Thermal Propulsion Systems Roadmap 2020

Narrative Report

February 2021 | Version 1.0

Overview: Thermal Propulsion Systems

Although the internal combustion engine has been the bedrock of automotive propulsion since the 1900s, a focussed effort on improved thermal efficiency, systems optimisation, hybridisation and new net-zero carbon fuels is required to meet stricter emissions regulations.

- Engine efficiency, commonly measured as Brake Thermal Efficiency, has continued to increase since the last TPS roadmap was published in 2017. For light duty vehicles, this is expected to reach 48% by 2025 and 53% by 2035. Engine developments for heavy duty vehicles could see 60% reached by 2035.
- Future thermal propulsion systems will include some level of hybridisation to manage stricter GhG emission standards and deliver higher overall system efficiencies. A radical shift away from fossil fuels is already underway with net-zero fuels favoured.
- Innovations in light duty vehicles include: the use of advanced coatings and materials to reduce heat loss; more efficient combustion through, for example, lean burn and water injection; together with integrated hybrid engines.
- In contrast, for heavy duty vehicles, with their unique duty cycles and powertrain architectures, innovations are likely from waste-heat recovery, low-temperature combustion and in the longer term, adaptations to use alternative fuels.
- Key benefits of ICEs are the high degree of equipment recyclability, low LCA impact and a mature repurposing & remanufacturing industry backbone. Engines are already manufactured at carbon-neutral plants, worldwide.
- Significant research is underway to find sustainable net-zero alternatives to fossil fuels that take advantage of well-known production systems, established materials supply and low-cost manufacturing of ICE. These fuels are a new feature of the 2020 TPS roadmap and represent the key to meeting green-house gas emission and air quality targets in the long term.
- Our survey of experts showed that cost parity between ICE and BEV is expected by 2035, driving a radical shift from existing fossil fuels to alternatives, in particular bio-fuels and hydrogen. Several of these fuels including bio-fuels and e-fuels can partly or fully replace the existing fuel mix in current engines. Modification of the engine opens up the possibility of using a wider range of synthetic fuels. Industry experts are very confident that new ICE architectures with sustainable net-zero are achievable near-term.
- Recycling regulations and consideration of whole life impacts are encouraging a wide range of approaches across supply chains from design for disassembly and remanufacturing to recycling of components and more efficient production. It is important that life-cycle principles are embedded in new net-zero fuel combustion systems.

Foreword and Acknowledgements

The APC would like to acknowledge the extensive support provided by industry and academia in development and publishing this roadmap.

We are grateful to the Automotive Council for entrusting us with the product and technology roadmaps refresh and their continued support.

This work has received significant support from BEIS (Department for Business, Energy and Industrial Strategy).

Neville Jackson
On behalf of the
UK Automotive Council

I am delighted to share the 2020 automotive propulsion technology roadmaps developed closely in collaboration with industry by the Advanced Propulsion Centre. These roadmaps define critical future targets and the most promising pathways to achieve a decarbonised and more sustainable future vehicle parc. They are an essential tool in developing a focused R&D agenda, particularly relevant for collaborative innovation.

The roadmaps build on the foundations of original UK Automotive Council roadmaps and developed further by the APC in 2017. These have been refreshed to reflect the urgency in transitioning to the UK target of net-zero emissions by 2050. The rate of change in propulsion technologies has accelerated rapidly in recent years; electrified vehicle adoption is on the rise, battery prices have come down faster than previously forecast, alternative zero-emission technologies like fuel cells are maturing at significant pace and clean fuels for combustion, including hydrogen, are emerging to replace existing fossil fuels.

However, there are significant challenges to overcome as the rate of change must increase further, requiring more intensive R&D and commercialisation that will deliver affordable products to market that are even more attractive for consumers. The 2020 technology roadmaps have been developed by industry expert surveys and panels, delivering a consensed view of future automotive propulsion targets, technologies and timescales.

Our aim with this report is to support the automotive sector with insights and a common technology focus to accelerate and deliver world-class solutions. The roadmaps are an important source of information in building collaborative R&D opportunities to address future mobility challenges, goods transport and off-highway vehicle research and development.

