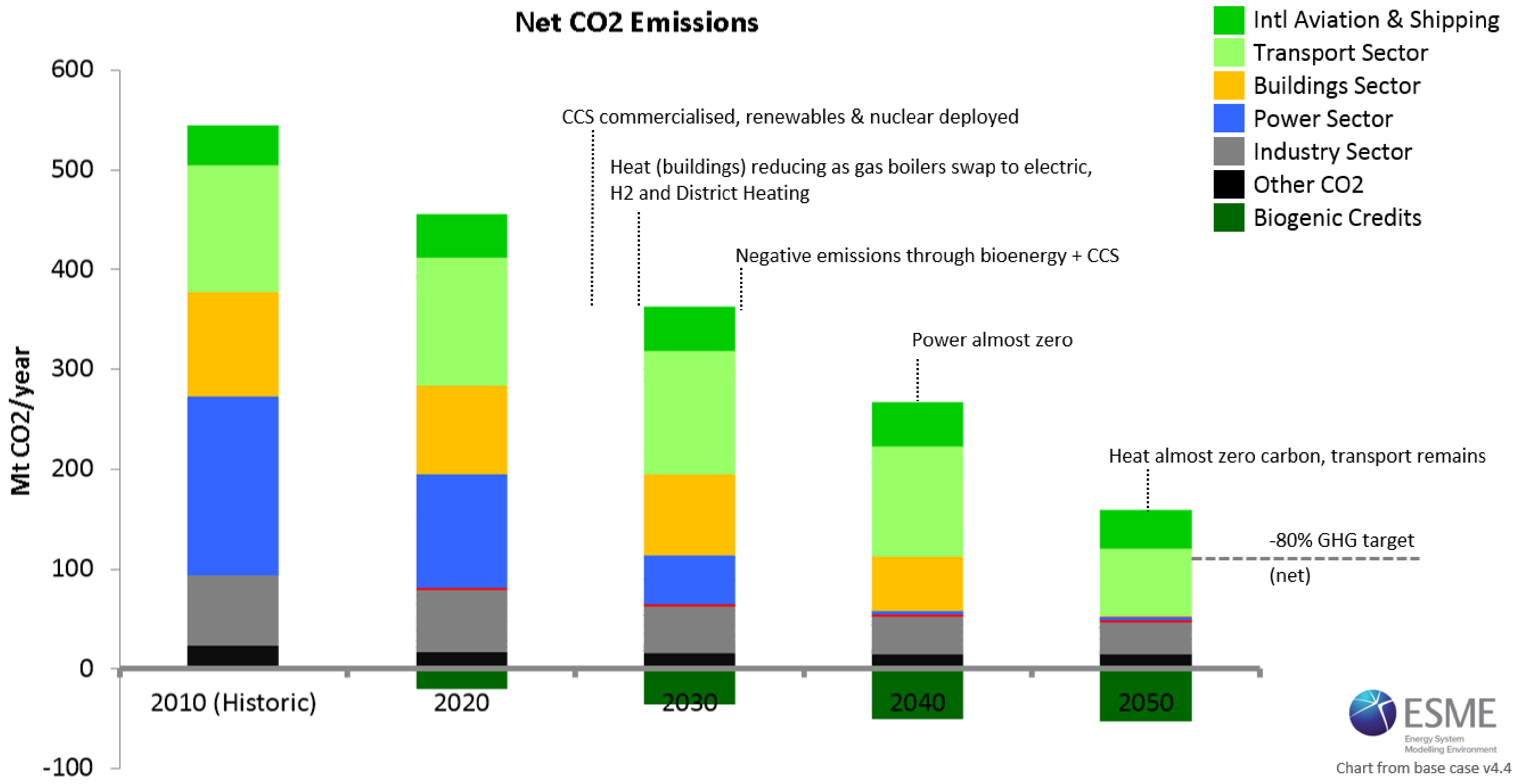
ESME and the wider ETI modelling suite



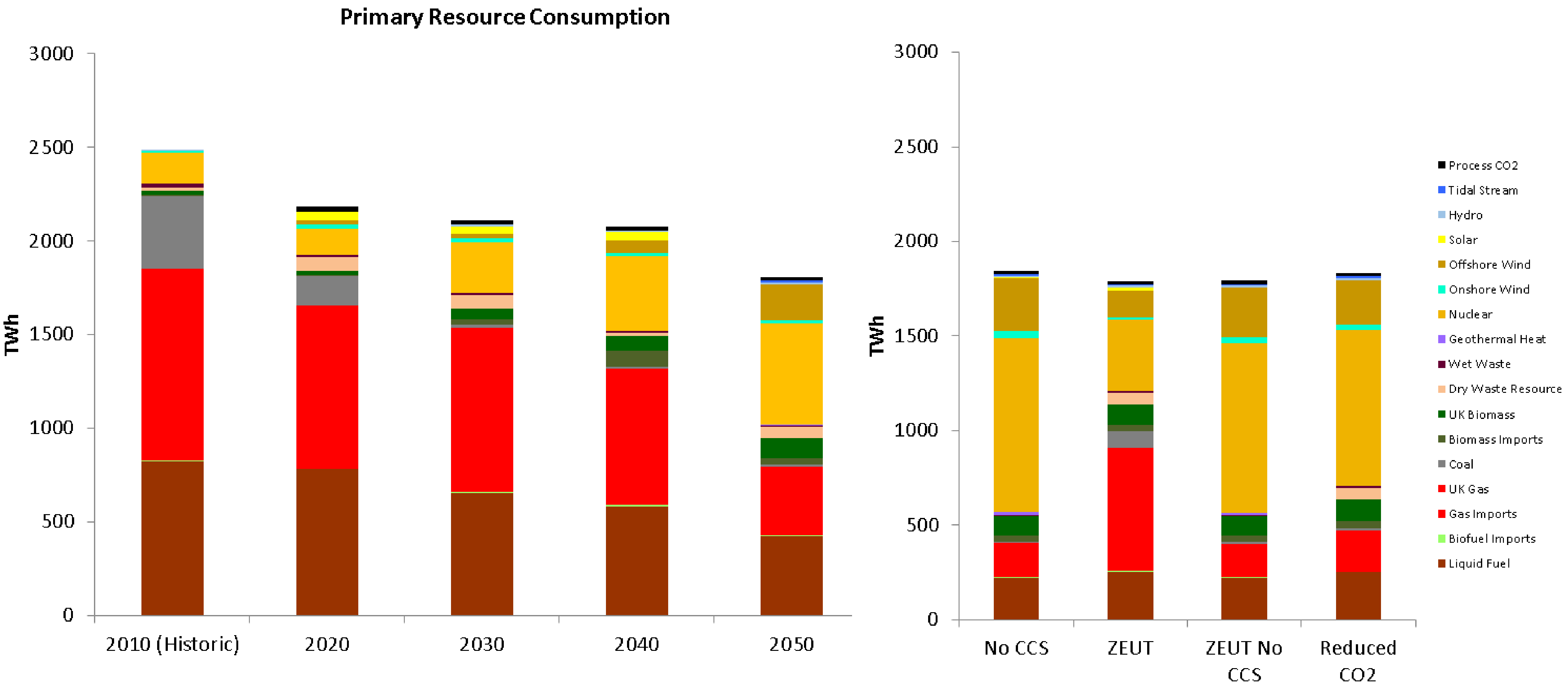
Approach - Testing the Uncertainty

Scenario	Scenario Description	Transport Sector				System and Overall Constraints	
		HGV Sector	MGV Sector	LGV (Van) Sector	Car Sector	Other System Restrictions	CO_2 Target
Base Case	All technologies availbe to ESME in the latest version as of 2018 are available to be selected	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No other restrictions	80% reduction of GHG from 1990 levels
No CCS	Carbon Capture and Storage (CCS) is the most valuable technology for ESME to select. Removing it as a technology option to select generally changes a large proportion of the technology selected and drastically increases the overall system cost.	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	All technologies which use and store carbon (CCS) are unable to be selected	80% reduction of GHG from 1990 levels
Zero Emission Urban Transport	The Road to Zero signalled the ambition for light duty vehicles from the DfT and BEIS and the Clean Air Strategy highlighted the need to redcue roadside air pollution. Cities in the UK are looking to implement zones to restrict the highest emitting vehicles in the short term and create zero emission zones in the long term to improve air quality. This scenario addresses some of these issues by restricting freight delivery by smaller MGV and LGV to be zero emission as well as cars.	No restrictions over vehicle selection	Progressive CO_2 reduction from today concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	Progressive CO_2 reduction from the 2020 target of $147gCO_2/km$ concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	Progressive CO_2 reduction from the 2021 target of $95gCO_2/km$ concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	No other restrictions	80% reduction of GHG from 1990 levels
Zero Emission Urban Transport No CCS	This scenario combines the previous two.	No restrictions over vehicle selection	Progressive CO_2 reduction from today concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	Progressive CO_2 reduction from the 2020 target of $147gCO_2/km$ concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	Progressive CO_2 reduction from the 2021 target of $95gCO_2/km$ concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	All technologies which use and store carbon (CCS) are unable to be selected	80% reduction of GHG from 1990 levels
Reduced CO_2 Target Sensitivity	The Paris agreement restricts global temperature rise to 2°C. There is currently no definition of what this might mean for the UK. This scenario tests the sensitivity to increasing our current GHG reduction target beyond 80% .	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No other restrictions	Increased GHG target to 90% reduction of GHG from 1990 levels. Current 2050 ESME target is 105MT/yr which is reduced to 65MT/yr.

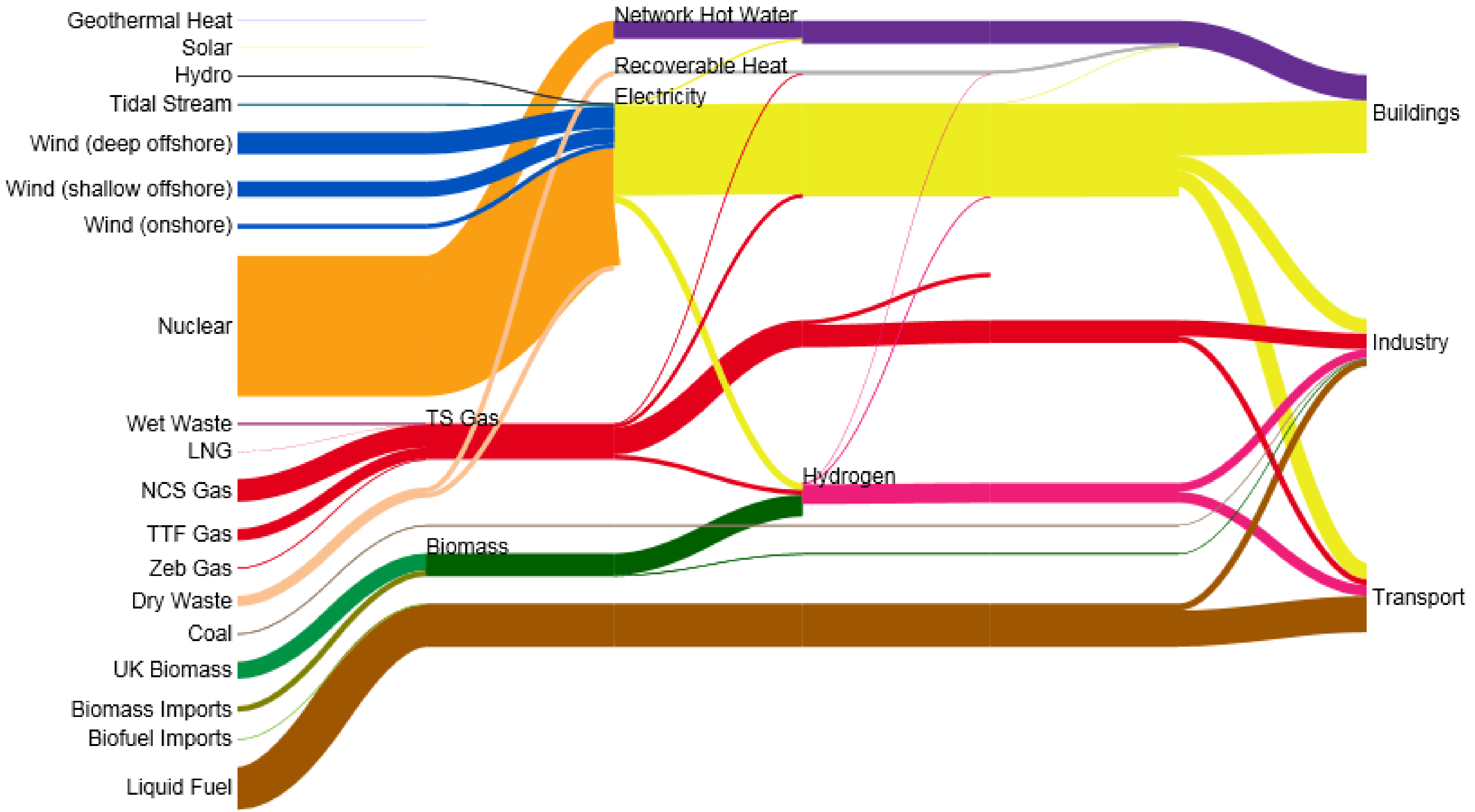
Least Cost Optimal Route to Decarbonisation



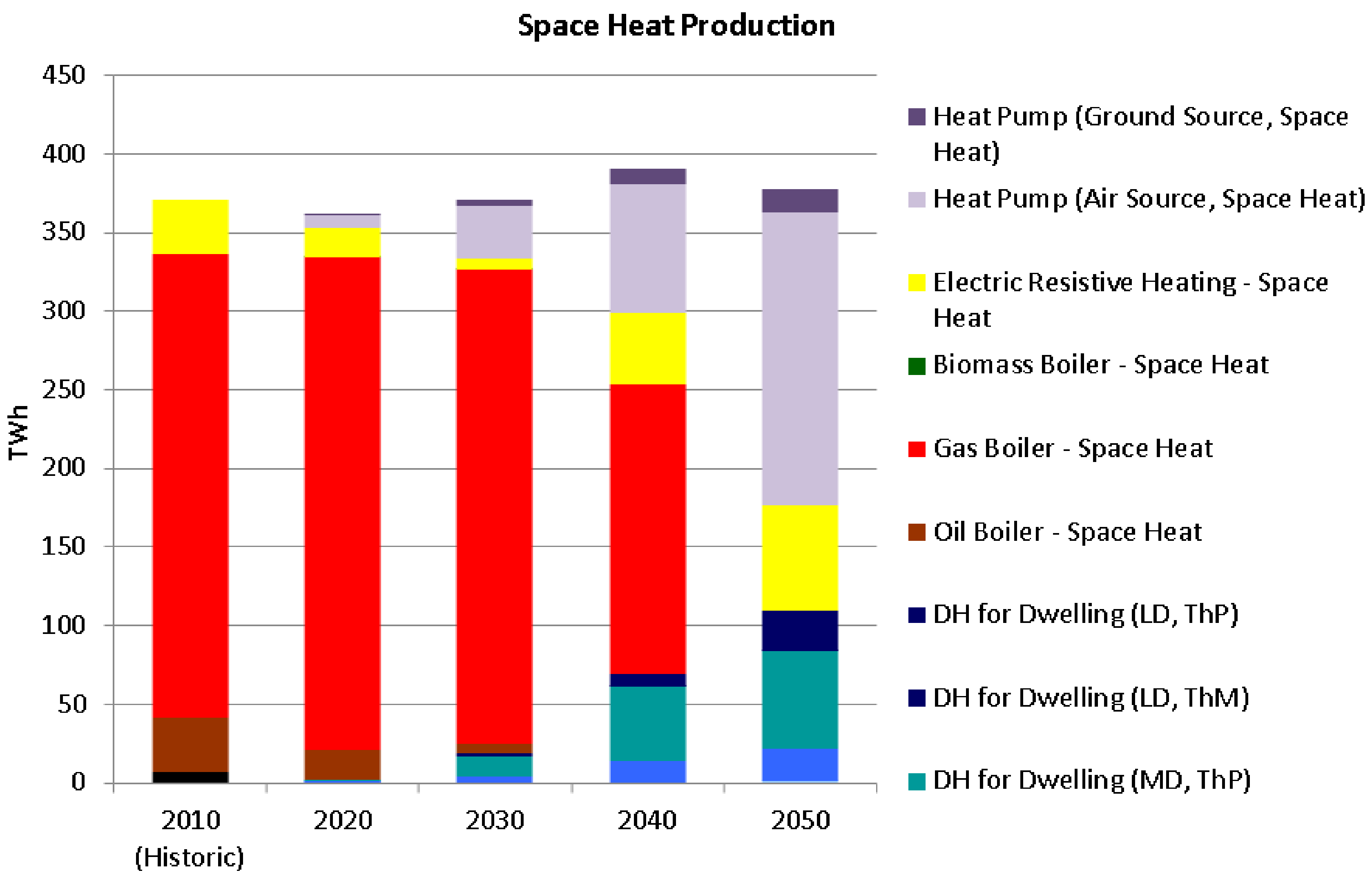
Energy System Resource Consumption



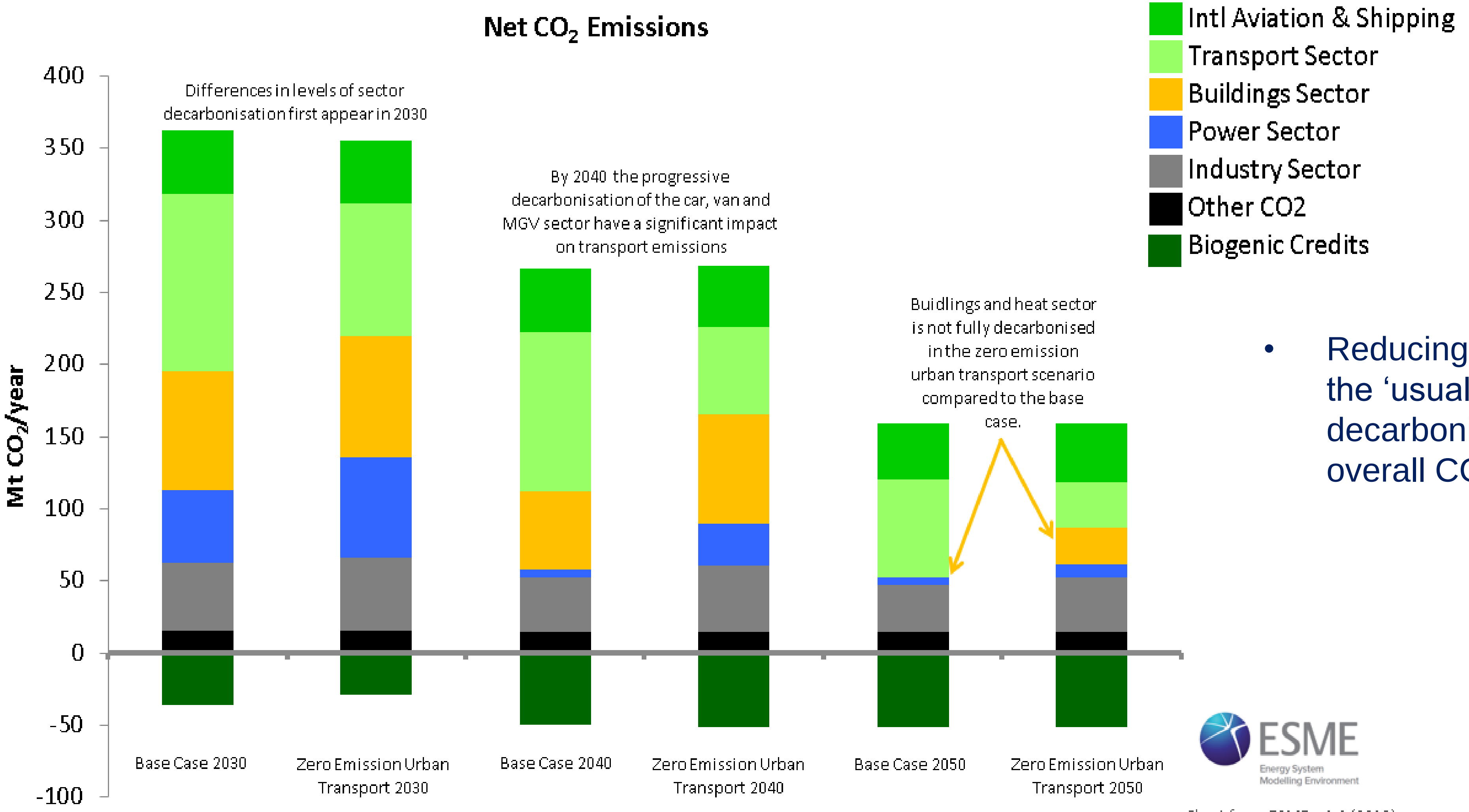
Example System Solution Sankey



Space Heat Production



Zero Emission Urban Transport



- Reducing transport emissions beyond the ‘usual’, reduces the need to decarbonise other sectors to meet the overall CO_2 target.