Prof Chris Brace
University of Bath, APC Spoke

Thermal propulsion systems will remain at the forefront of technology to 2040 and beyond. We know that engines will still be important for the foreseeable future, but we are much less sure what they will be burning in that time period.

Progress towards net-zero means that fuels must be decarbonised rapidly. Reduced carbon fuels for today's fleet are a critical part of this work. Further progress will be possible with radically new sustainable fuels, for which we will develop new efficient engine and propulsion system technologies.

I am hugely optimistic that engineering and science can help us to bring the benefits of clean, sustainable mobility to ever more of the world's population.

Prof Rob Morgan
University of Brighton, APC Spoke

This roadmap, unlike the 2017 version is aligned to meeting the net-zero target. The critical importance of a rapid transition to sustainable fuels came through strongly during its development. There will be a range of fuel solutions with different impacts on the future requirements of the powertrain and a tremendous opportunity to cut carbon emissions quickly and sustainably especially in the 'hard to electrify sectors' such as long-haul freight.

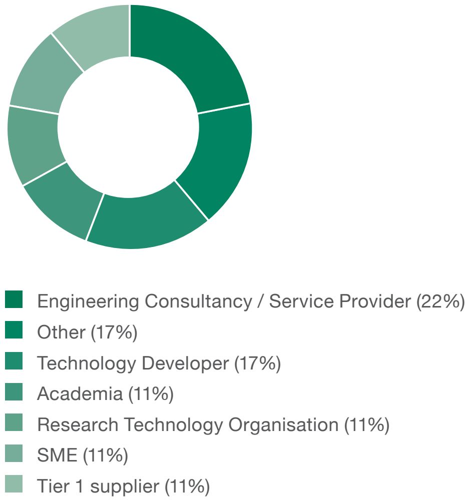
The roadmap was developed with inputs from a broad range of industrial and academic experts and given the challenges and complexity of the problem, a remarkable consensus was achieved. I personally feel privileged to have participated in this project and hope the roadmaps are helpful in guiding the sector in delivering a clean, sustainable future.

Insights from the 2020 Industry Experts Online Survey

A radical shift in fuels used in combustion engines is underway as cost parity between BEVs and ICE appears likely by 2035.

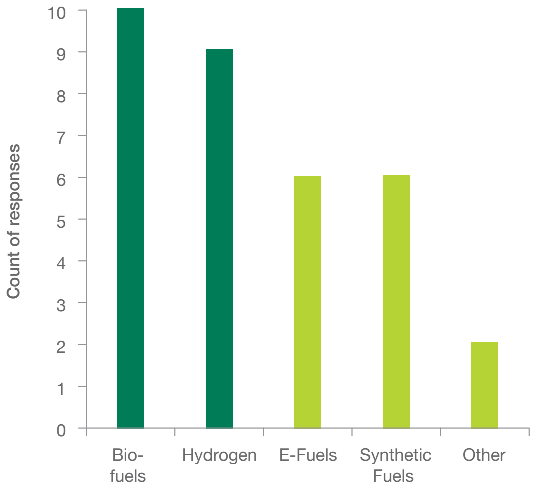
Technology survey respondants

A spread of industry specialists responded to the online technology survey carried out in September 2020.



Which fuels are expected to dominate the combustion engine market by 2040?

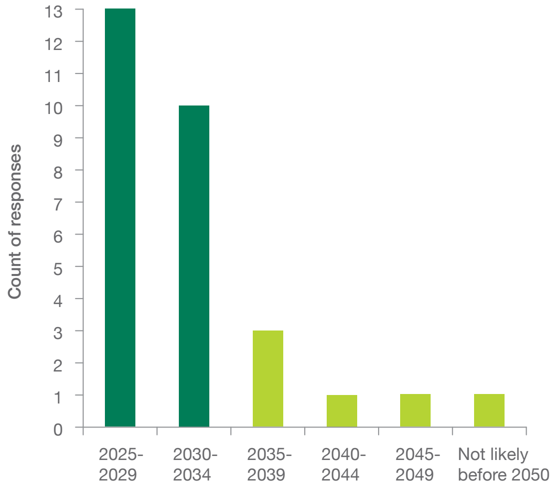
The fuels most likely to dominate the light duty combustion engine market by 2040 are bio-fuels and hydrogen.