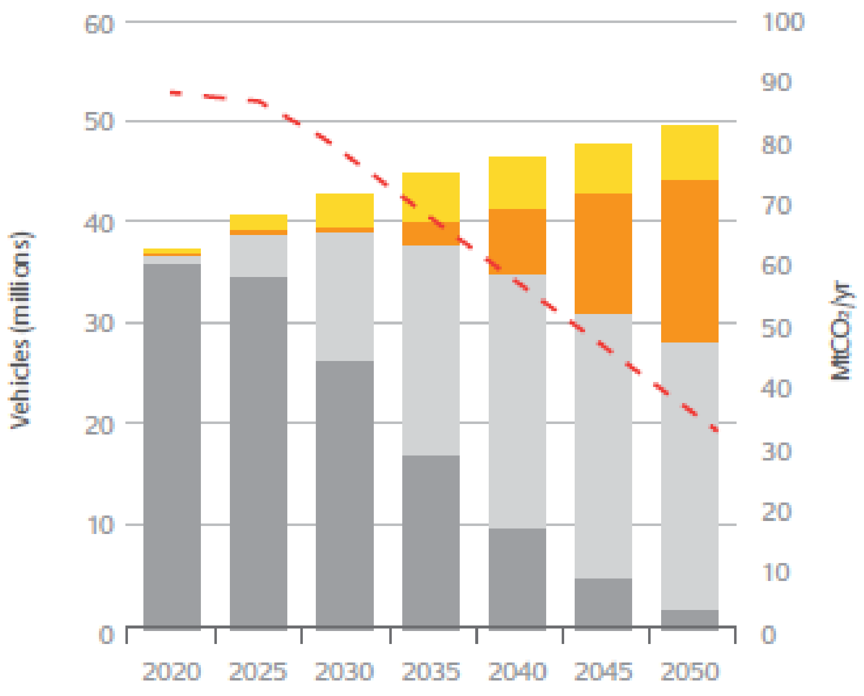
Chart from ESME v4.4 (2018)

Scenario Variations

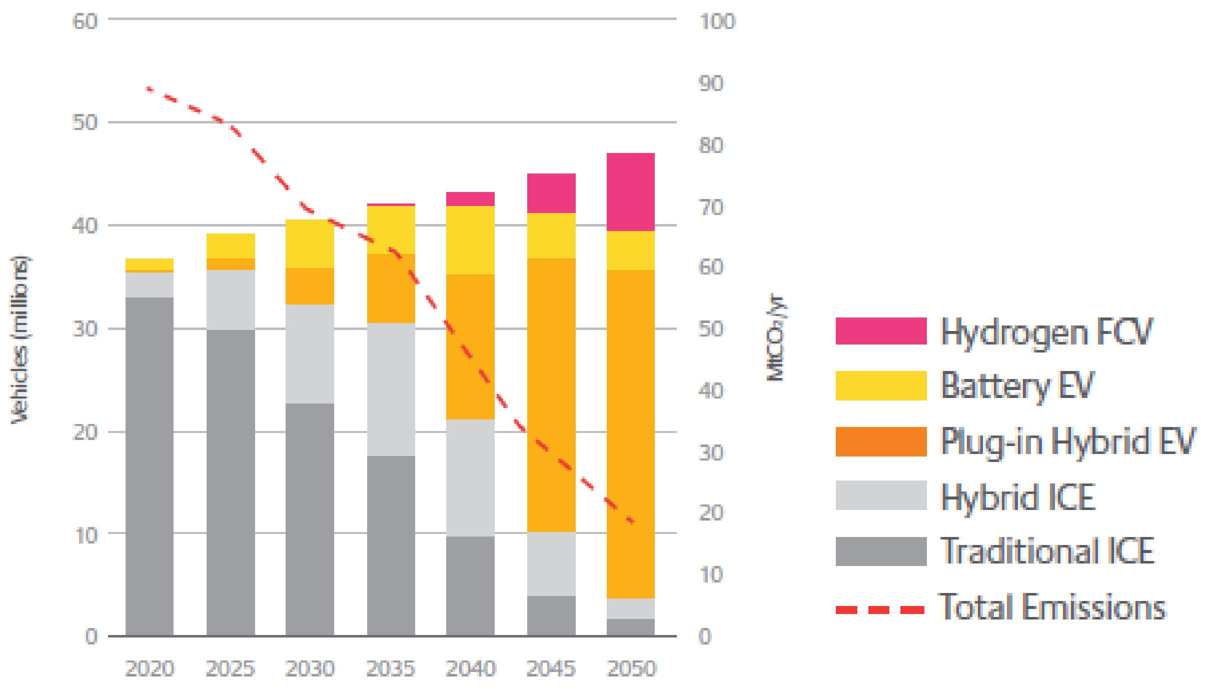
Reaching **21m-36m** electric vehicles*, and up to **8m** fuel cell vehicles, by 2050

Reducing average vehicle emissions by **70-94%**

CLOCKWORK



PATCHWORK



Summary

- There is likely to be competition across sectors for the same resources.
- To meet the 2050 CO_2 target freight could be fuelled by carbon based fuels.......
- But……
    - Factors such as air quality emission constraints will have significant impacts.
    - Increasing the CO_2 reduction beyond the 80% to meet the Paris 1.5 or 2 degree C targets will require zero emission transport.
- Decisions made to decarbonise other sectors will effect transport and freight decarbonisation.
- Existing CO_2 targets for the HGV sector.
- Practicalities…..

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TEN YEARS OF INNOVATION 2007—2017

For all general enquiries telephone the ETI on 01509 202020.

For more information about the ETI visit www.eti.co.uk

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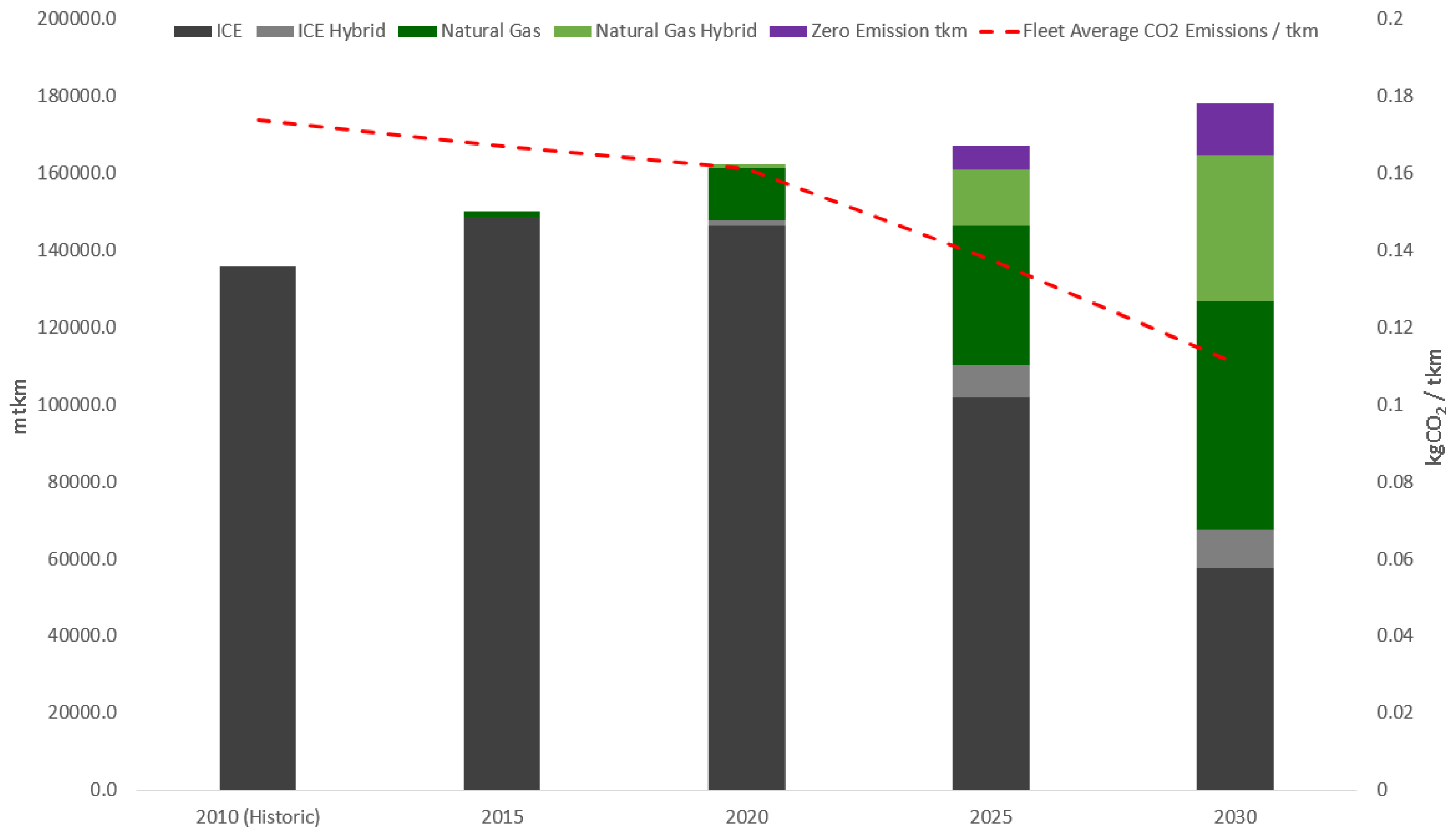
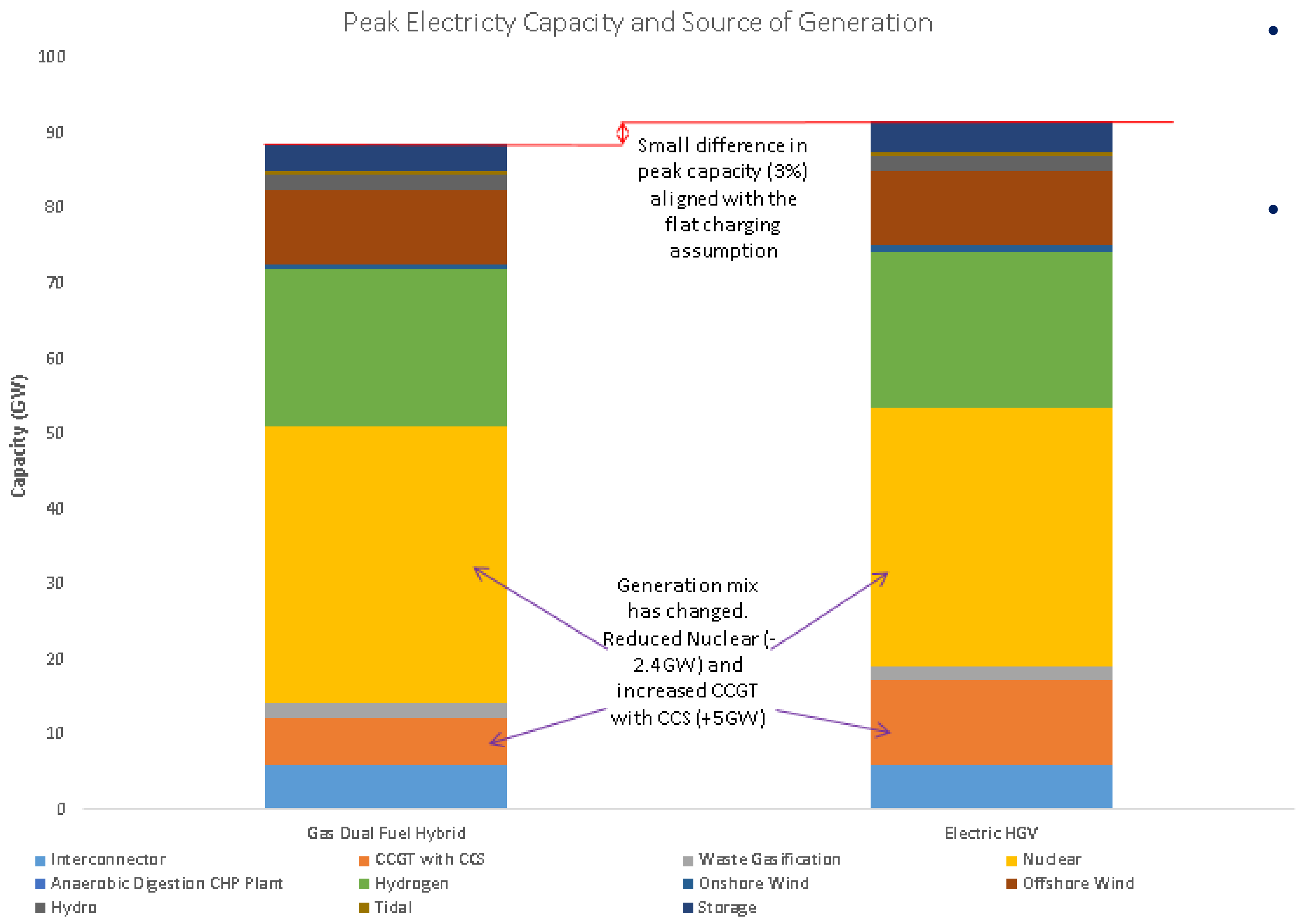
The ETI can also be followed on Twitter @the_ETI

HDV CO_2 Legislation - 2030 HGV and MGV Fleet

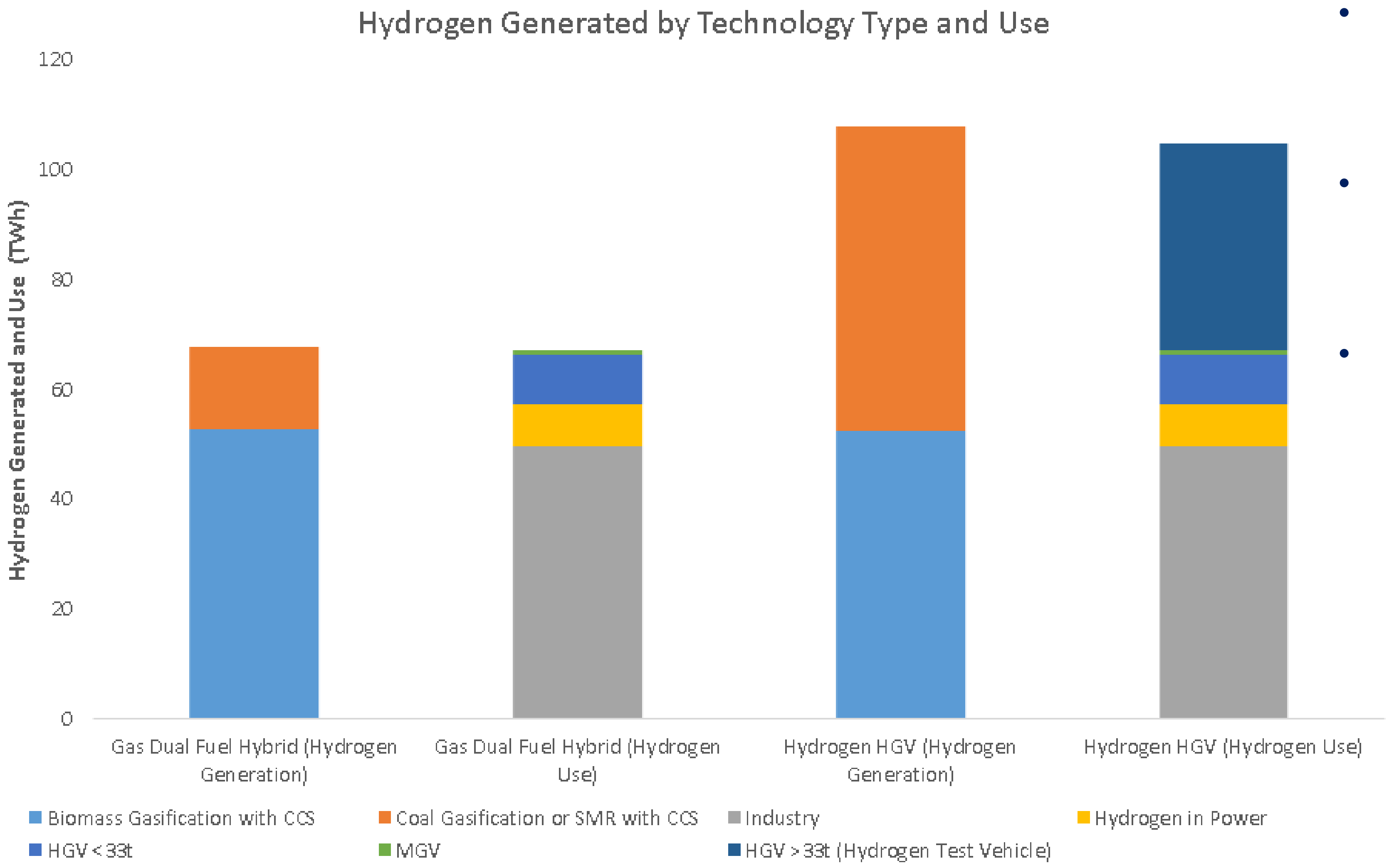


Effects of deploying Electric HGVs



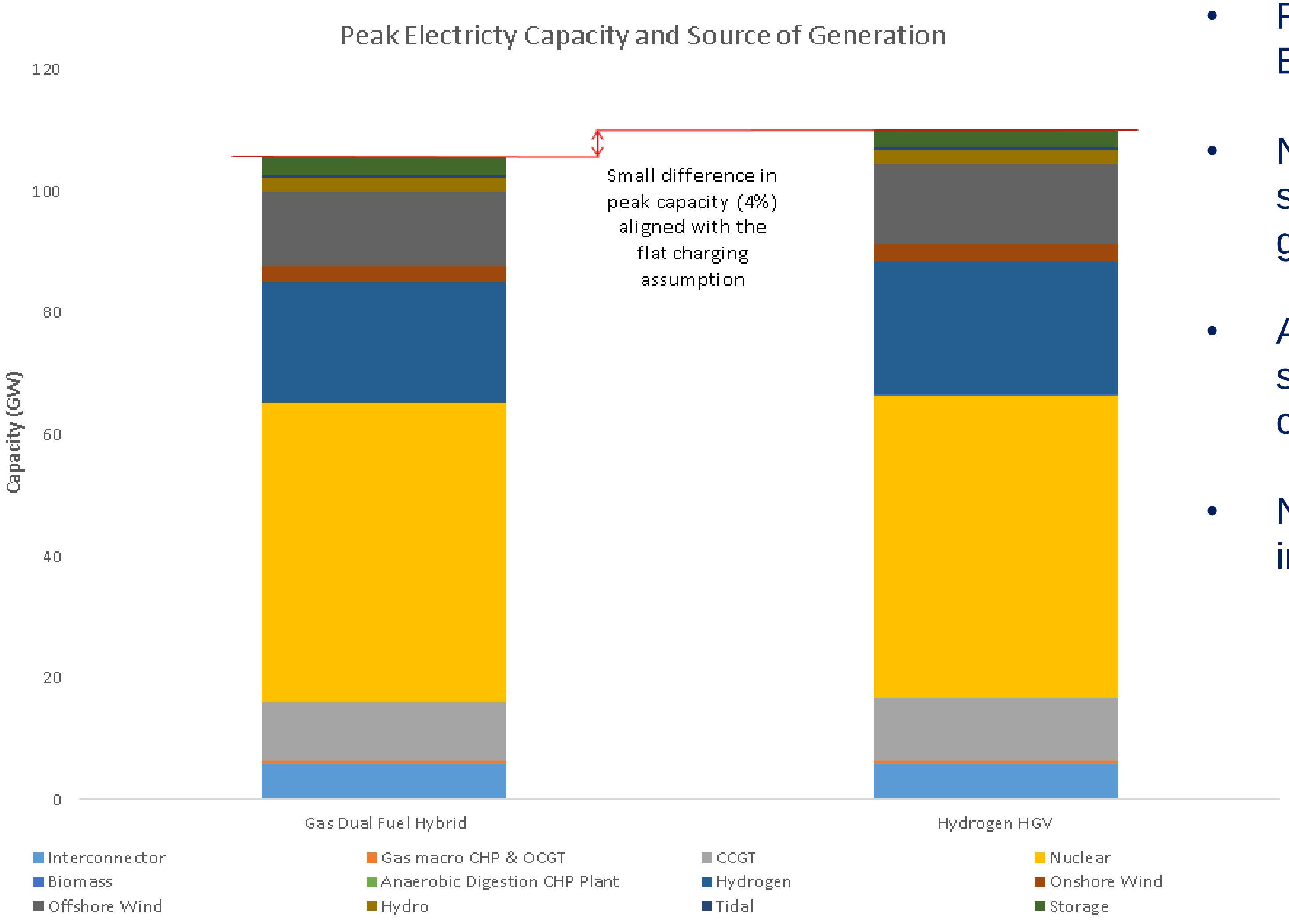
- Assumed a middle ground ('flat') charging profile which requires additional peak generation capacity.
- Electricity generation mix changes slightly.

Effects of deploying Hydrogen HGVs



- Any deployment of hydrogen vehicles required additional hydrogen generation capacity.
- Usually exhaust production of hydrogen by biomass gasification with CCS.
- Industry is always a big user of hydrogen.

Effects of deploying Hydrogen HGVs



- Removing CCS requires hydrogen generation by Electrolysis.
- Not enough hydrogen required (in the HGV sector alone) to merit building storage and generating outside of the peaks.
- All generation using electrolysis for the HGV sector requires additional electricity generation capacity.
- No imports of hydrogen/ammonia are assumed – international market.

Supergen Bioenergy

Transport biofuels

The Future of Thermal Propulsion Systems and Fuels
25 April 2019, University of Warwick

EPSRC Engineering and Physical Sciences Research Council

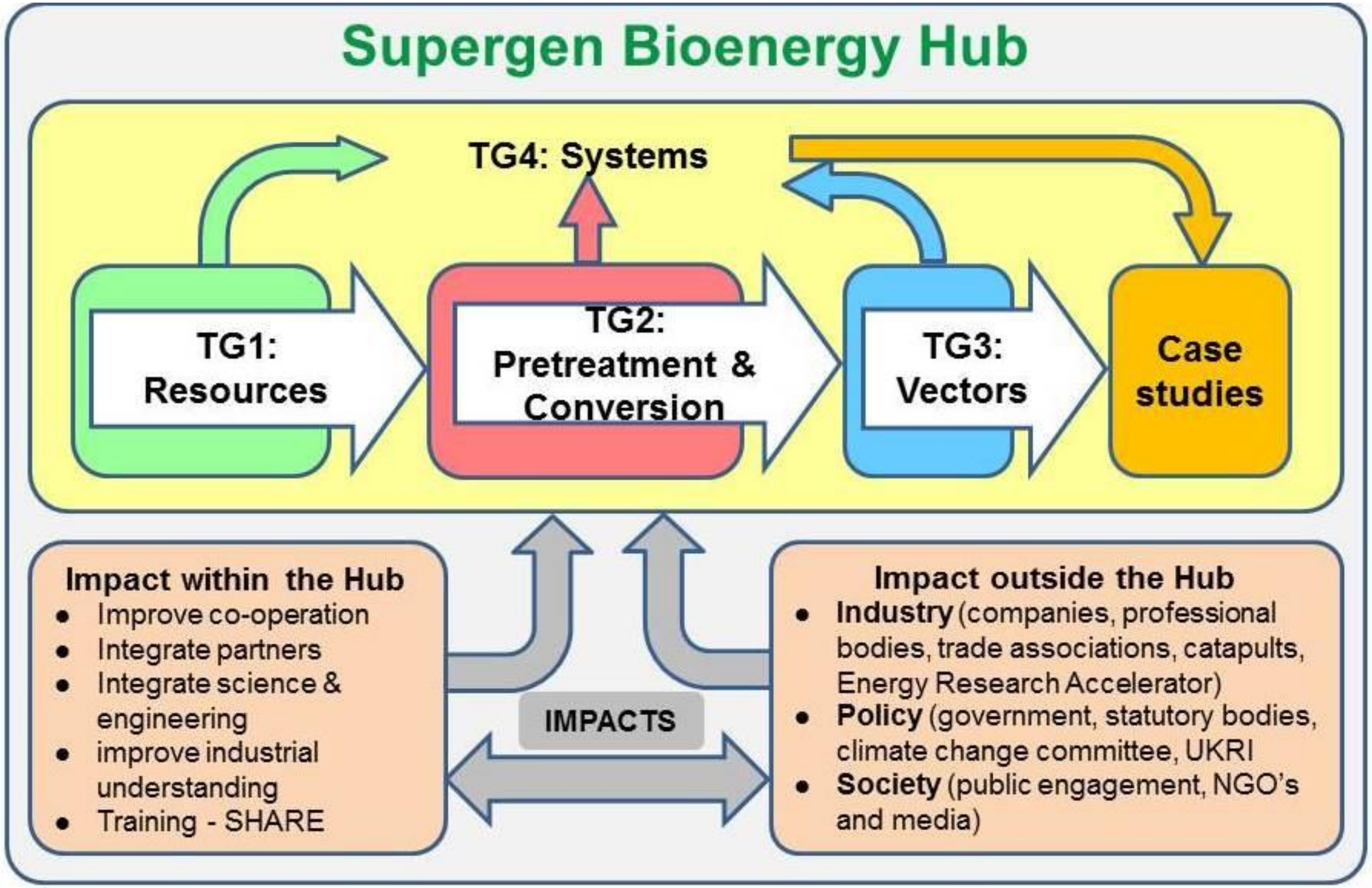
BBSRC bioscience for the future

Aston University Birmingham

EBRI European Bioenergy Research Institute

Energy and Bioproducts Research Institute

Bioenergy systems



EPSRC Engineering and Physical Sciences Research Council
BBSRC bioscience for the future
Supergen
Transformative energy research for a secure lower-carbon future