NB: Bio-fuels cannot currently be supplied in high volumes due to bio-waste supply constraints.

When will cost parity be achieved between BEVs & ICE?

When asked when BEV and ICE would achieve cost parity, almost 80% of responders thought this would be possible before 2035.



NB: This could be sooner for high volume small passenger cars.

Technology Indicators and Drivers

Technology indicators for light duty and heavy duty applications

Technology indicators that industry is likely to achieve in a mass-market competitive environment.

Brake Thermal Efficiency (BTE)

	2020	2025	2035
Light Duty	42%	48%	53%

	2020	2025	2035
Heavy Duty	47%	55%	60%

Notes:

- BTE refers to Peak Brake Thermal Efficiency.
- BTE is a common indicator for engine efficiency. The values listed are best-in-class figures.
- Although single point peak BTE values are shown, these are not accurate indicators of real world vehicle efficiency which will vary across propulsion technologies and product applications.

Green House Gas and Air Quality Regulation Drivers

☐ *Defined driver* ▨ *Predicted driver*

Light Duty	$CO_{2}e$ Emission	95 g/km (NEDC)	-15% (WLTP)	PC -37.5% and Van -31% (WLTP)	Towards net-zero $CO_{2}e$ and LCA compliance
	Pollution and Resource	Euro 6d / EPA Tier 3	Euro 7 / EPA Tier 3	Holistic environmental impact legislation (VOC, resource use, land use) and LCA compliance	
Heavy Duty	$CO_{2}e$ Emission	CO_{2}: VECTO Uptake	CO_{2}: -15%	CO_{2}: -30%	Towards net-zero $CO_{2}e$ and LCA compliance
	Pollution and Resource	Euro VI / EPA 2015 NRE Stage V	Euro VII / EPA 2015 NRE Stage V+	Euro VII + / EPA 2015 MY27 NRE Stage V++	Holistic environmental impact legislation (VOC, resource use, land use) and LCA compliance

▲ 2020 ▲ 2025 ▲ 2030 ▲ 2035 ▲ 2040 ▲ 2045 ▲ 2050 ▲ ...

Technology indicators for light duty and heavy duty applications

Technology indicators that industry is likely to achieve in a mass-market competitive environment.

Technology indicators
In 2020, these replace targets in the roadmaps, providing a direction of travel and an approach to measuring best-in-class performance for this technology.

Brake Thermal Efficiency (BTE)

	2020	2025	2035
Light Duty	42%	48%	53%

	2020	2025	2035
Heavy Duty	47%	55%	60%

Brake Thermal Efficiency (BTE)
The indicators for light duty and heavy duty vehicles are provided separately, as their duty cycles and technology selection differ.

Green House Gas and Air Quality Regulation Drivers

☐ *Defined driver* ▨ *Predicted driver*

Light Duty	CO_2e Emission	95 g/km (NEDC)	-15% (WLTP)	PC -37.5% and Van -31% (WLTP)	Towards net-zero CO_2e and LCA compliance
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Regulation Drivers
Evolving CO_2 emissions, pollution and resources regulations are shown on the TPS roadmap. These strongly influence the development and implementations of combustion engine technologies.

General notes

Although higher peak BTEs are possible, e.g. by tuning the engine to a single optimisation point, this is impractical in achieving what we are really after – increased 'net' duty cycle efficiencies.

Averaged drive cycle BTE values are preferred that quantify system efficiency, but were unavailable. Peak BTE provides an indicator of trajectory development and innovation.

The projections have been derived from senior experts within industry via APC-facilitated workshops.

Technology indicators for light duty and heavy duty applications

Technology indicators that industry is likely to achieve in a mass-market competitive environment.