Potential for UK Bioenergy

- Up to 45% of UK bioenergy demand[1]
- 10% electricity (baseload)
- 50% heat (industrial, district, gas)
- 20% liquid fuels (aviation, shipping, heavy duty/mobile plant)

1. Welfle A., Gilbert P., Thornley P., Securing a bioenergy future without imports, Energy Policy, vol 68, 2014

Biofuels Rationale

- Secure
- Resilient
- Flexible
- Low carbon
- Economic

Secure, Resilient

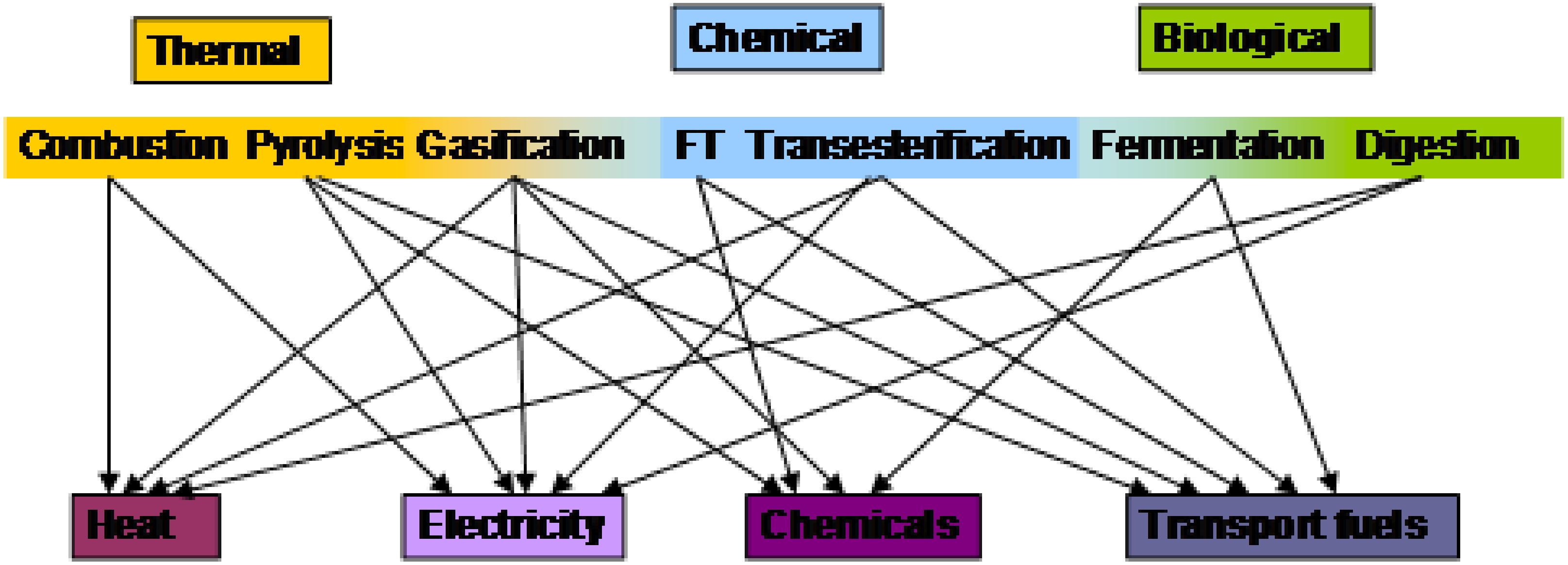








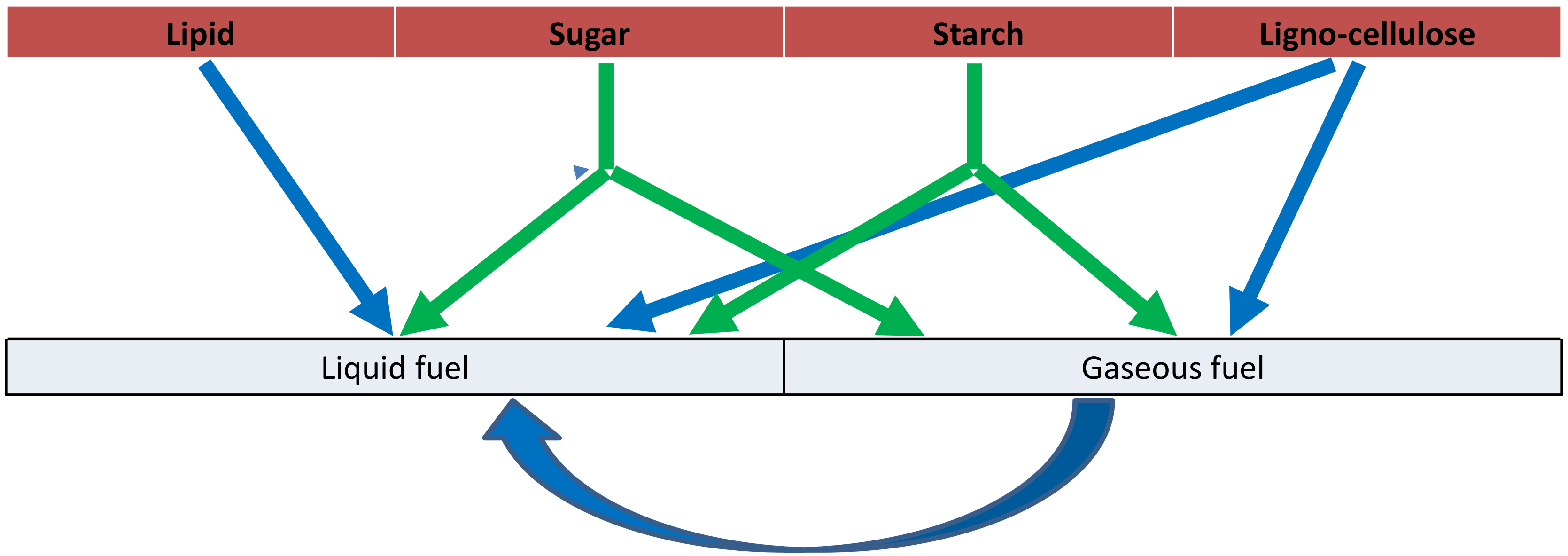
Flexible



Thornley, P., "Biofuels Review", Report for Government Office for Science, prepared as part of the Foresight Programme, June 2012

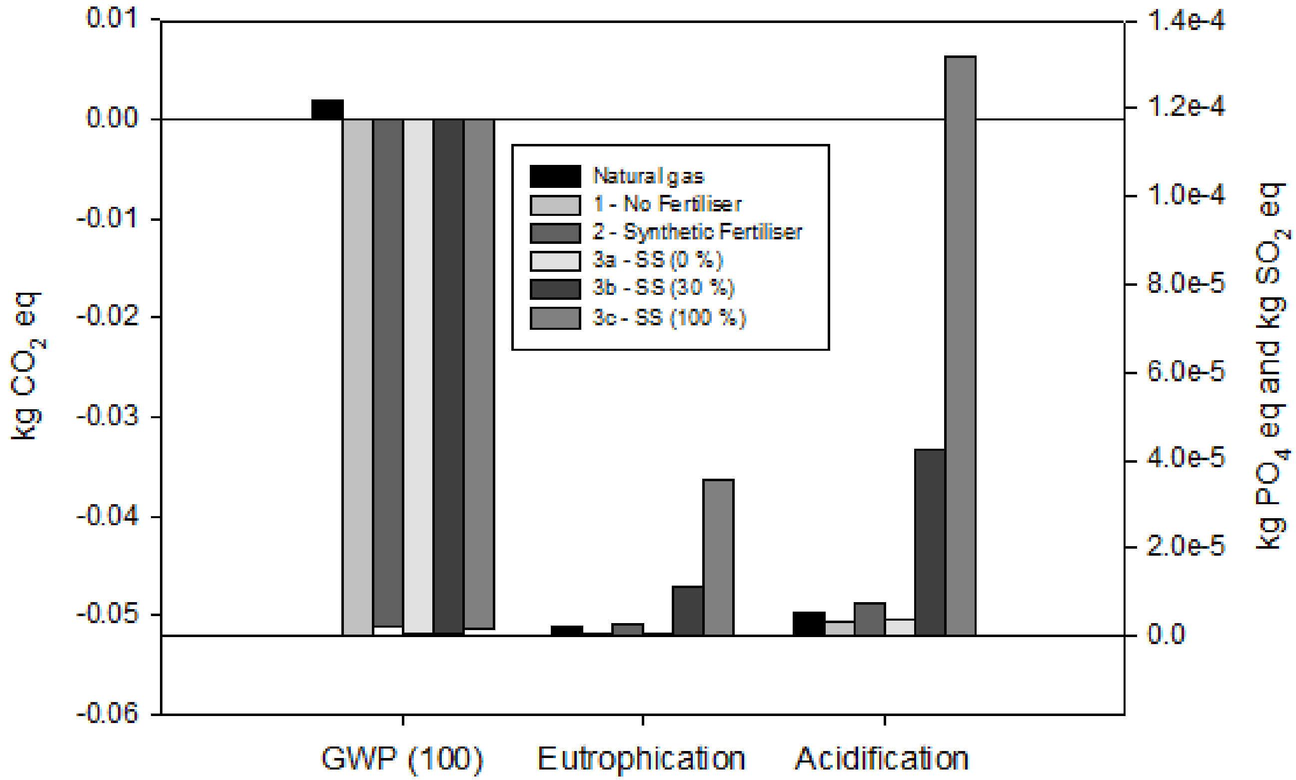
Flexible

Chemical and biological pathways



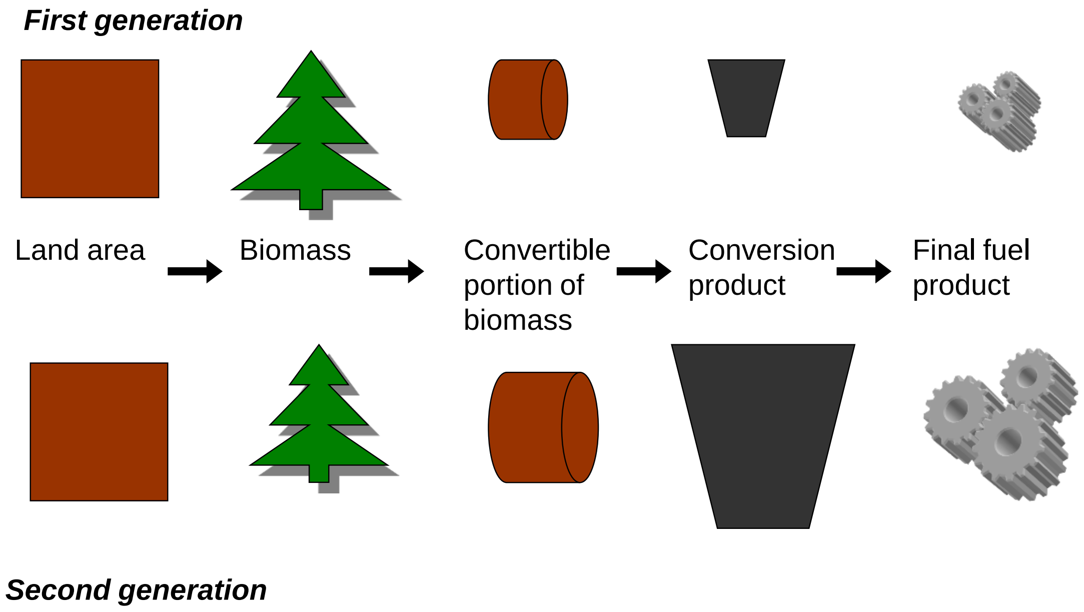
Low carbon feedstock

- Variation of GHG emissions with fertilizing regime



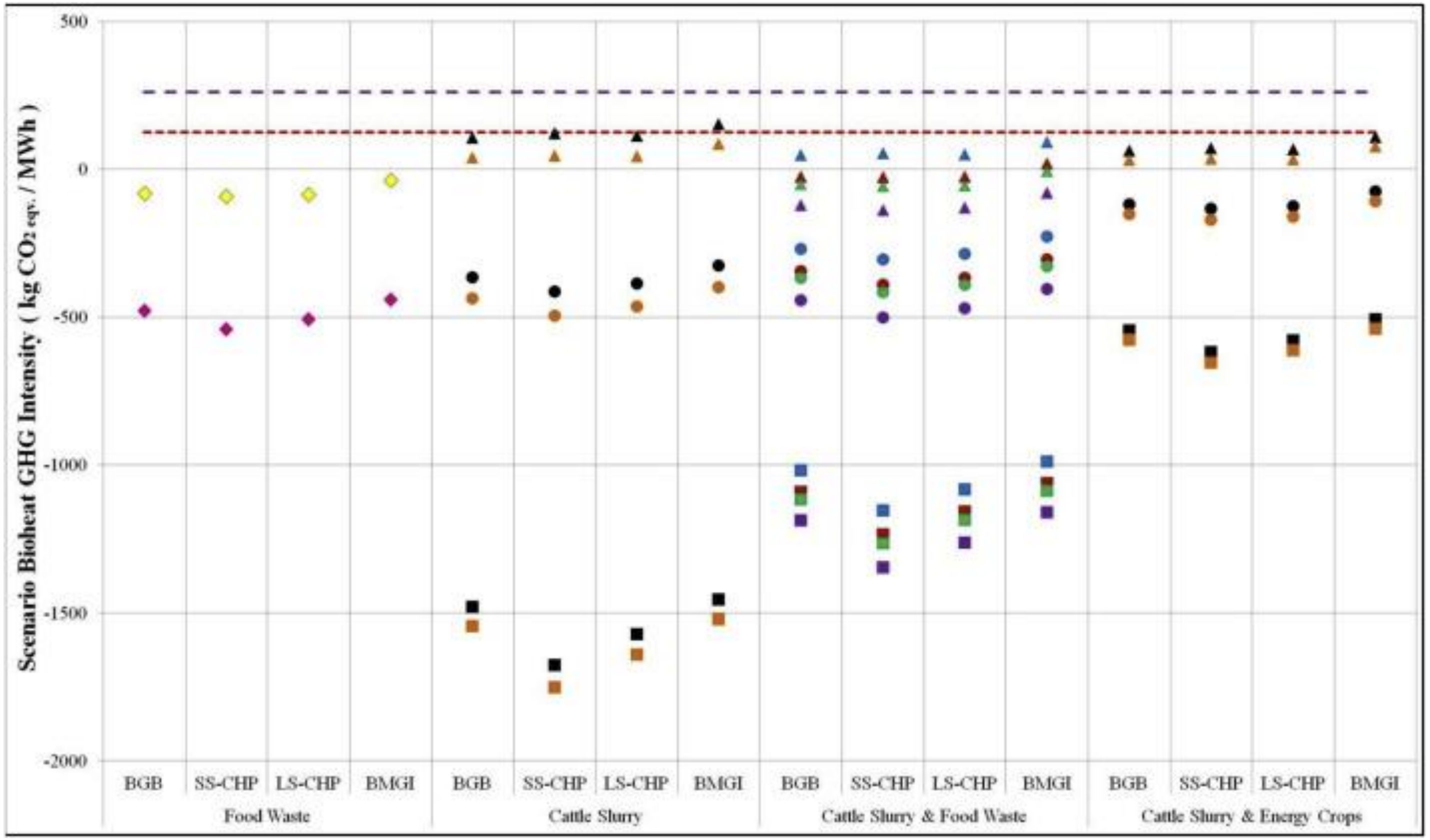
1 Gilbert et al., *""The influence of organic and inorganic fertiliser application rates on UK biomass crop sustainability", Biomass and Bioenergy 35 (2011), 1170-1181,*

Low carbon conversion



Thornley, P., “Biofuels Review”, Report for Government Office for Science, prepared as part of the Foresight Programme, June 2012

Low carbon – wider impacts



Welfle, A., Gilbert, P., Thornley, P., Stephenson, A., Generating low carbon heat from biomass: Life-cycle assessment of bioenergy scenarios, Journal of Cleaner Production 149, 448-460, 2017

Fuel challenges

- Oxygen content
- Physical contamination
- Moisture content
- Variability
- Ash composition
- Environmental contaminants e.g. metals, N
- Catalyst poisoning
- Material impacts e.g. corrosion, fouling

Evolution of UK Bioenergy

- Near term flexible heat and power (diverse feedstocks, pollutants, materials, ecosystem benefits, circular economy, pre-treatment)
- Medium term fungible hydrocarbons (catalysis, pre-treatment, yield increases)
- Long term gaseous vectors (gasification, AD, hydrogen) and negative emissions

Supergen
Bioenergy

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Emma Wylde

e.wylde@aston.ac.uk

www.supergen-bioenergy.net

EPSRC
Engineering and Physical Sciences Research Council

BBSRC
bioscience for the future

Medium Term Engine Evolution

The Future of Thermal Propulsion Systems and Fuels Workshop

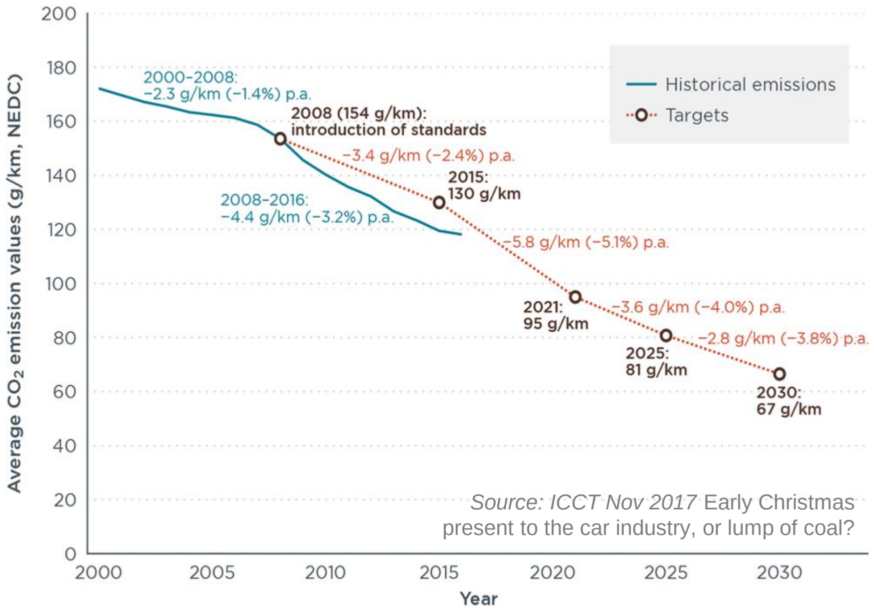
25th April 2019

Adrian Cooper

Head of New Technology

MAHLE Powertrain Limited

Challenges



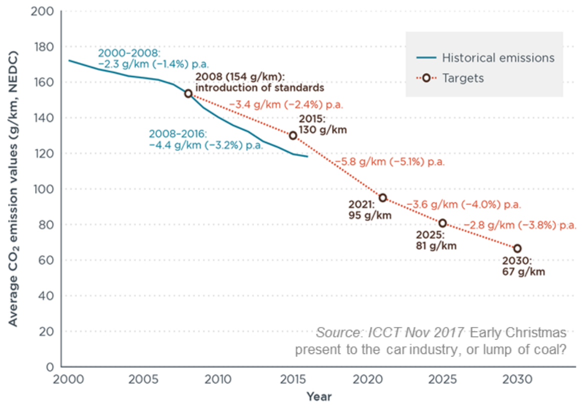
CO_2 Targets

Emissions Legislation

Challenges

MAHLE Powertrain

- Requirements:



CO_2 Targets

Emissions Legislation

- Changing landscape & ownership models


Photo of smog: http://www.blueskyinvm.com/ourfirm/

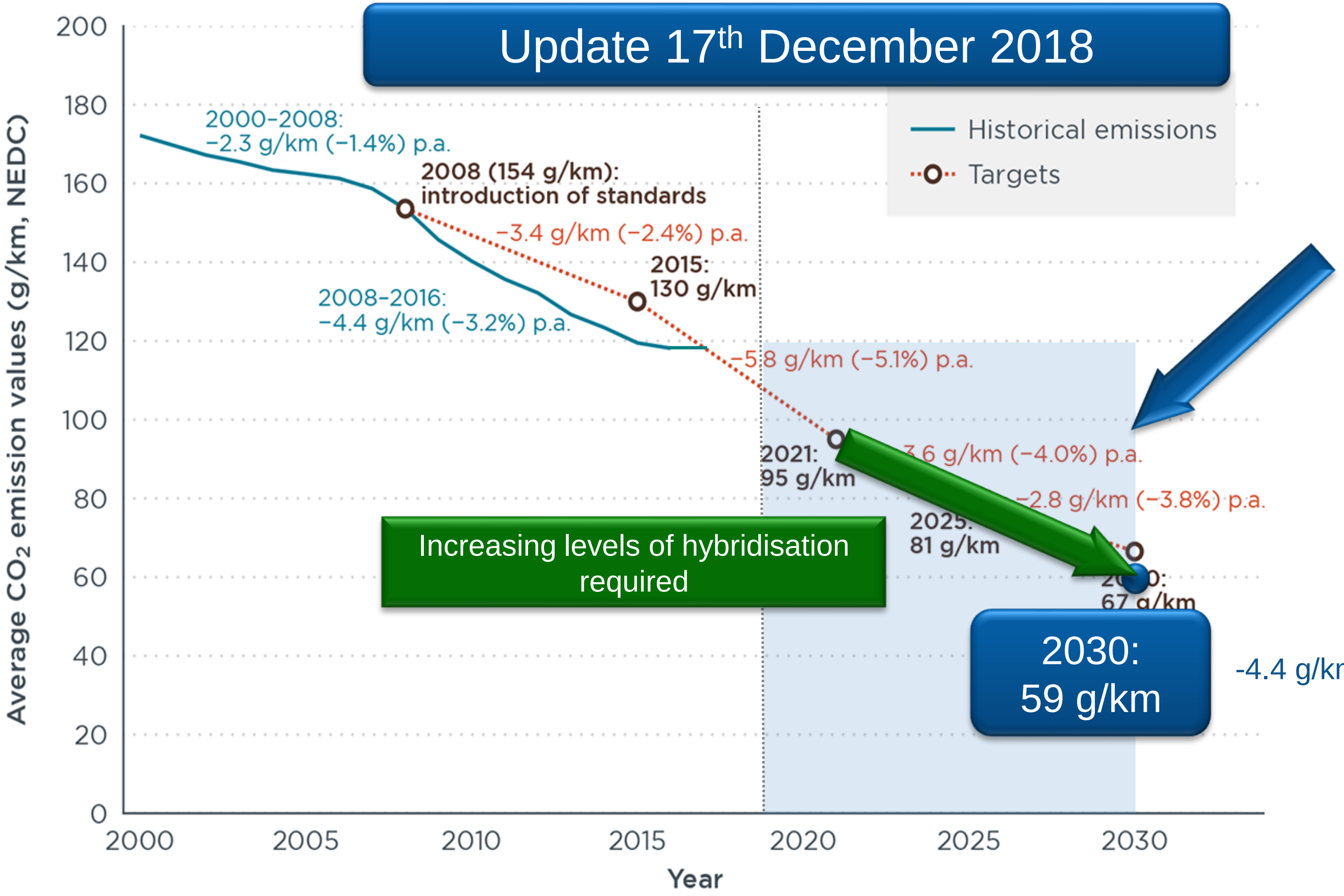
Clean air zones

Car sharing

Autonomy

- Other Influences:
- Customer Demands:
  - Cost of ownership
  - Refinement
  - Performance
  - Durability
- Politics
- Image & public perception

Fleet CO_2 Requirements



Would require pure ICE vehicle engine cycle average brake thermal efficiency to double over next decade

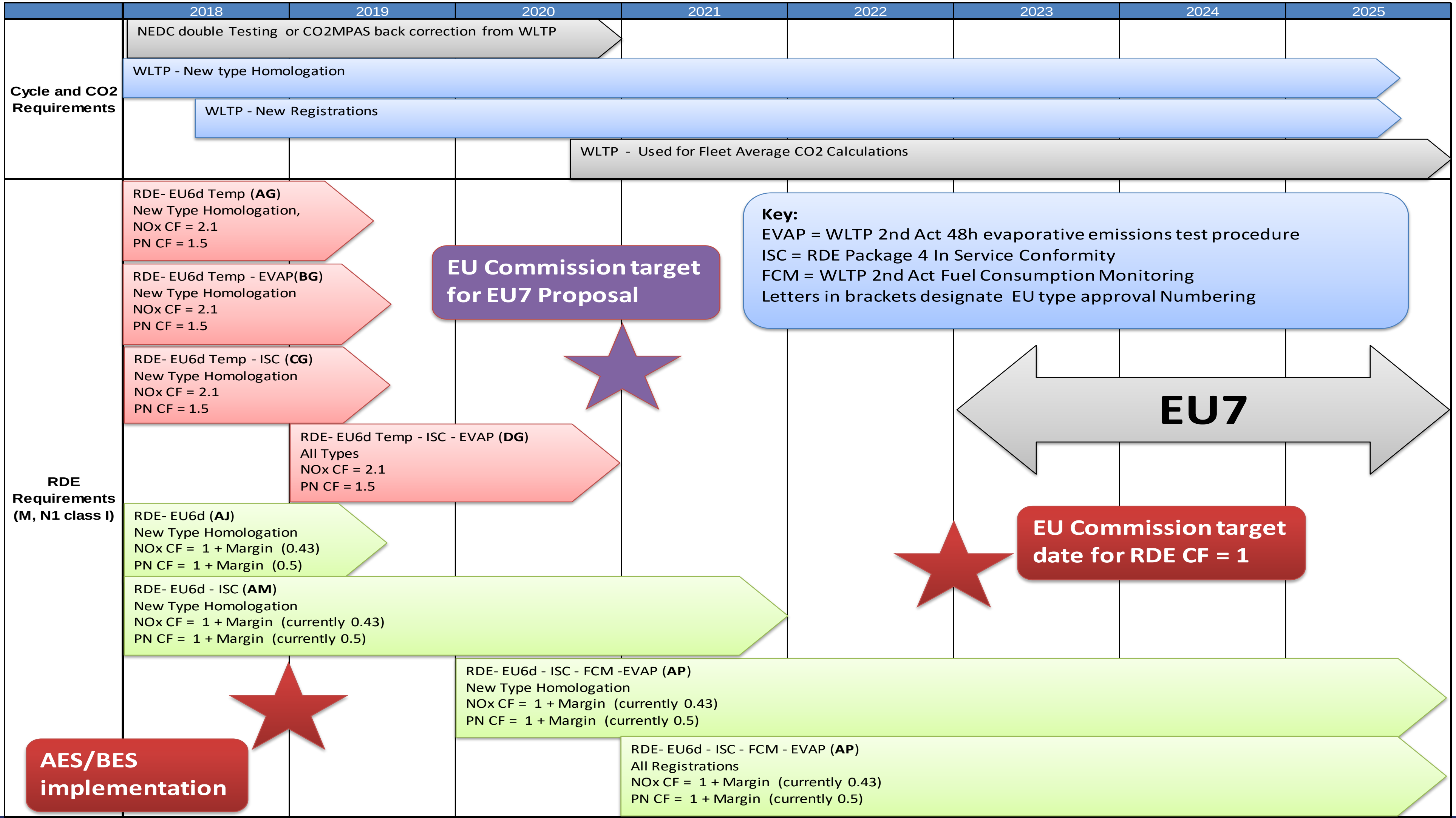
-4.4 g/km (-5.4%) p.a.

CO_2 targets are driving manufacturers towards increased electrification

Targets based on 1400 kg vehicle mass for “average vehicle”

Source: ICCT Nov 2017 Early Christmas present to the car industry, or lump of coal?

Future Certification Requirements

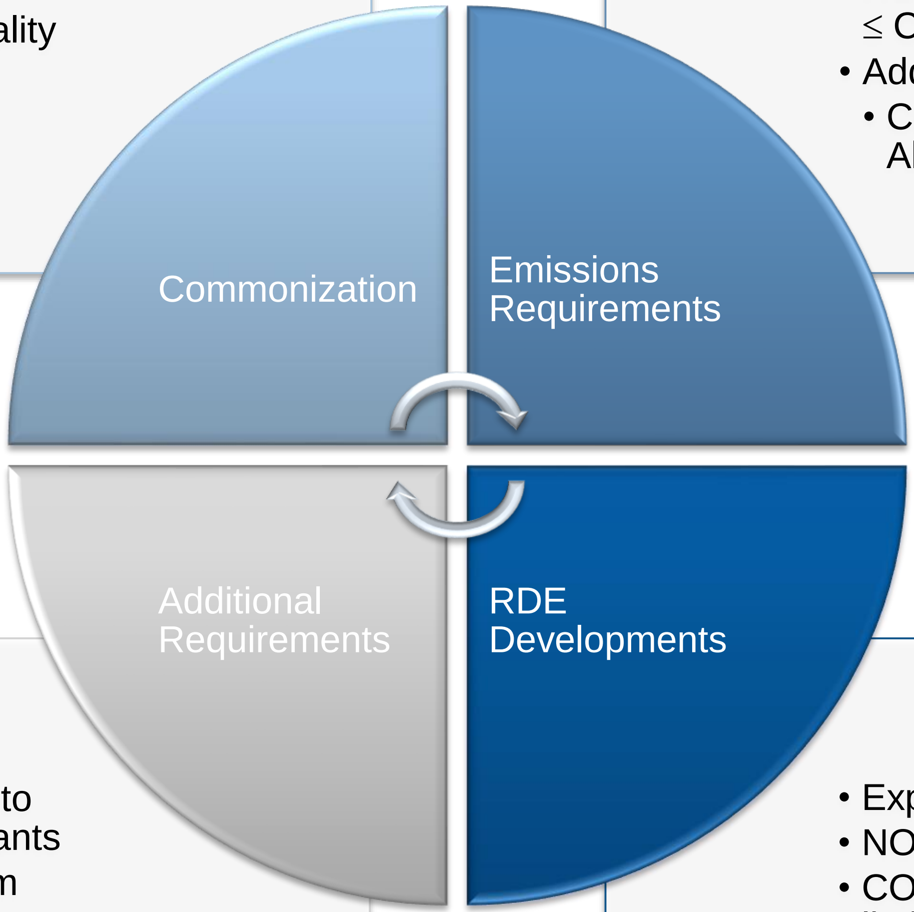


Medium Term Engine Evolution

EU7 – MAHLE View

- Fuel Neutrality
- Technology Neutrality

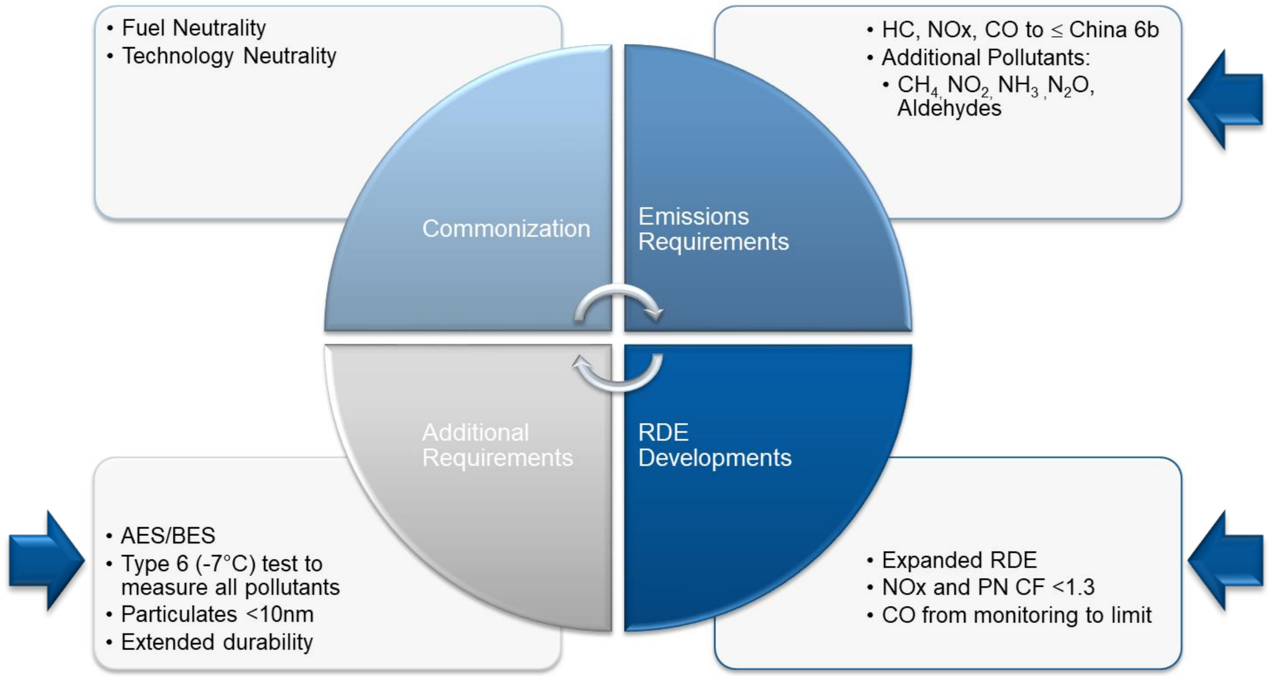
- HC, NOx, CO to ≤ China 6b
- Additional Pollutants:
  - CH_4, NO_2, NH_3, N_2O, Aldehydes



- AES/BES
- Type 6 (-7°C) test to measure all pollutants
- Particulates <10nm
- Extended durability

- Expanded RDE
- NOx and PN CF <1.3
- CO from monitoring to limit

EU7 – MAHLE View



PN

- GPF virtually mandatory
  - $\eta_{filtration}$ for GPF typically >75%
  - Smaller particles from PFI: $\eta_{filtration}$ >95%
- Typical base engine changes:
  - Injector to HDEV6 (350bar FIE system)
  - Increased attention to thermal management
- Improved EMS control
  - PN influence
  - Torque Boosting system support for cold ICE dynamic operation

Whole area λ=1

- Full RDE region compliance
  - Debate over entire map λ=1
- Low speed scavenging not allowed
  - Recover knee point: via eBoosting, eTurbo, eSC
  - Avoid knee point: Torque Boosting

After-treatment

- Sizing driven by RDE and robustness
  - Increased size and loading
- GPF package driven by platform / package
  - Addition of close-coupled

Engine Evolution

Engine measures:

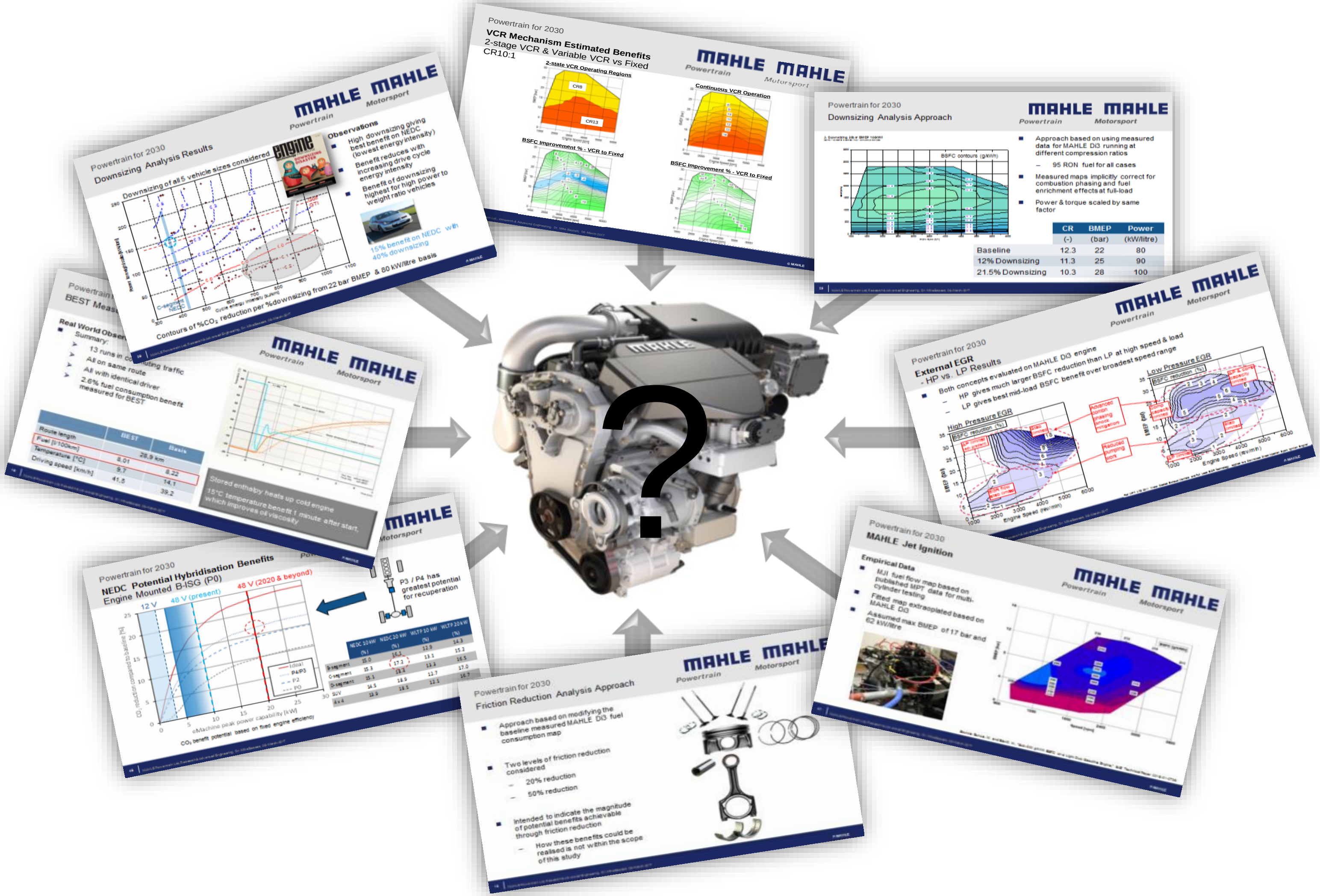
- Whole area λ=1 operation
- Higher fuel pressures
- Advanced boosting systems
- Additional after treatment solutions
- Enablers for higher CR / higher performance at λ=1 for same CR:
  - High & Low pressure EGR
  - Water Injection
  - Advanced combustion systems

Alternative fuels:

- Biofuels / CNG

Increased electrification:

- PHEV & MHEV applications
- Different operating strategies
- Low cost / high efficiency engine



Engine Evolution

MAHLE Powertrain

Engine measures:

- Whole area λ=1 operation
- Higher fuel pressures
- Advanced boosting systems
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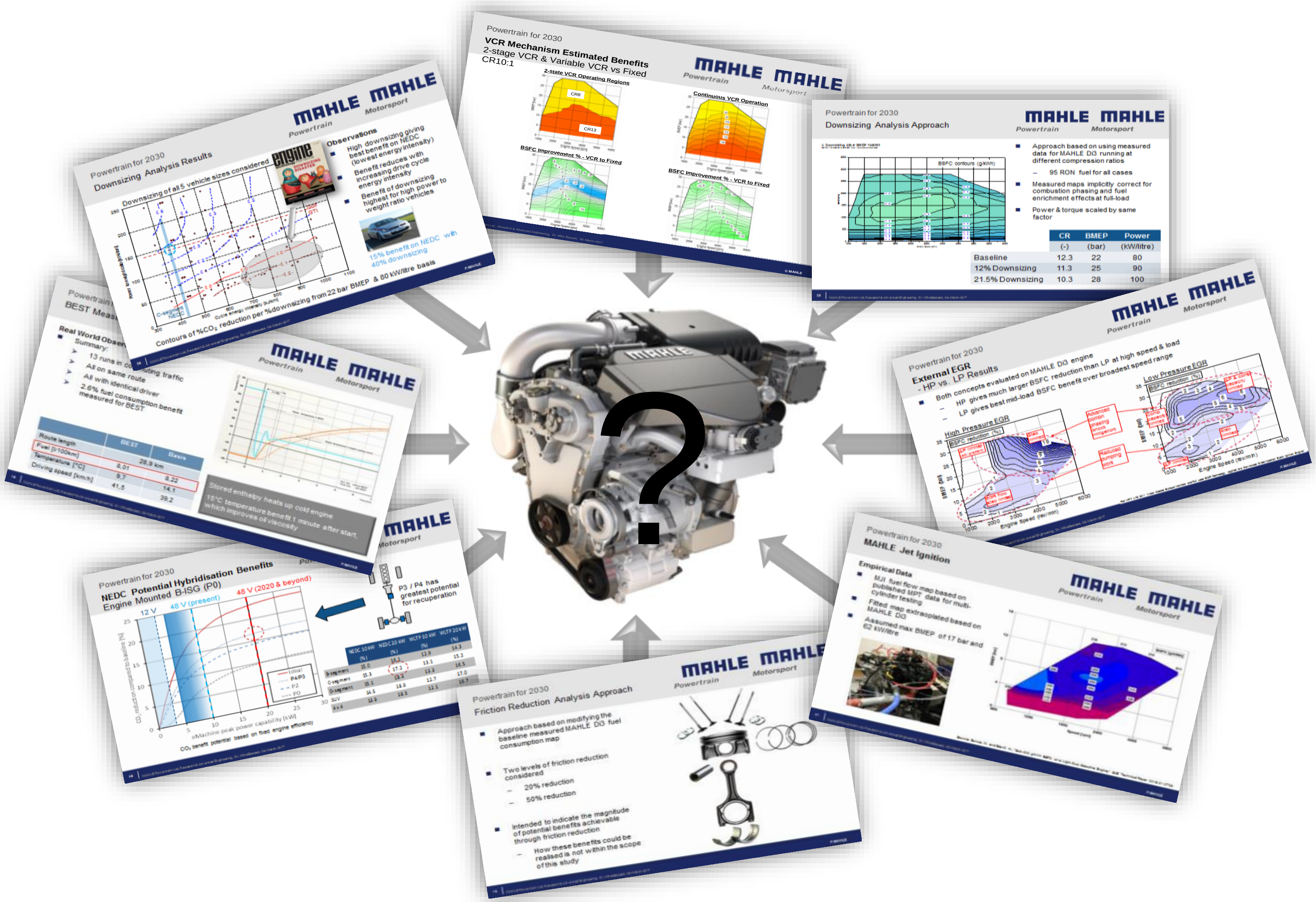
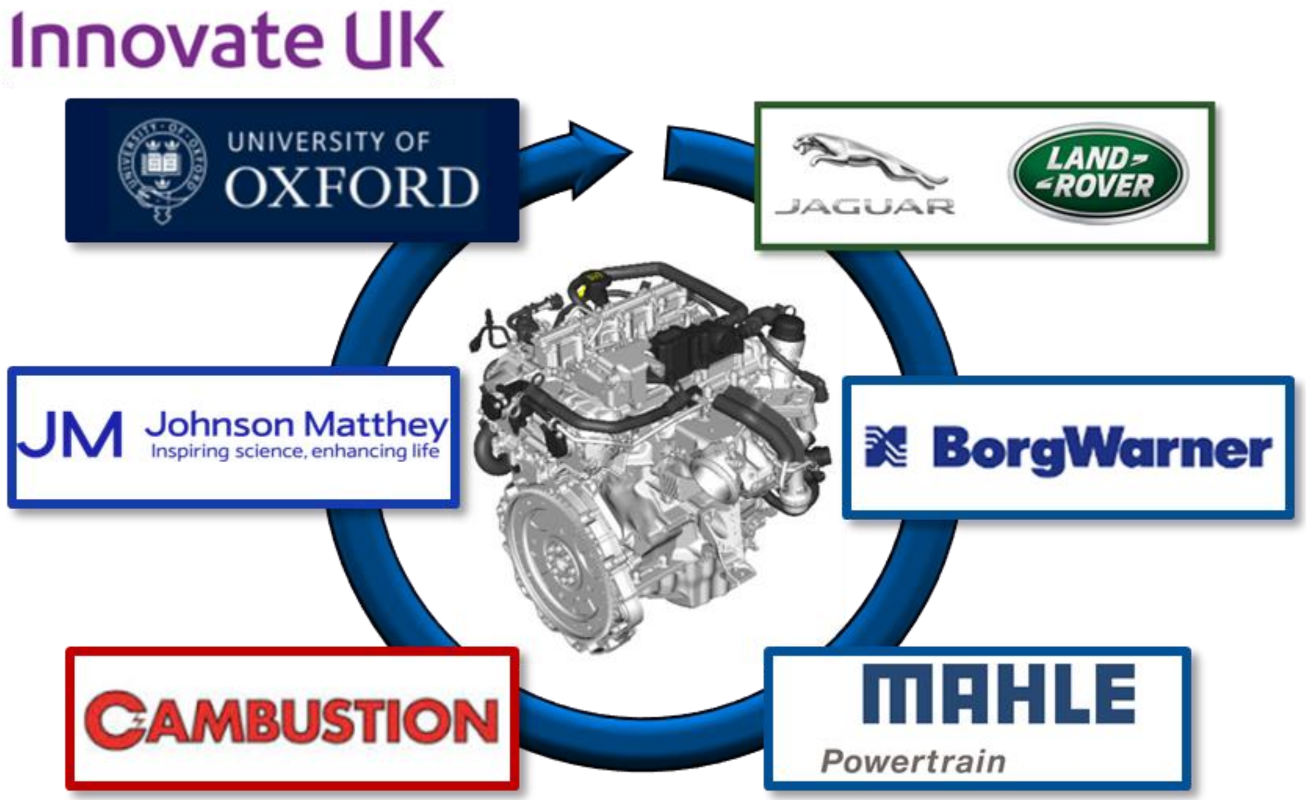


Advanced Boosting Systems

MAHLE Powertrain

HyPACE – Hybrid Petrol Advanced Combustion Engine



Aims:

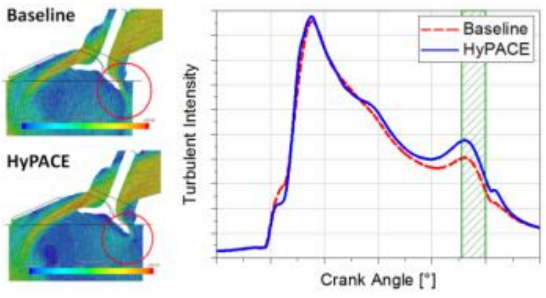
- **10%** vehicle fuel economy benefit
- Specific output of **90-100 kW/l**
- Maximise area of **λ = 1** operation
- Target application in **MHEV & PHEV** platforms
- Evaluate after-treatment systems to meet forthcoming requirements

Advanced Boosting Systems

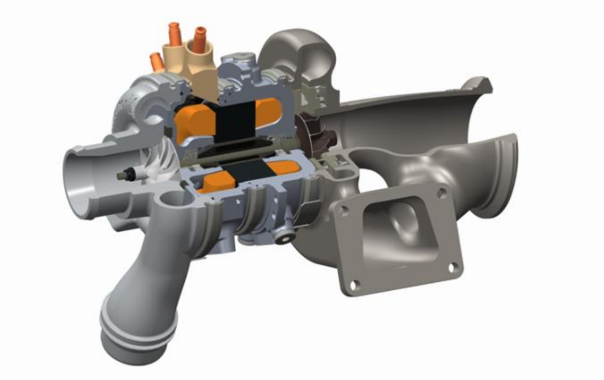
MAHLE Powertrain

Summary:

Revised intake port



BorgWarner eTurbo™



-23%

-4.6%

90kW/l @ λ = 1

Improved BSFC

Extended λ = 1

-70%

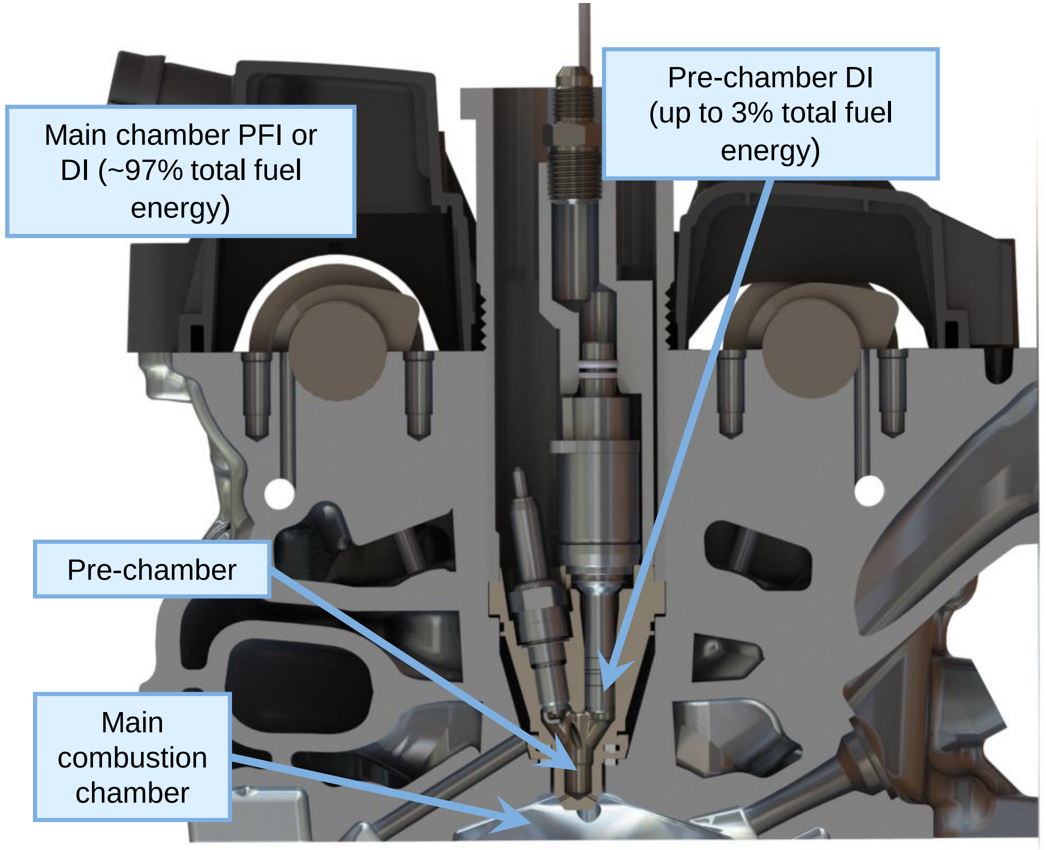
2-3% Benefit

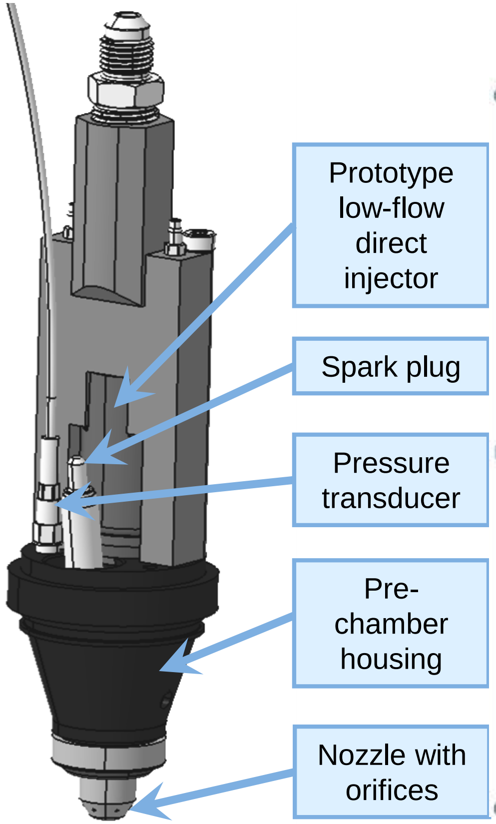
Faster Transients

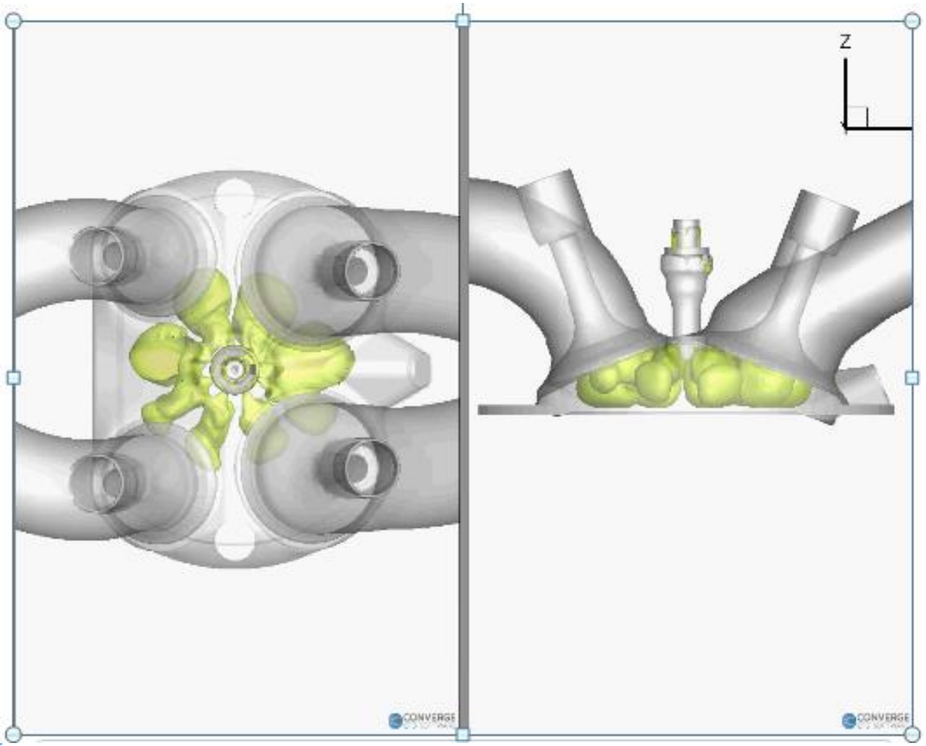
Energy Recovery

Advanced Combustion Systems

- MAHLE Jet Ignition® replaces the spark plug in a SI engine with a pre-chamber combustor
- Enables faster combustion, improved knock tolerance and increased dilution tolerance



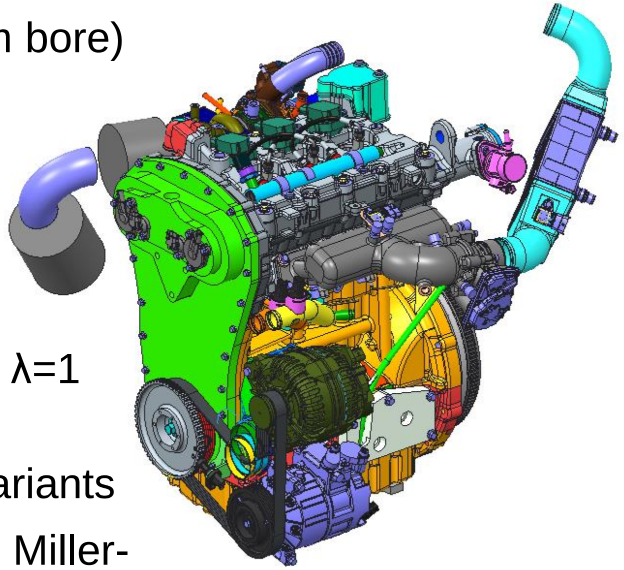




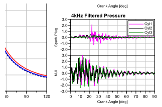
Advanced Combustion Systems

- Application of MAHLE Jet Ignition® to the MAHLE Downsizing engine

- **US based testing**
- High Efficiency Lean Variant
  - Based on 1.5 litre (83mm bore)
  - Targeting 45% brake thermal efficiency
- Lean boost concept
- **UK based testing**
- High Efficiency / Performance λ=1 Variant
  - Based on 1.2 & 1.5 litre variants
  - Adaption for High CR with Miller-cycle and EGR studies
  - High Specific output variant >100kW/l



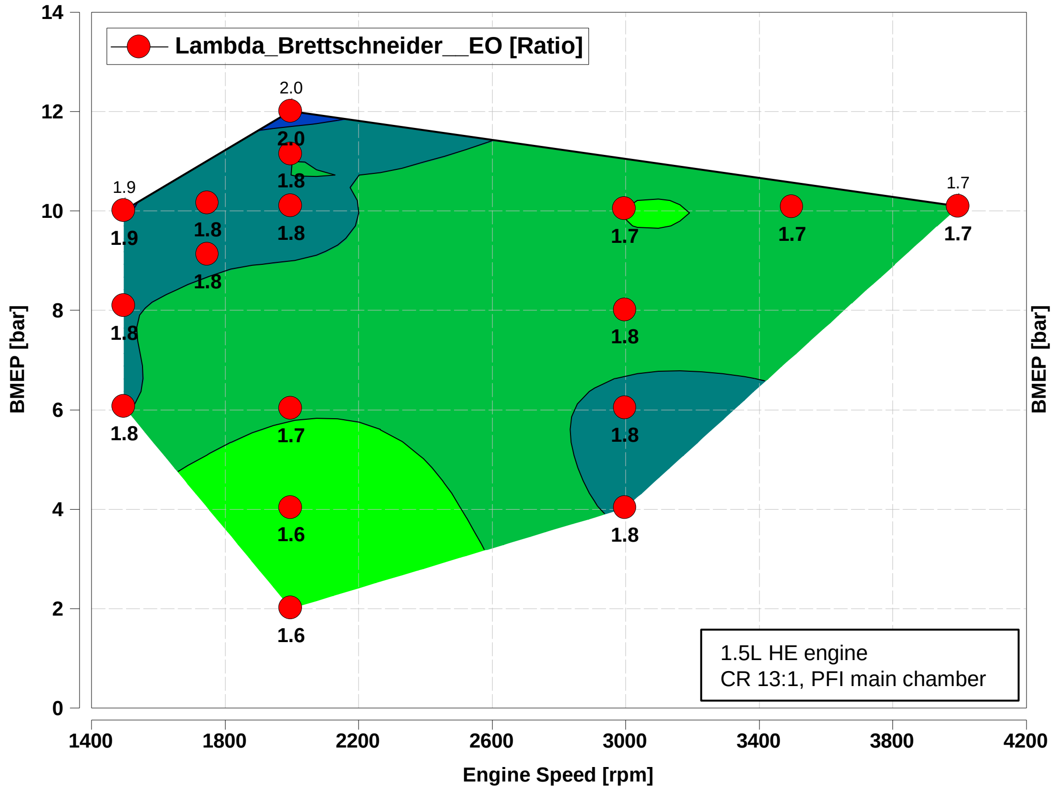
- **Passive MJI Combustion**

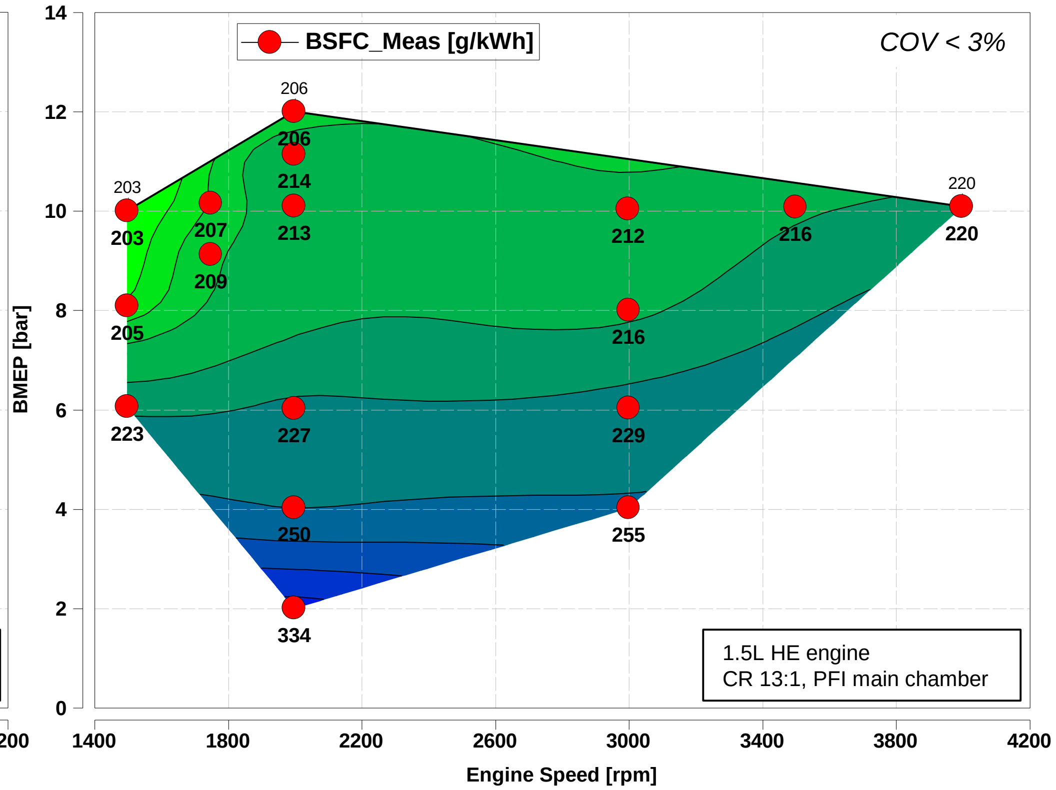


	MFB 50%	10-90% Burn Duration	PMax	RMax	COV NMEP
CSP	17.4	25.9	71.2	1.98	2.54
MJI	8.6	15.4	90.9	5.2	0.85

Advanced Combustion Systems

- Minimum BSFC achieved on baseline geometry = 203 g/kWh at compression ratio = 13:1
  - Corresponds to peak BTE = 41%
  - Optimal CA50 throughout the displayed mini-map, indicating that an increase in CR is feasible





Alternative Fuels

MAHLE Powertrain

CNG Optimised DI3

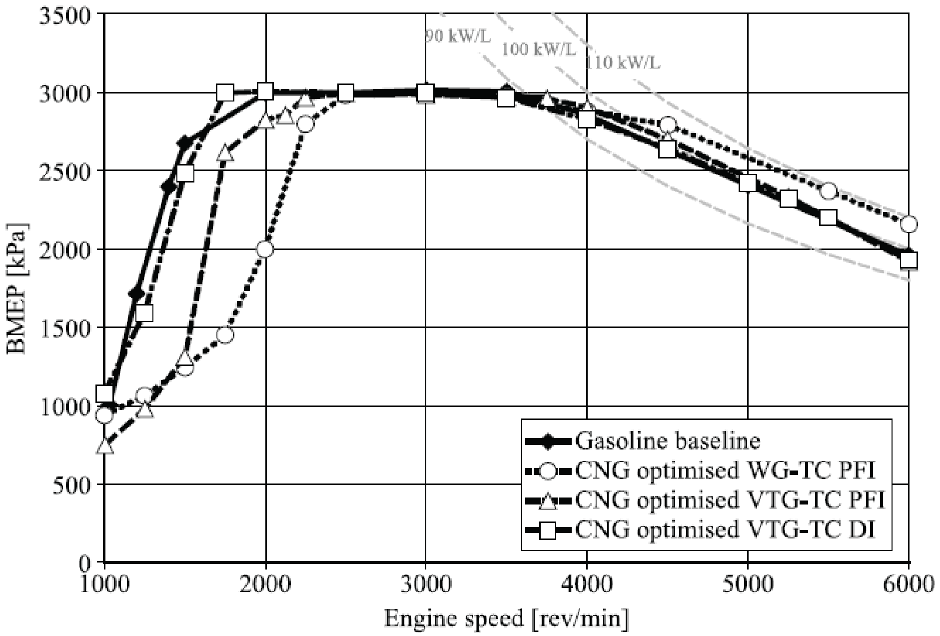
- CNG MAHLE technology demonstrator engine
  - Optimised for CNG operation
- Cylinder and power cell unit components and valves redesigned to perform at 180 bar peak cylinder pressure
- VTG turbocharger operating at up to 260k rev/min

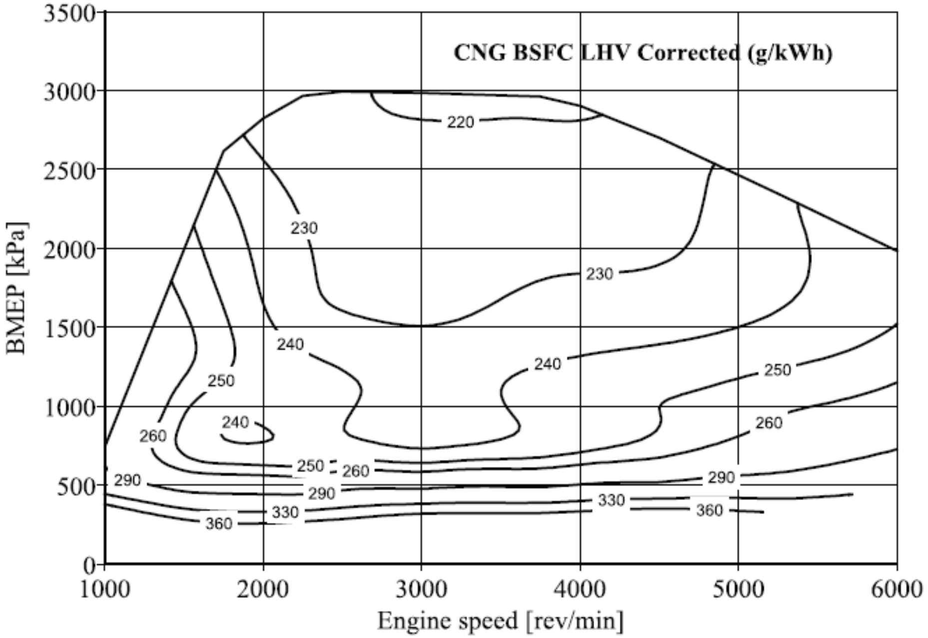
Main Dimensions and Engine Data		
Configuration	-	In-line 3 Cylinder
Capacity	cm^3	1200
Bore	mm	83.0
Stroke	mm	73.9
Compression Ratio	-	13.3 : 1
Turbocharger	-	BMTS 1-stage, VTG
Peak Power	kW	120 (5000-6000 min^{-1})
Specific Powe	kW/litre	100 (5000-6000 min^{-1})
BMEP	bar	30 (1600-4000 min^{-1})

- 980°C Max turbine inlet temperature

Alternative Fuels

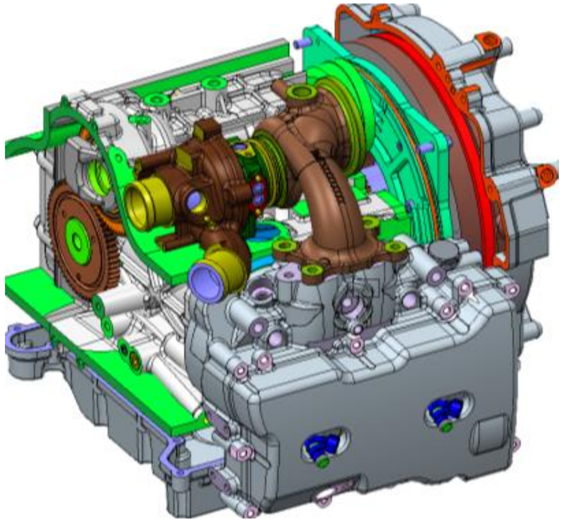
- High downsizing of a CNG engine with very low emissions
- **18-24% CO_2 reduction** compared to gasoline
  - Even on aggressive and real world cycles
  - Up to 50% lower CO_2 at maximum power





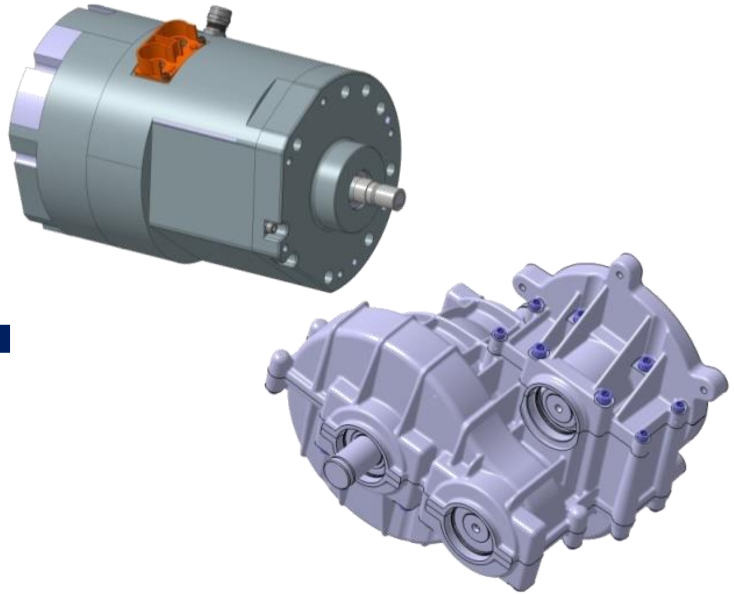
Low Cost High Efficiency Engine

MAHLE Powertrain



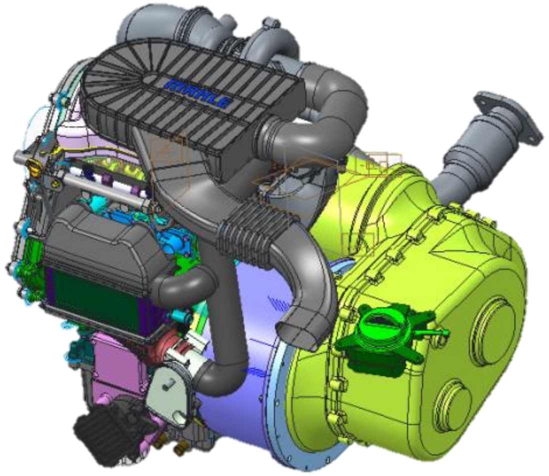
"MAHLE Dedicated Hybrid Engine"