Brake Thermal Efficiency (BTE)

	2020	2025	2035
Light Duty	42%	48%	53%

	2020	2025	2035
Heavy Duty	47%	55%	60%

Light duty

In order to achieve proposed fuel economy requirements, engines must make better use of the available fuel energy. Regardless of how efficient the engine is, there will still be a significant fraction of the fuel energy that is rejected in the exhaust and coolant streams.

Engine efficiency, commonly measured as brake thermal efficiency, has continued to increase since the last TPS roadmap was published in 2017. By 2026, a standard 4-stroke is expected to achieve a BTE of 48–50%, with the potential of a further increase to a BTE of 52% by applying Organic Rankine Cycle principles. Current commercial engines are capable of achieving a peak BTE of 42% or higher.

Heavy duty

Heavy duty powertrain efficiency will continue to improve - significant advances are expected through waste heat recovery and radical new engine concepts.

There are examples of production programmes for heavy goods vehicles targeting a BTE of 55% by 2026, achieving Euro VII emission standards and super ultra-low emission vehicle (SULEV) compliance, based on water injection technology to reduce the compression work. By 2030, some engine developers are targeting a BTE of 60% by adding ORC, cylinder deactivation and other high efficiency principles.

dicted driver

37.5% and Van -31% (WLT

Resource

Holistic environmental impact legislation (VOC, resource use, land use) and LCA compliance

Heavy Duty	CO_2e Emission	CO_2: VECTO Uptake	CO_2: -15%	CO_2: -30%	Towards net-zero CO_2e and LCA compliance
	Pollution and Resource	Euro VI / EPA 2015 NRE Stage V	Euro VII / EPA 2015 NRE Stage V+	Euro VII + / EPA 2015 MY27 NRE Stage V++	Holistic environmental impact legislation (VOC, resource use, land use) and LCA compliance

General notes

The defined and predicted drivers for GhG are listed under the CO_{2e} (carbon dioxide equivalent) section. For any quantity and type of greenhouse gas, $CO_{2}e$ signifies the amount of CO_2 which would have the equivalent global warming impact.

NEDC: The New European Driving Cycle, last updated in 1997, is designed to assess the emission levels of car engines and fuel economy in passenger cars (which excludes light trucks and commercial vehicles).

WLTP: The world harmonised light duty vehicles test procedure is a global, harmonised standard for determining the levels of pollutants, CO_2 emissions and fuel consumption of traditional and hybrid cars, as well as the range of fully electric vehicles.

Light duty

The indicators are taken from the European Commission CO_2 emission performance standards for cars and vans (2020 onwards) regulation documentation. The standard for passenger cars and vans are listed separately in the roadmap.

Pollution and resource are provided as a separate category to support the range of natural resource considerations becoming increasingly important for automotive manufacturing. This includes air, water, land, biological and raw materials.

The Euro 6d standard for light duty vehicles is required for all new cars to be type-approved from January 2020 and this incorporates the real driving emissions requirement for an oxides of nitrogen (NOx) limit. The Tier 3 standard refers to a set of fuel and vehicle standards adopted by the Environmental Protection Agency (EPA), closely aligned with California LEV III standards, that are being phased in over the period 2017–2025. The regulation also tightens sulphur limits for petrol. Increasingly stringent and more holistic natural resource regulations are expected in this category.

Heavy duty

A similar approach to GhG and pollution mitigation is demanded for heavy duty vehicles. VECTO, the new simulation tool that has been developed by the European Commission, is used for determining CO_2 emissions and fuel consumption from heavy duty vehicles (trucks, buses and coaches) with a gross vehicle weight above 3.5 tonnes.

Other regions like Japan and the US have opted for fuel economy or CO_2 standards, similar to light duty vehicles. Japan for example, on average, is mandating a 11.9% improvement in fuel economy for trucks by 2025 from a 2015 baseline.

European emission standards for engines (category NRE) used in new non-road mobile machinery have gradually more stringent tiers, known as Stage I to V standards. Stage V regulation introduced a new limit for particle number emissions. The PN limit is designed to ensure that a highly efficient particle control technology, such as wall-flow particulate filters, be used on all affected engine categories. In additional to other changes, the Stage V regulation also tightened the mass-based PM limit for several engine categories, from 0.025 g/kWh to 0.015 g/kWh.

Progressively stringent standards for heavy duty and off-highway vehicles can be expected from 2035 onwards.

Green House Gas and Air Quality Regulation Drivers

Light Duty	$CO_{2}e$ Emission	95 g/km (NEDC)	-15% (WLTP)	PC -37.5% and Van -31% (WLTP)	Towards net-zero $CO_{2}e$ and LCA compliance
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Roadmap 2020

Thermal Propulsion Systems

Technology Roadmap

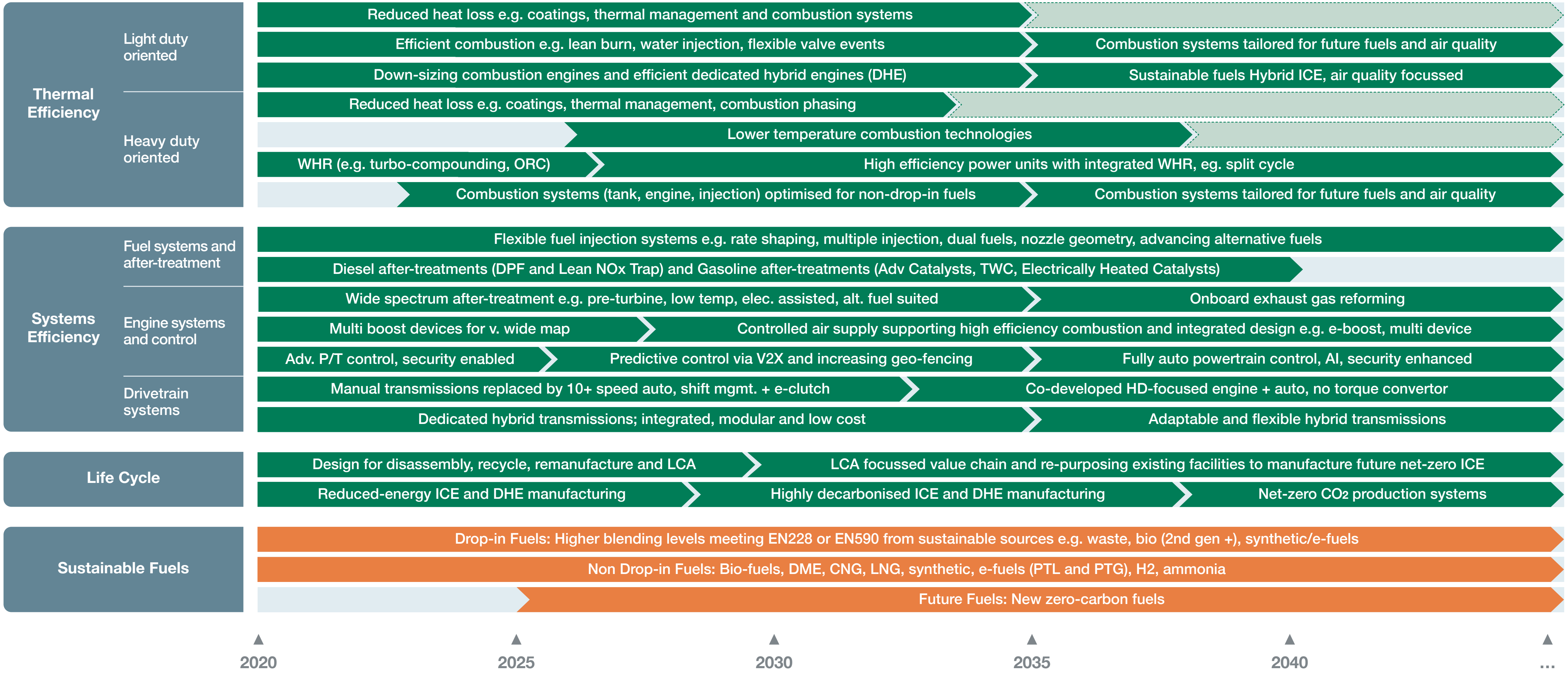
Technology indicators for
2020-2035 can be seen on page 1

This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption. Specific application-tailored technologies will vary from region to region.