+



"MAHLE Integrated Electric Powertrain"
eAxle plus generator

=



MAHLE

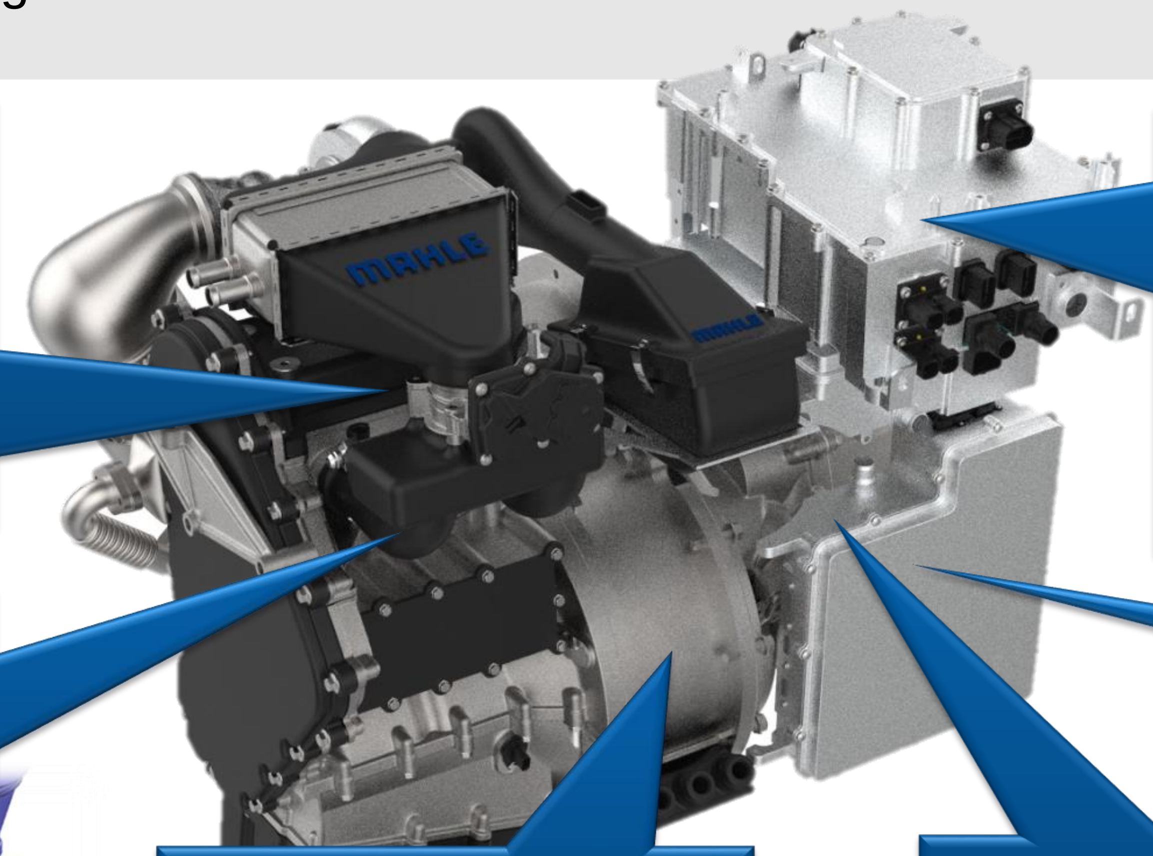
MODULAR POWERTRAIN

MAHLE Modular Powertrain

- Electric powertrain provides full vehicle dynamic performance without IC engine
- IC maintains battery SOC when battery depleted – series and parallel mode capable

Low Cost High Efficiency Engine

MAHLE Powertrain

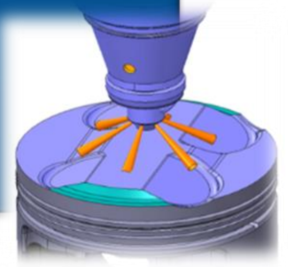


Simplified, high-efficiency, ICE

Electric drive enables ICE power to be reduced to ~1/3 of conventional

High-efficiency, ICE

Advanced pre-chamber combustion



Integrated generator
Series hybrid mode

Compact, high-power, traction motor and power electronics provides fully electric drive capability.

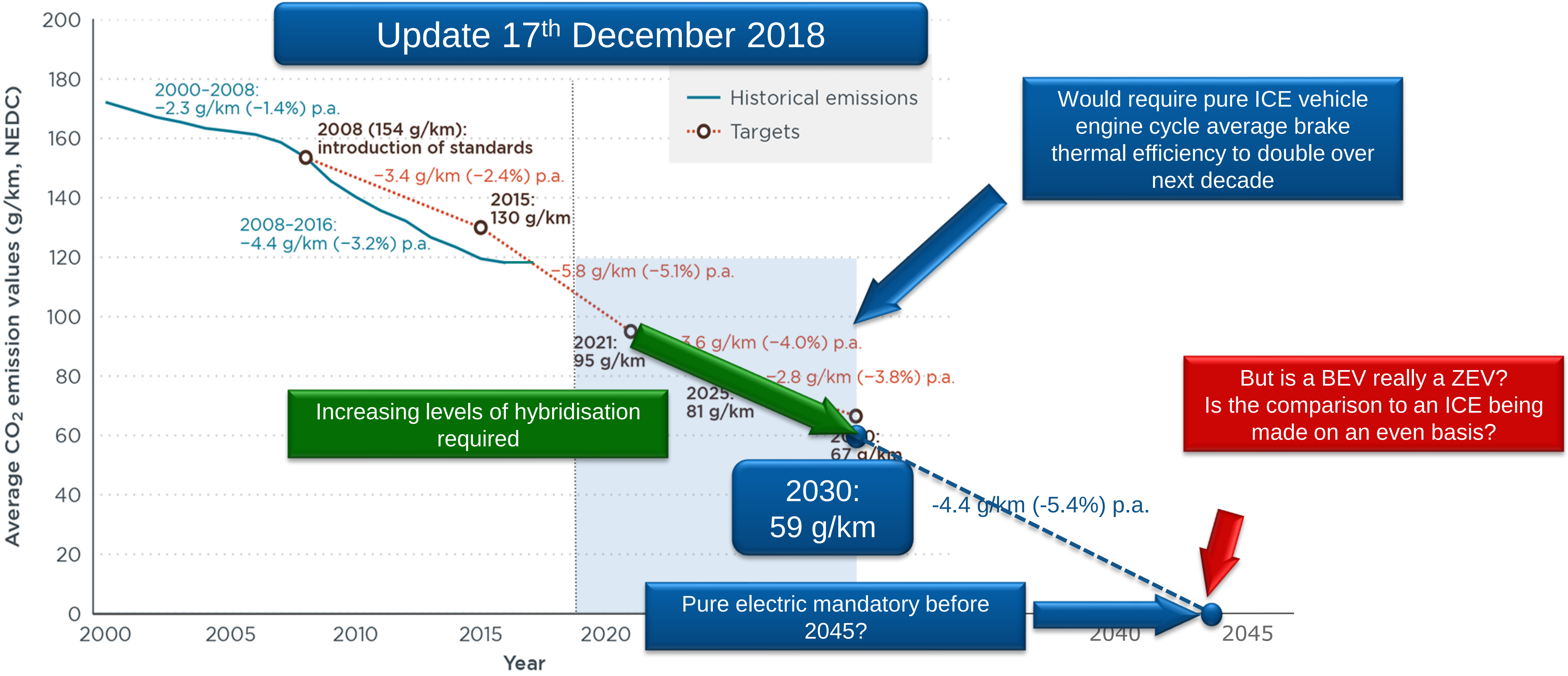
Removes transients from ICE

Multi-speed transmission

Dual operating mode
Series/parallel modes

Hybridisation enables ICE power to be reduced and reduction of transient operation

Fleet CO_2 Requirements



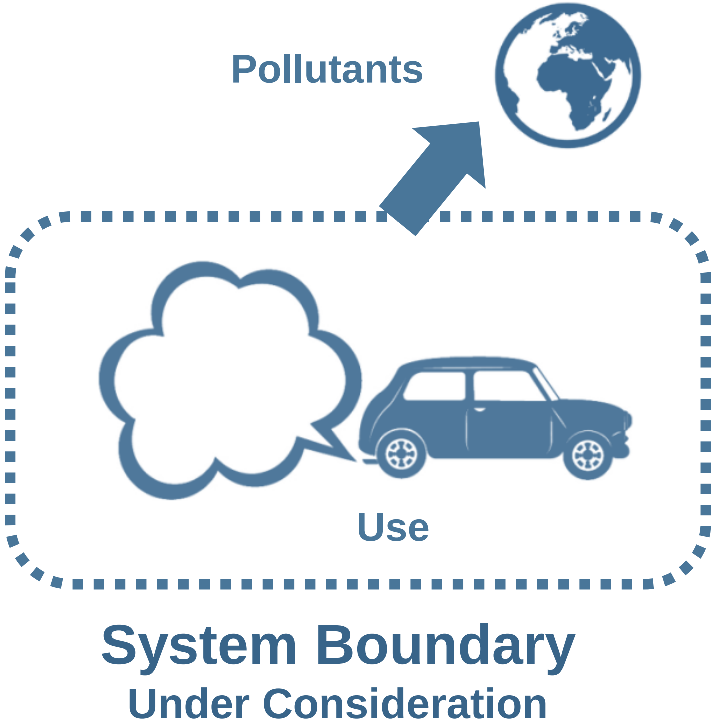
CO_2 targets are driving manufacturers towards increased electrification

Targets based on 1400 kg vehicle mass for “average vehicle”

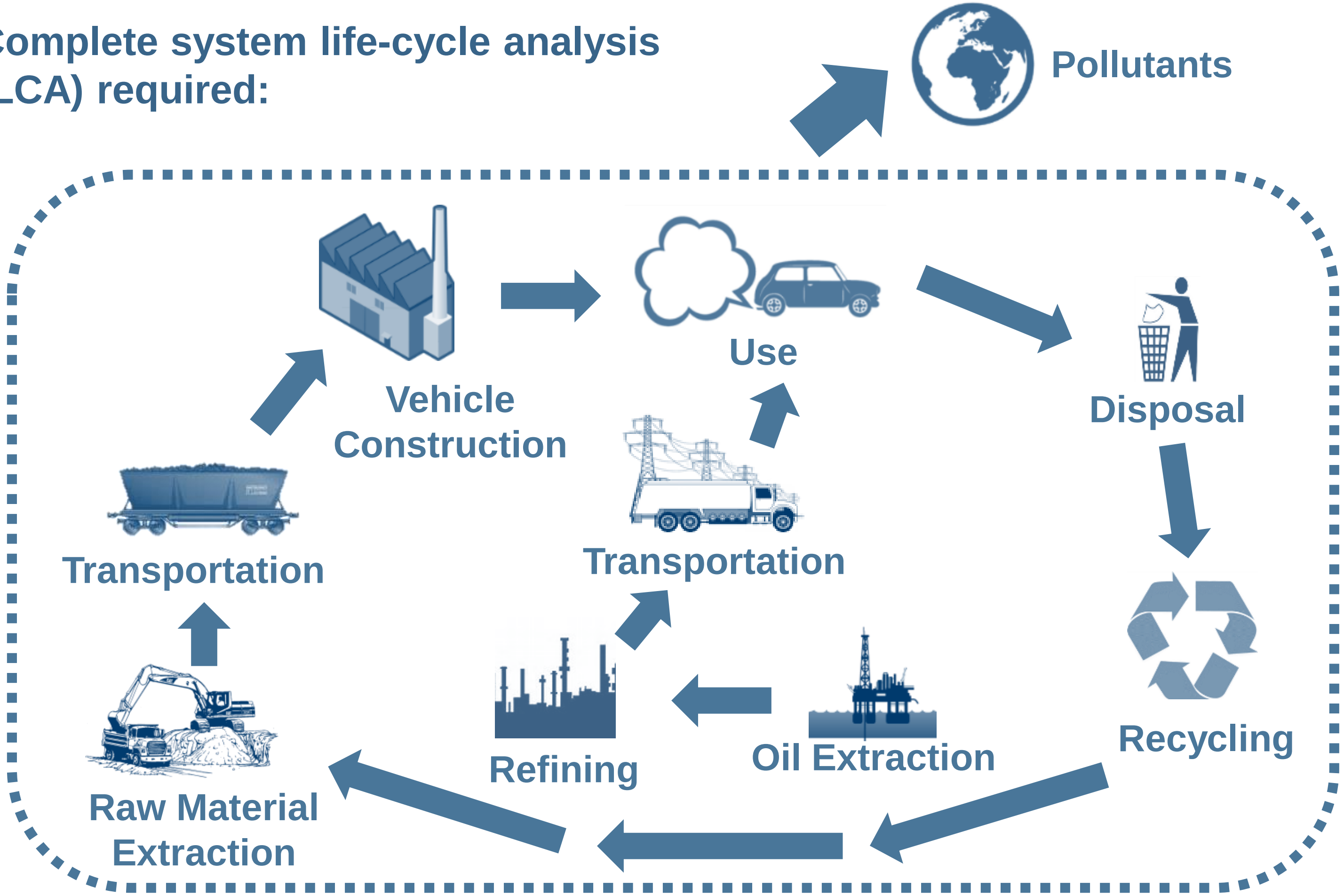
Source: ICCT Nov 2017 Early Christmas present to the car industry, or lump of coal?

Life-cycle Analysis

Typically only in use tailpipe emissions considered:

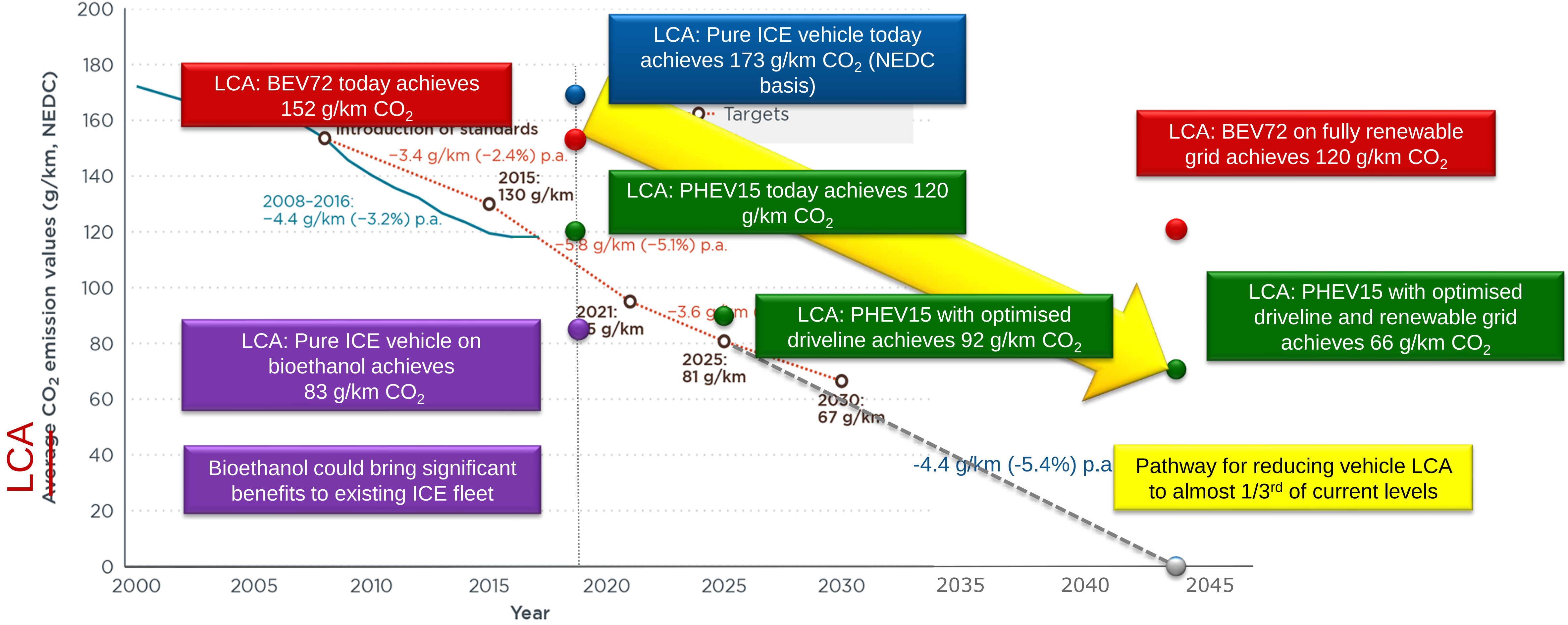


Complete system life-cycle analysis (LCA) required:



Need to consider the whole system lifecycle

Fleet CO_2 Requirements – Where are we on a LCA basis?



CO_2 targets are driving manufacturers towards increased electrification

Targets based on 1400 kg vehicle mass for "average vehicle"

Source: *ICCT Nov 2017* Early Christmas present to the car industry, or lump of coal?

Summary

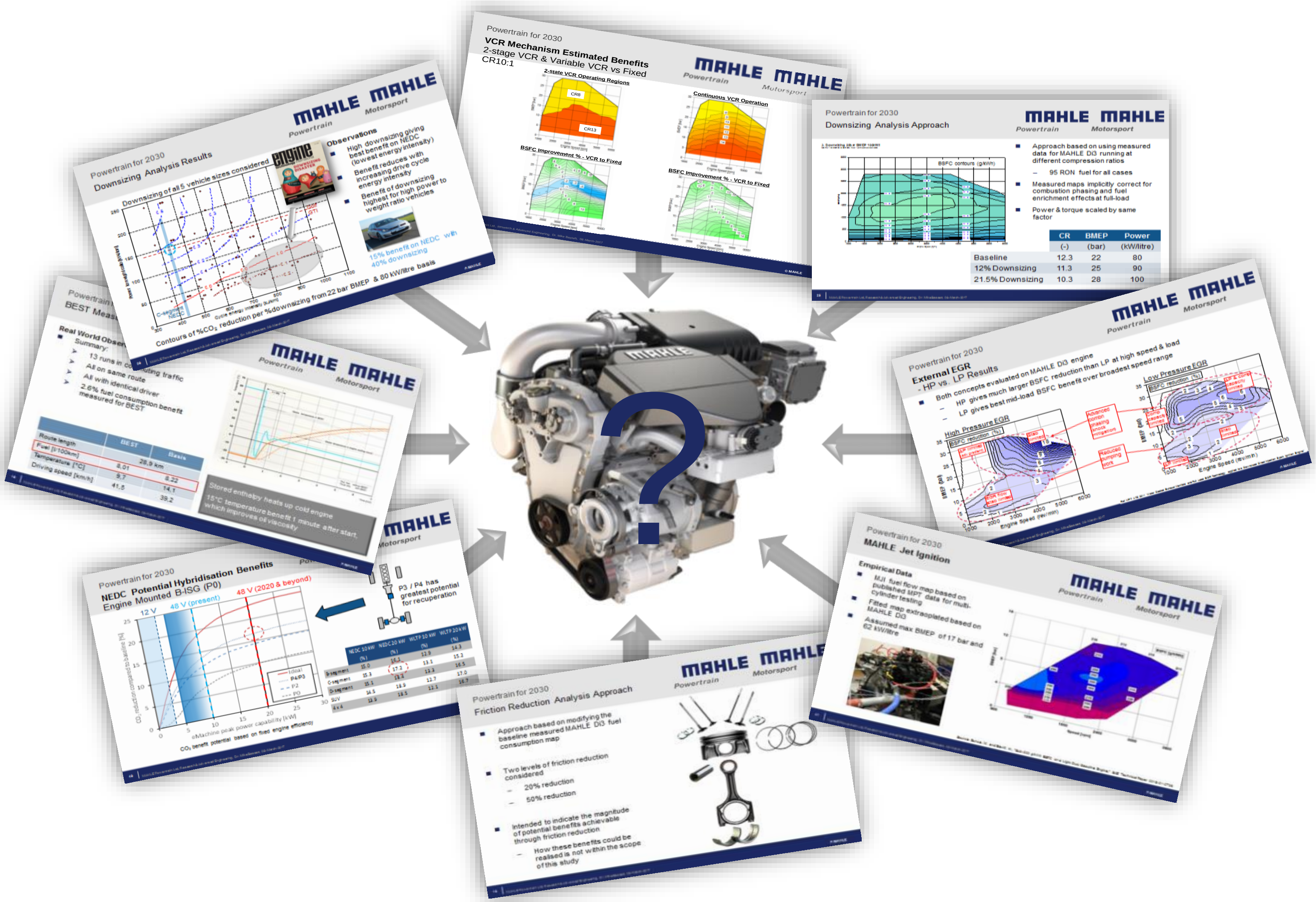
MAHLE Powertrain

- Many competing technologies & solutions
- Challenging & changing demands
- Technology dilemma:
  - Choose a technology to pursue
    - High risk
  - Develop several
    - High cost
- Electrification opens up new development opportunities
- Lots of potential left to develop engines for new applications
- Hybrid & alternative fuels offers potential for low life-cycle CO_2 emissions

Powertrain technology diversification is challenging and will remain so for the next decade

MAHLE Powertrain

- **Thank you for your attention**



Longer-term and disruptive R&D in internal combustion engines

Andrew Smallbone

25th April 2019

Sir Joseph Swan Centre for energy research

Newcastle University

A new generation of internal combustion engines

Future energy vector infrastructure

Compact

Lightweight

Efficient

Cheap to manufacture

Zero tailpipe emissions

Reduced life-cycle CO_2 emissions

Range-extender

The value proposition grows stronger for heavier & longer range vehicles

Active research areas

- Historically a very active research space
- Incremental improvement of conventional ICE
- Disruptive technologies of interest
  - Split-cycle engine
  - Free-piston engine
  - ZECCY engine
  - However there are others…advanced rotary, turbines *etc.*

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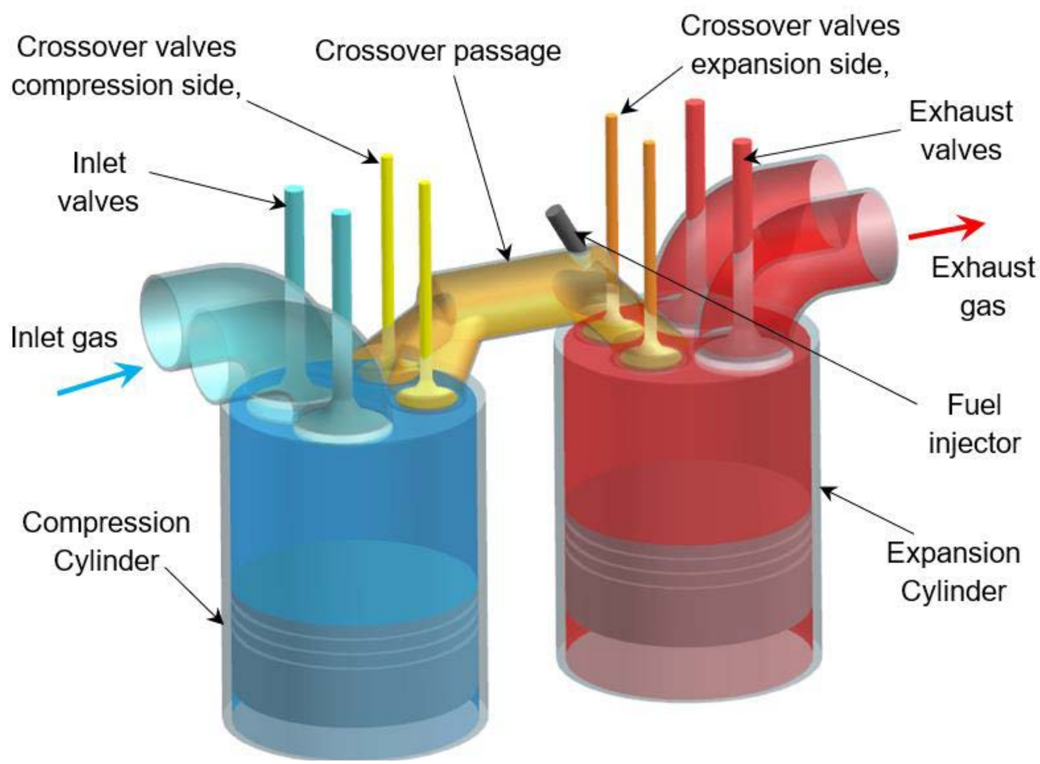
The split-cycle internal combustion engine

Split cycles

Concept

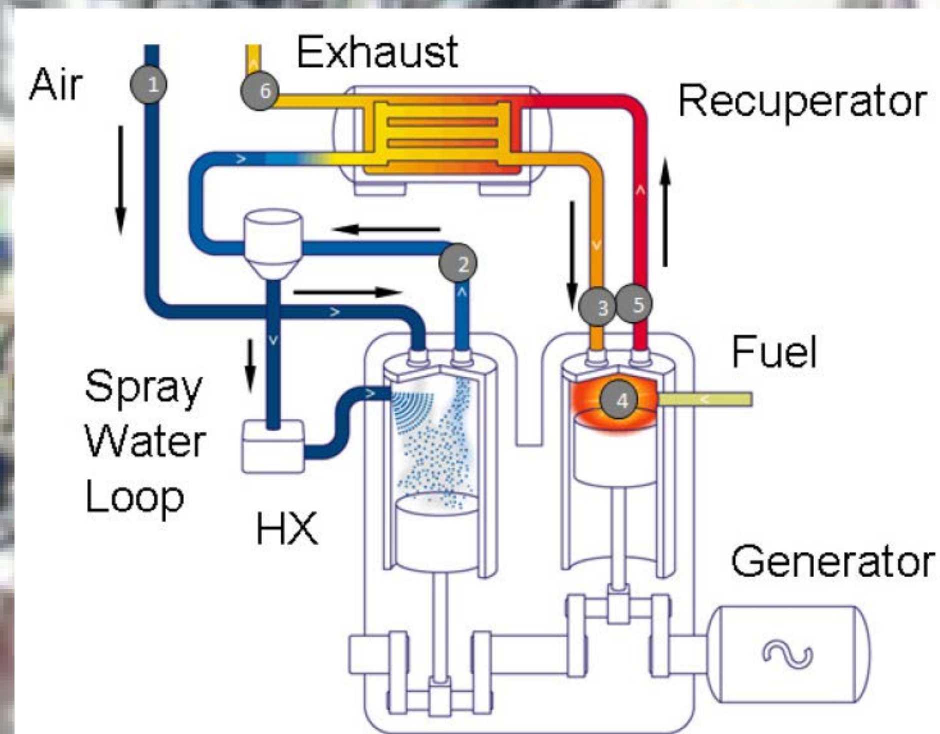
- Split cycles separate compression, expansion and combustion/heat transfer
- Opportunity for Brayton/Joule Cycles
- More *"Miller-like"* cycles
- High pressure ratios mean higher efficiency
- +50% brake thermal efficiency possible targeting 60%
- Systems from Ricardo/Brighton, Illinois Institute of Technology, Scuderi, Newcastle (Linear) follow similar principles.



FINNERAN, J. ... et al, 2018. A review of split-cycle engines. International Journal of Engine Research, doi:10.1177/1468087418789528.

Split-cycle with compression cooling

- Combines thermal differential offered by cryogenic energy and combustion.
- Liquid water (or even nitrogen injection) during compression.
- Diesel during expansion.
- Integrated WHR
- Targeting HDV sector

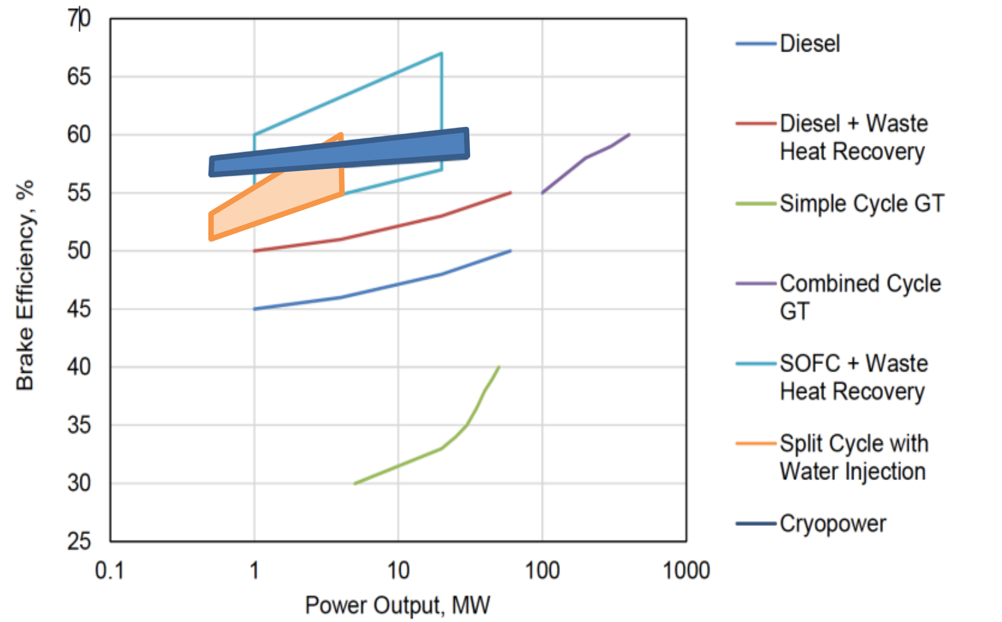


SAE2017-24-016

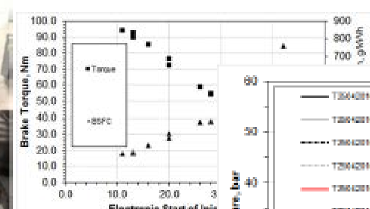
Split cycles

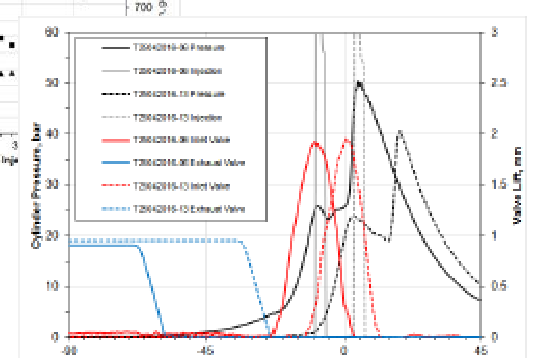
Split-cycle with compression cooling

- Carry some cooling liquid
- Specific power density is a challenge
- Efficiency similar to SOFC technology
- Opportunities for low temperature combustion & thus low NO_x/PM
- Targeting HDV sector
- Extensive 1D simulation carried out
- Testing of “hot” part of cycle underway in Brighton



Adam Gurr (2016) “The 60% Efficiency Reciprocating Engine: A Modular Alternative to Large Scale Combined Cycle Power” CIMAC 2016 paper Nº 267





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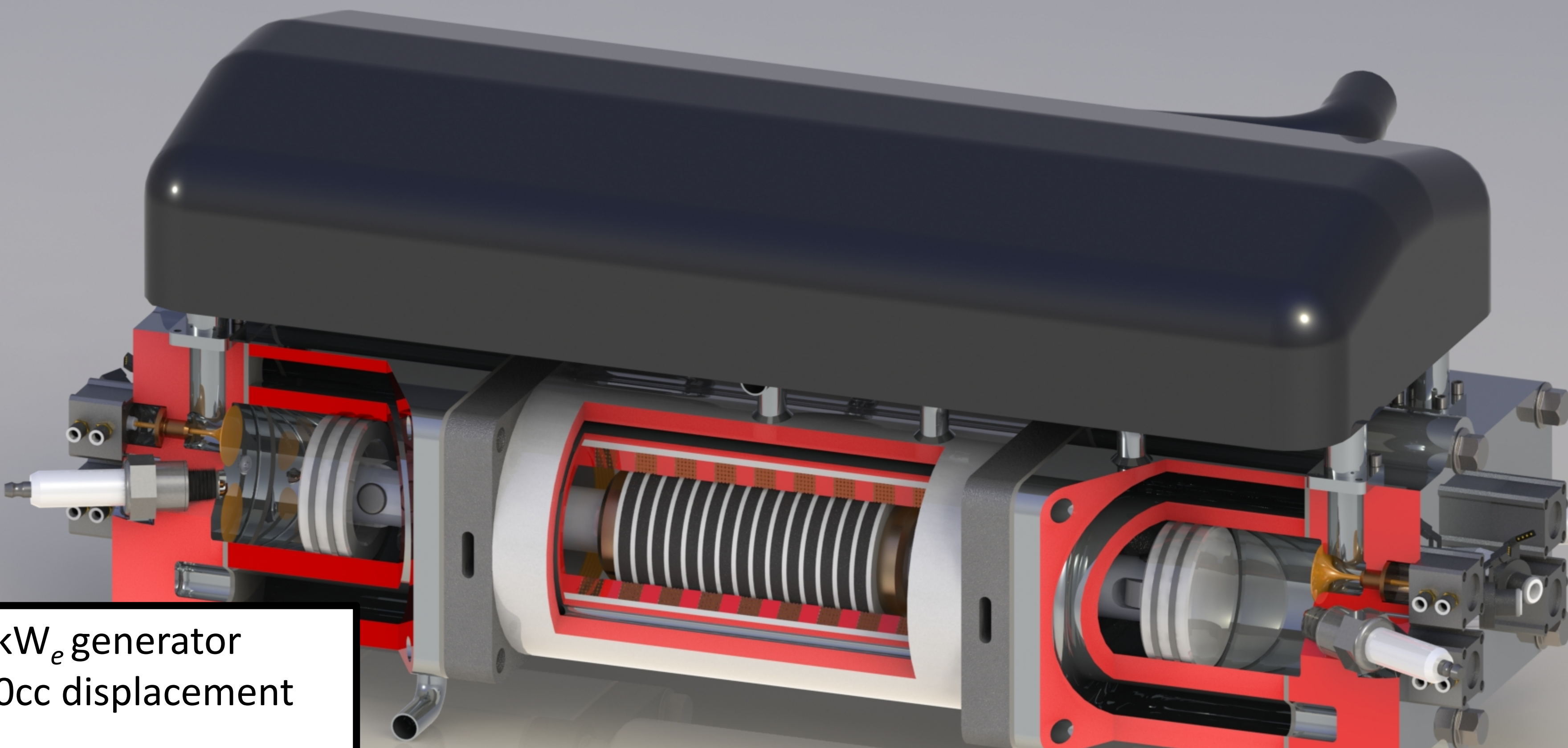
The free-piston engine generator (FPEG)

Free Piston Engine Generator (FPEG)

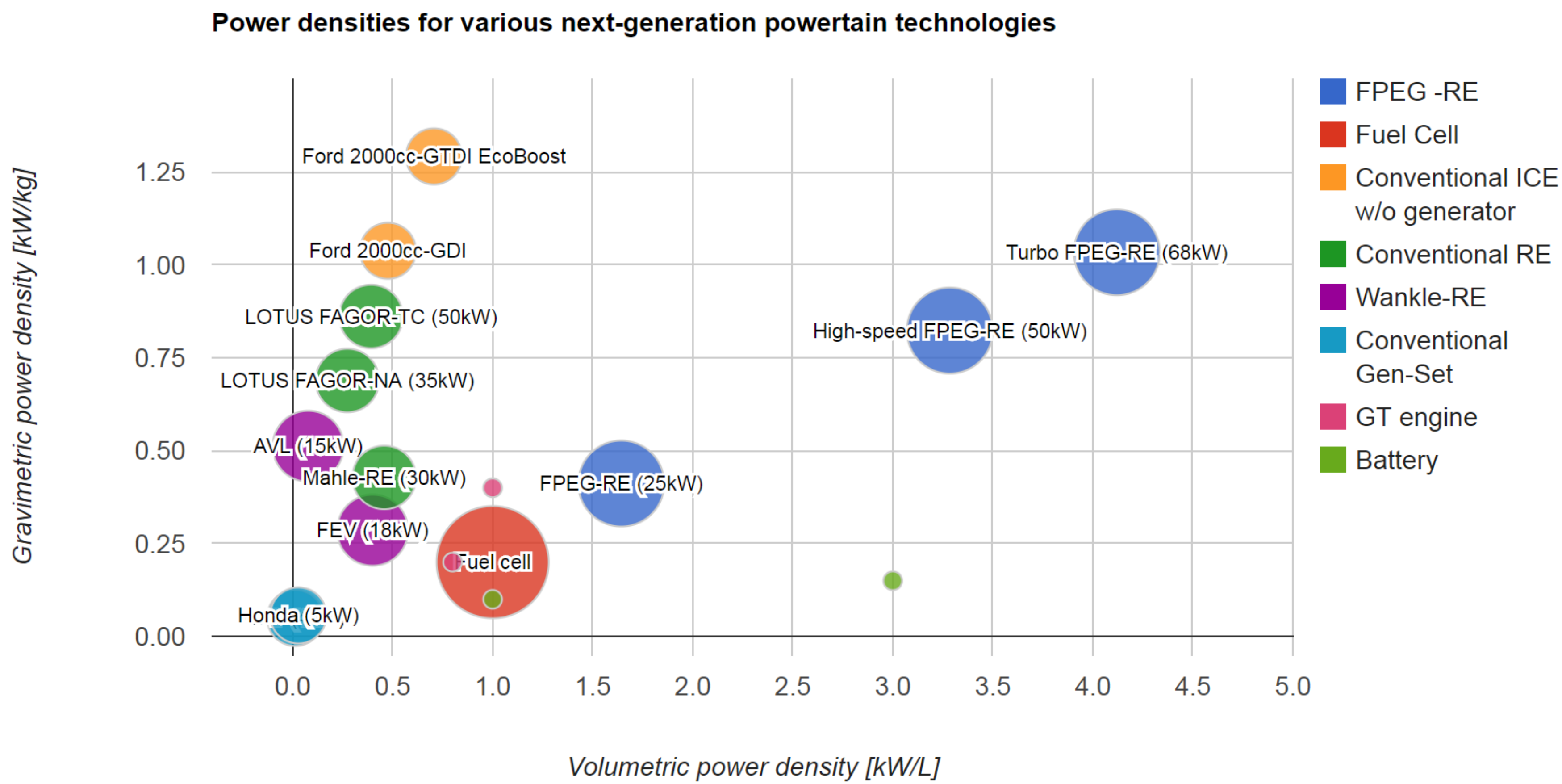


24kW$_e$ generator
800cc displacement

Standard gasoline fuel
Port injection
4 cylinder VVT
Two linear machines

<u>Active research programmes:</u> *Toyota, Newcastle University, DLR, Sandia National Labs, BIT,…*

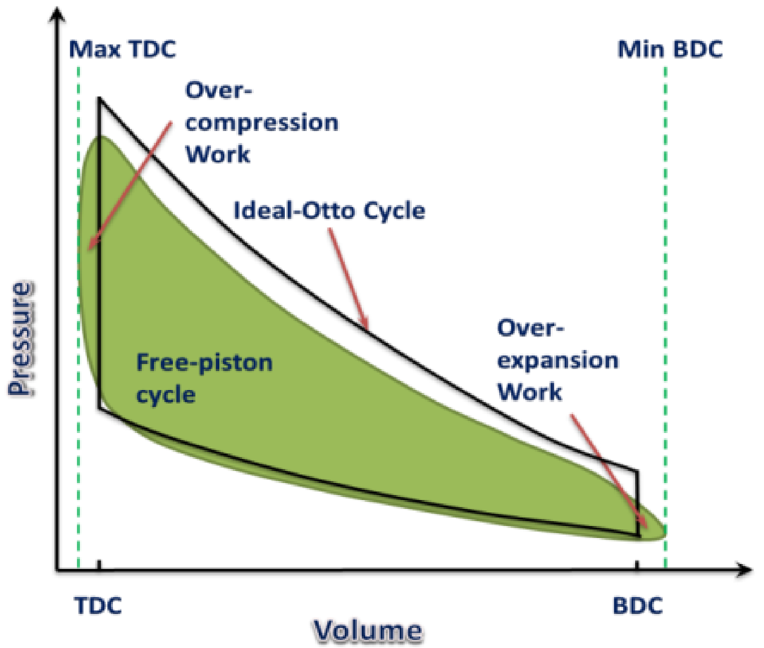
Free Piston Engine Generator (FPEG)



- 60% smaller and 25% lighter than a conventional IC engine generator and similar advantages over fuel cell technology.
- increase speed and turbo-charging – much greater advantages – almost all incremental ICE developments also apply to FPEGs.

Free Piston Engine Generator (FPEG)

Thermal and electrical efficiency



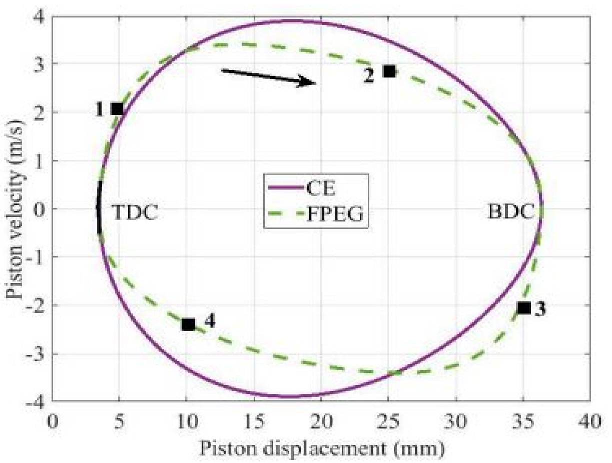
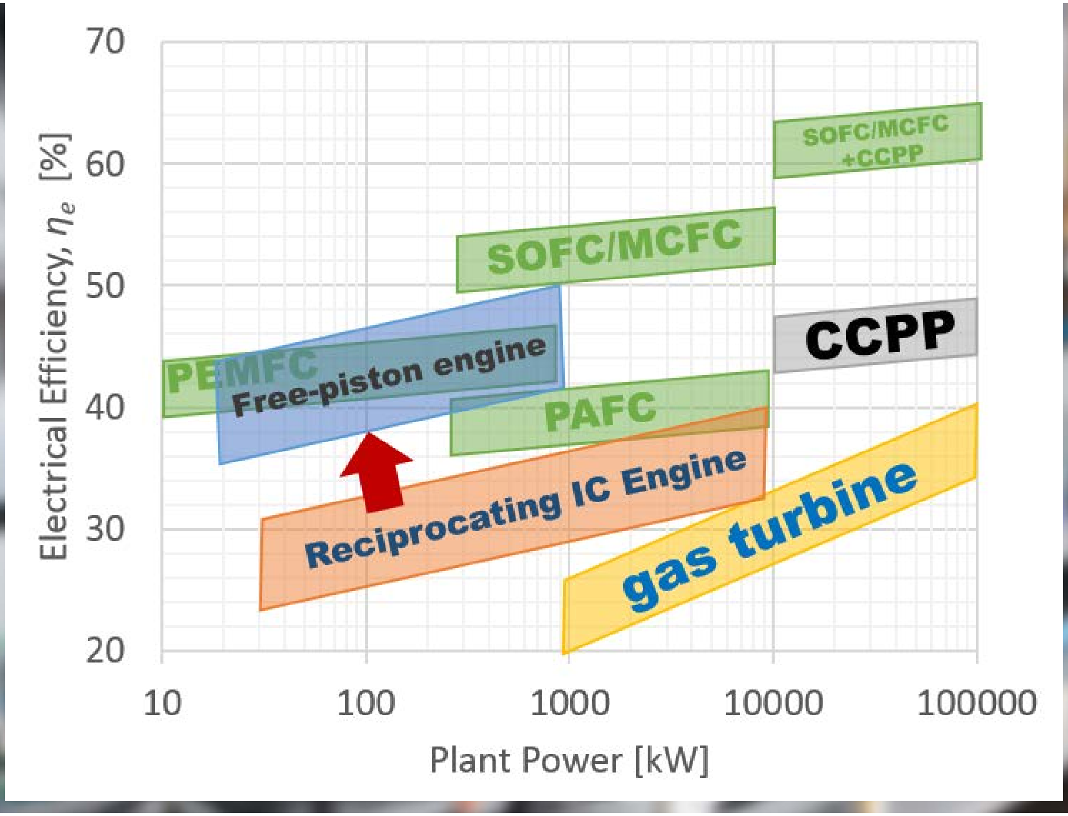


Figure 4. Comparison of FPEG and CE piston velocity.

- lower frictional and heat transfer losses than conventional IC engines.
- increased thermal efficiency due to the ability to control piston velocity profile and extend cycle compression and expansion.
- Compression ratio is a software control decision

Free Piston Engine Generator (FPEG)



- FPEG configurations have proven thermal efficiencies of between 40 and 50%.
- 30% higher electrical efficiency than existing reciprocating IC engine generators and similar electrical efficiency as existing PEM fuel cells

Current status

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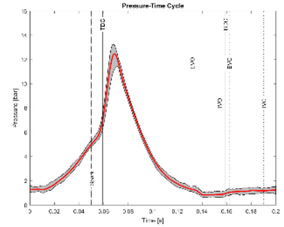
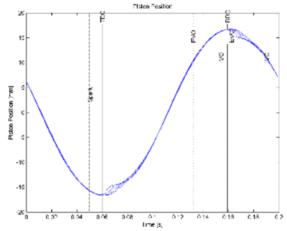
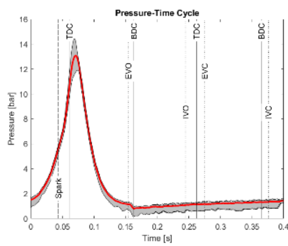
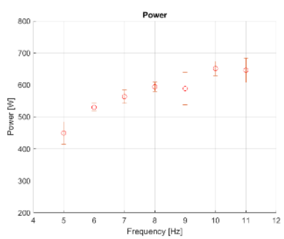
- Innovate UK project complete (IDP12)
- 4 patents approved
- Variable compression ratio, fuel injection and valve timing - controllable without physical changes.
- Operate either in 2 or 4 stroke mode
- switch between liquid and gaseous fuels – even during operation.
- transition from low-carbon to zero-carbon fuels (*i.e.* bioethanol and hydrogen).
- Robust to variations in fuel quality and contamination.
- future proof against changes to their supply and availability.

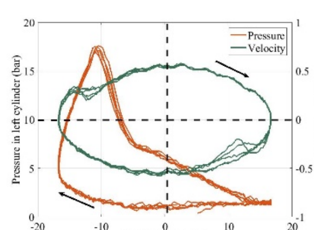
Video:
https://www.youtube.com/watch?v=u4b0_6byuFU



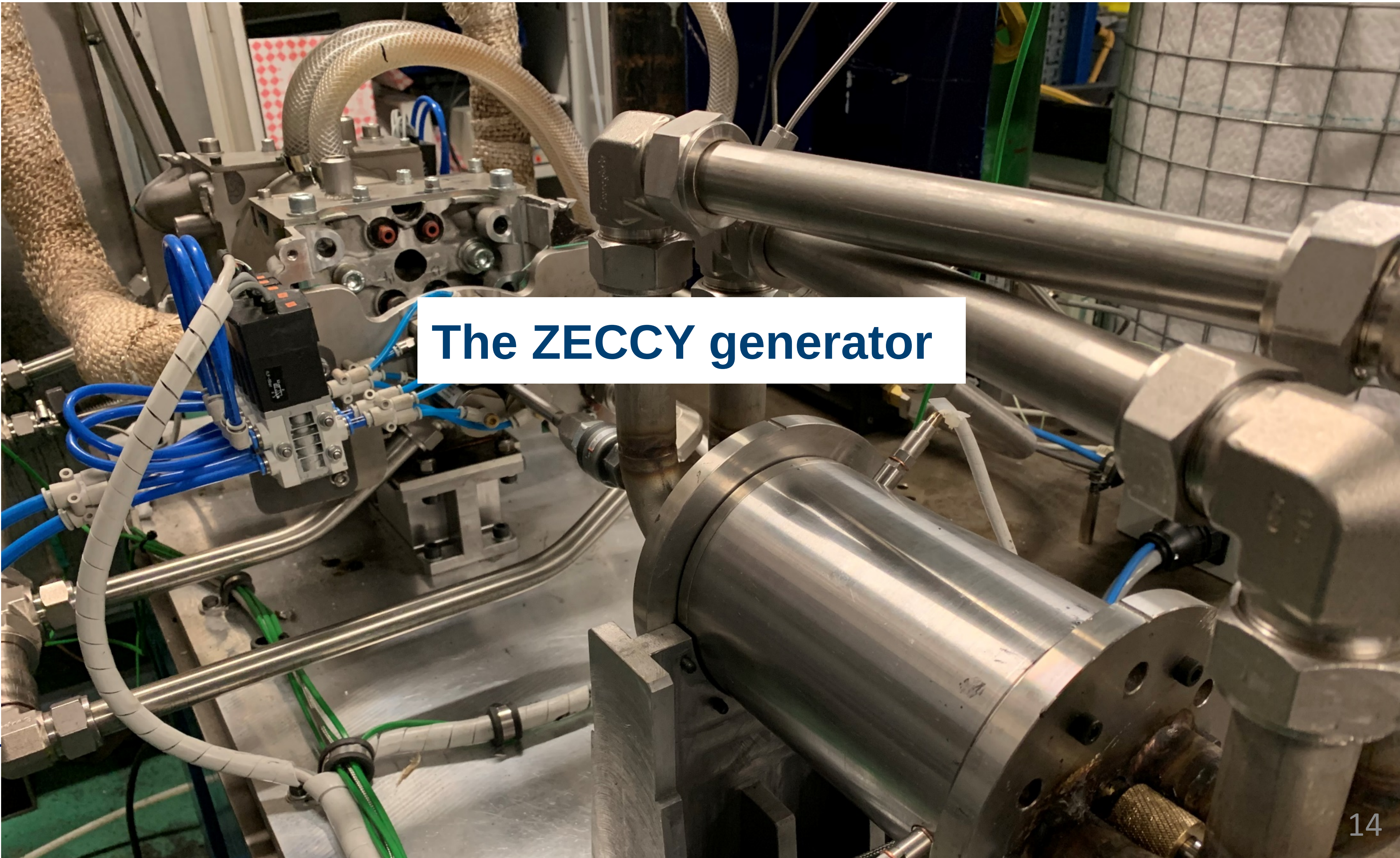






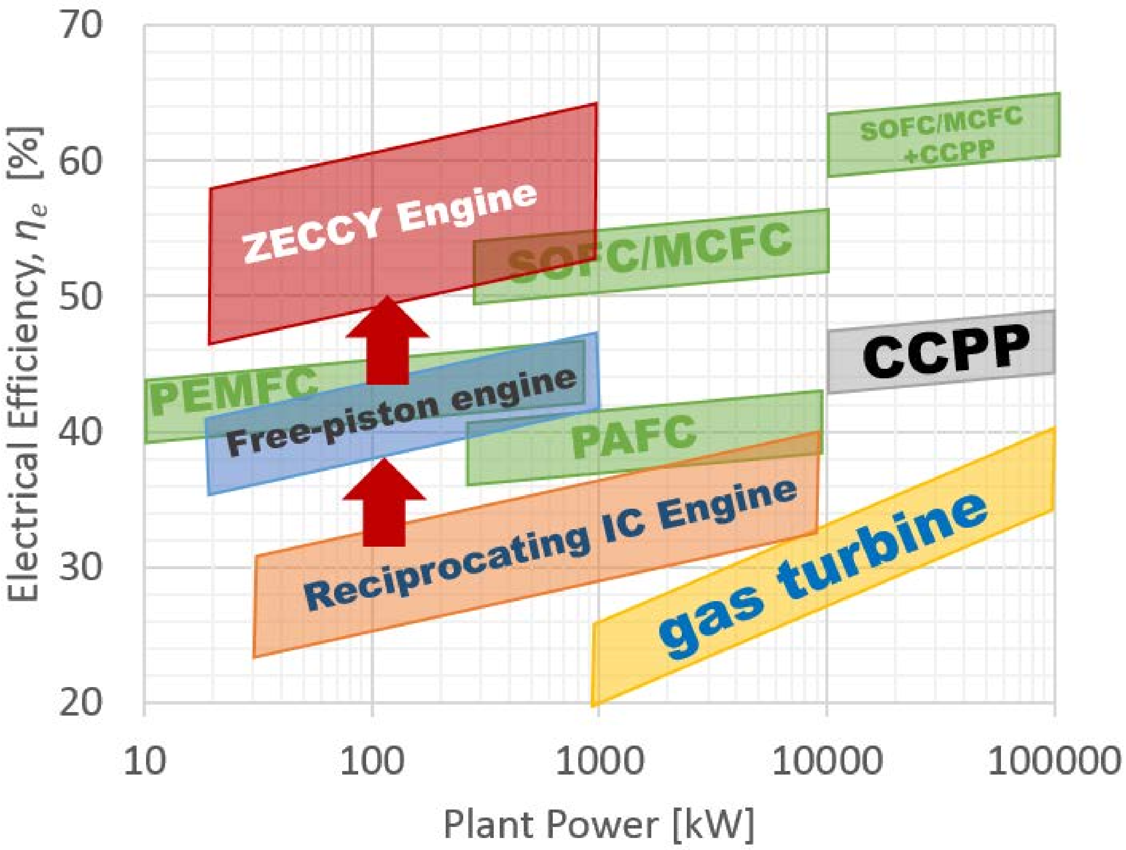


The ZECCY generator

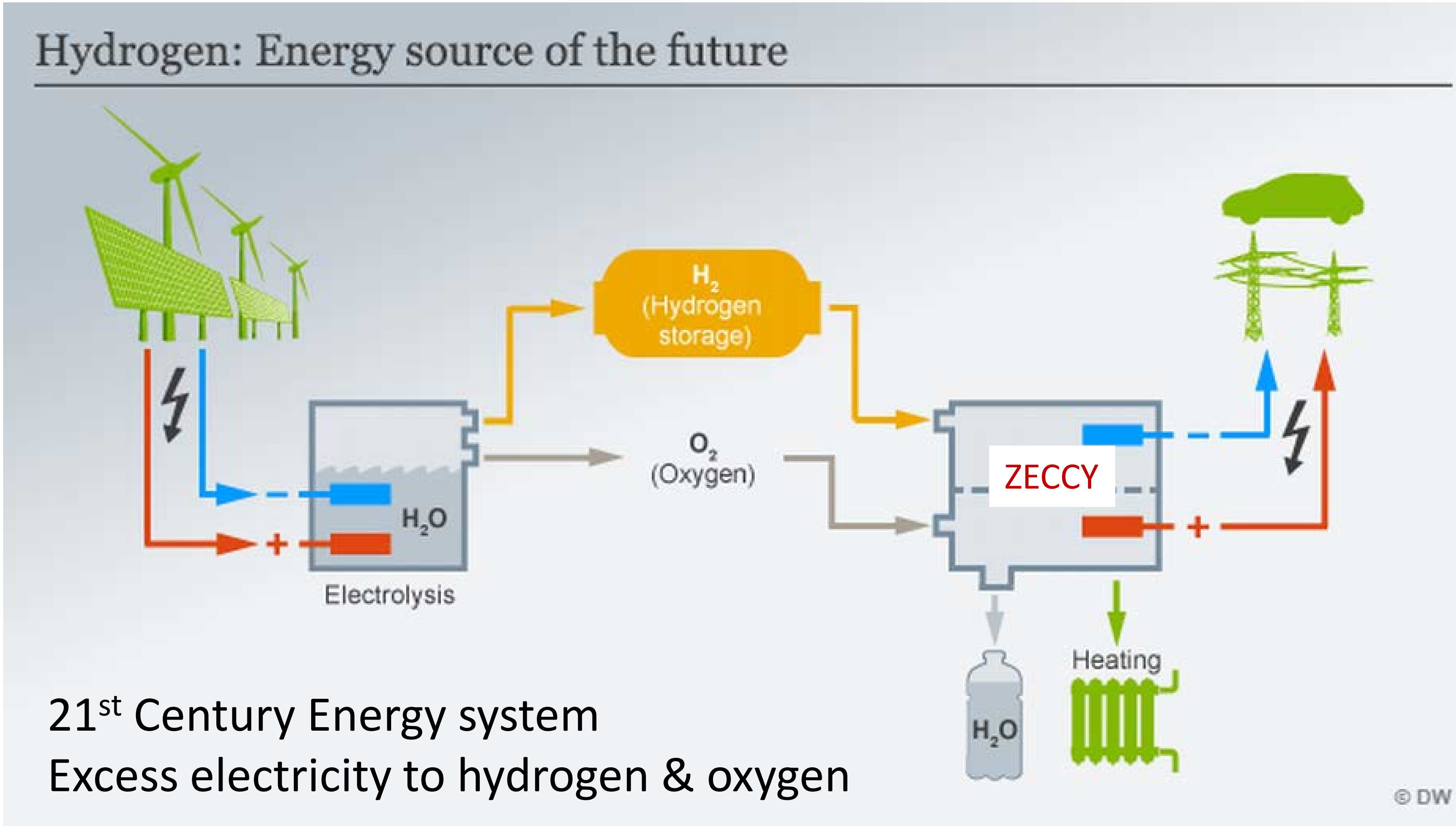


ZECCY generators

A Zero-Emission Closed-loop CYcle (ZECCY) engine generator



ZECCY engine

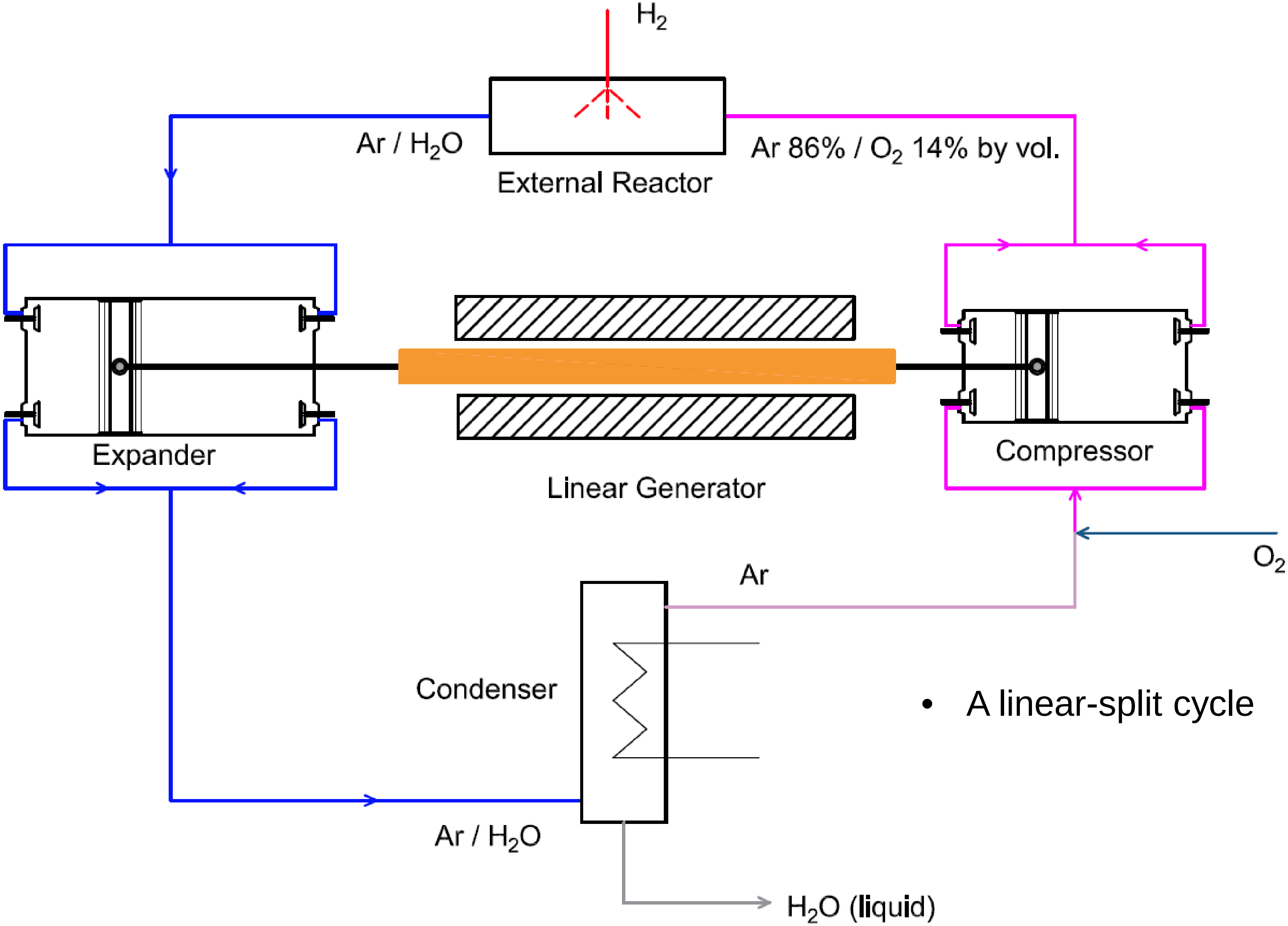


21st Century Energy system

Excess electricity to hydrogen & oxygen

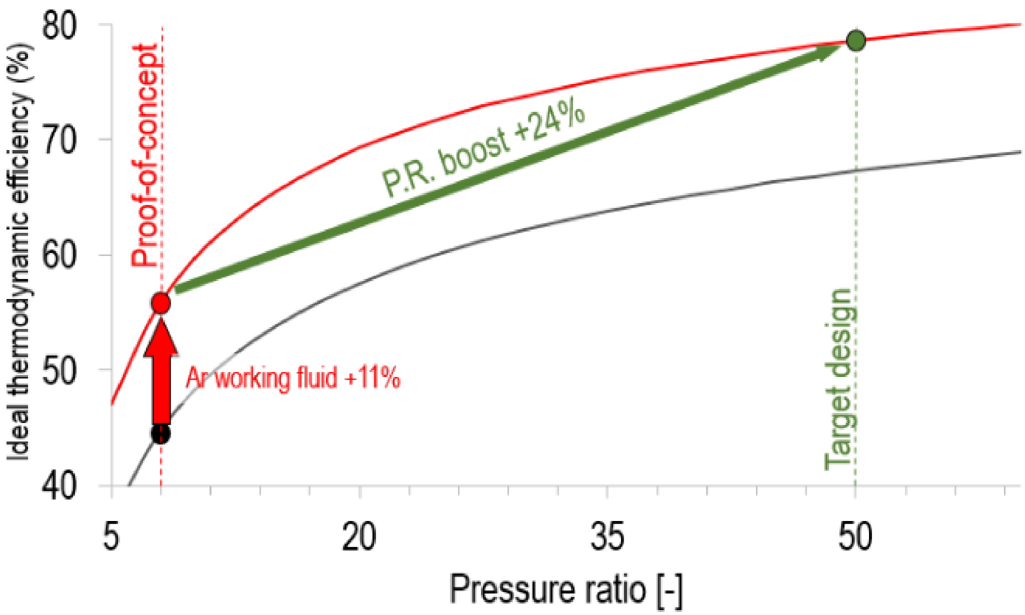
Support: EPSRC & Innovate UK (IDP13)

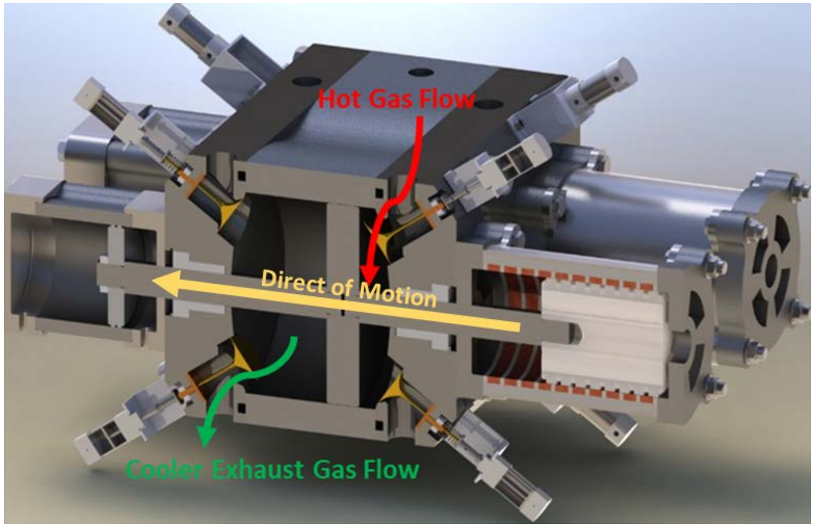
ZECCY engine



- A linear-split cycle

ZECCY engine





100kW concept design

- Based on a Brayton cycle
- Opportunity to go well beyond 50% thermal efficiency
- 30% higher electrical efficiency than existing reciprocating IC engine generators and similar electrical efficiency as existing PEM fuel cells

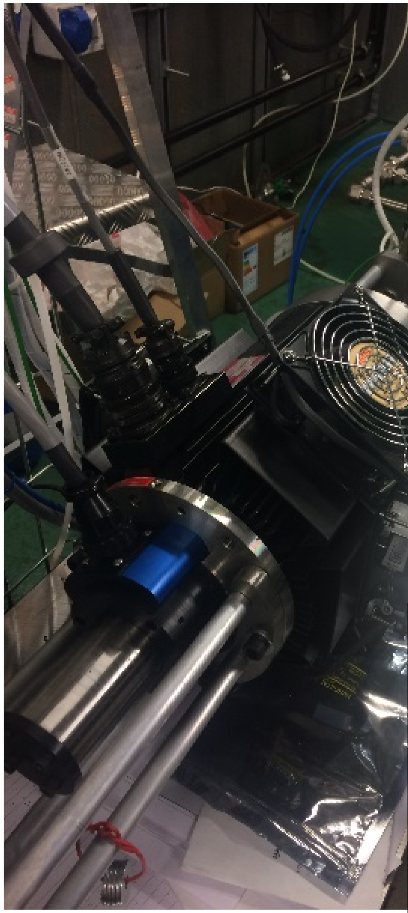
- Additional weight of carrying an oxygen tank
- Overall system (incl. tanks) weight similar to a hydrogen fuel cell for HGV
- CHP and powergen sectors are also potential applications

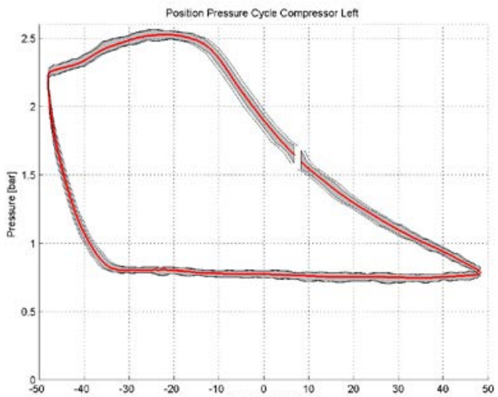
ZECCY engine

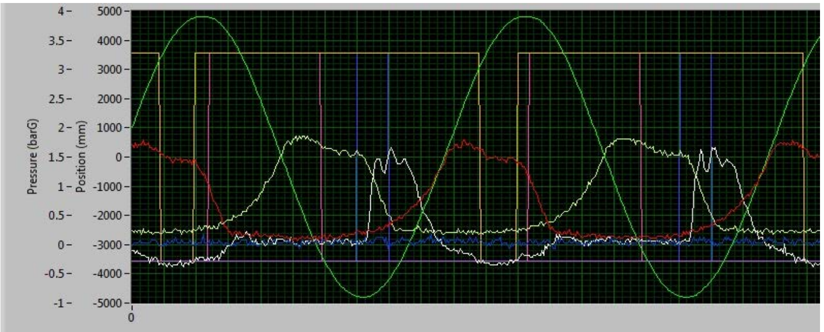
First ever ZECCY engine is now operational (30kW)

Testing so far
- Up to PR=4
- 20% O_2/80% Ar by mass with H_2

Observations
- Steady long-term operation in closed loop
- Flame is stable
- Only emission is water
- Increasing efficiency is now our target







Summary

- Developing disruptive low-TRL engine technology concepts is challenging
- Presented three concepts and prototype systems
- Opportunities to exceed 50% efficiency and upwards
- More to consider than system efficiency alone

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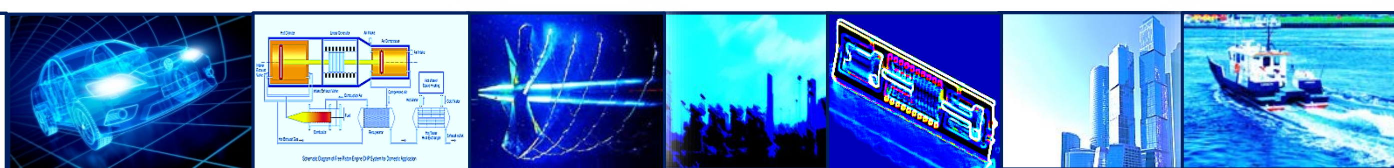

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