Dark bar: *Technology is in a mass market application. Significant innovation is expected in this time frame*

Transition: *Transitions do not mean a phase out from market but a change of R&D emphasis*

Dotted line bar: *Market Mature – technology has reached maturity. Likely to remain in mass market until it fades out where it's superseded*



Thermal Efficiency

Light duty oriented
- Reduced heat loss e.g. coatings, thermal management and combustion systems
- Efficient combustion e.g. lean burn, water injection, flexible valve events
- Combustion systems tailored for future fuels and air quality
- Down-sizing combustion engines and efficient dedicated hybrid engines (DHE)
- Sustainable fuels Hybrid ICE, air quality focussed

Heavy duty oriented
- Reduced heat loss e.g. coatings, thermal management, combustion phasing
- Lower temperature combustion technologies
- WHR (e.g. turbo-compounding, ORC)
- High efficiency power units with integrated WHR, eg. split cycle
- Combustion systems (tank, engine, injection) optimised for non-drop-in fuels
- Combustion systems tailored for future fuels and air quality

Systems Efficiency

Fuel systems and after-treatment
- Flexible fuel injection systems e.g. rate shaping, multiple injection, dual fuels, nozzle geometry, advancing alternative fuels
- Diesel after-treatments (DPF and Lean NOx Trap) and Gasoline after-treatments (Adv Catalysts, TWC, Electrically Heated Catalysts)
- Wide spectrum after-treatment e.g. pre-turbine, low temp, elec. assisted, alt. fuel suited
- Onboard exhaust gas reforming

Engine systems and control
- Multi boost devices for v. wide map
- Controlled air supply supporting high efficiency combustion and integrated design e.g. e-boost, multi device
- Adv. P/T control, security enabled
- Predictive control via V2X and increasing geo-fencing
- Fully auto powertrain control, AI, security enhanced

Drivetrain systems
- Manual transmissions replaced by 10+ speed auto, shift mgmt. + e-clutch
- Co-developed HD-focused engine + auto, no torque convertor
- Dedicated hybrid transmissions; integrated, modular and low cost
- Adaptable and flexible hybrid transmissions

Life Cycle
- Design for disassembly, recycle, remanufacture and LCA
- LCA focussed value chain and re-purposing existing facilities to manufacture future net-zero ICE
- Reduced-energy ICE and DHE manufacturing
- Highly decarbonised ICE and DHE manufacturing
- Net-zero CO_2 production systems

Sustainable Fuels
- Drop-in Fuels: Higher blending levels meeting EN228 or EN590 from sustainable sources e.g. waste, bio (2nd gen +), synthetic/e-fuels
- Non Drop-in Fuels: Bio-fuels, DME, CNG, LNG, synthetic, e-fuels (PTL and PTG), H2, ammonia
- Future Fuels: New zero-carbon fuels

Primary Technology Themes

Thermal Efficiency
- Light duty oriented
- Heavy duty oriented

Light duty oriented: This is a dedicated section on light duty combustion technologies. Smaller combustion engines and a move to dedicated hybrid engines (DHEs) are the key trends in this category.

Heavy duty oriented: The duty cycle and emission demands for HDVs are significantly different to light duty vehicles. Targeted improvements in combustion technology and redesigned drive-system architectures provide opportunities for lower emissions and improve fuel economy figures for short- and long-haul journeys.

Systems Efficiency
- Fuel systems and after-treatment
- Engine systems and control
- Drivetrain systems

Systems Efficiency:

Fuel systems and after-treatment has been separated in the 2020 roadmap to provide better clarity on technology changes and trajectories for on-board fuel delivery as well as CO_2 and pollutant-mitigating after-treatments.

Engine systems and control covers efficiency improvements through air, heat and exhaust gas management, parasitic loss reduction and advances in powertrain control.

Drivetrain systems enable thermal propulsion systems to operate in a reduced speed/load envelope, allowing significant efficiency and emissions improvements. Integrated and hybrid transmission are a key theme.

Life Cycle

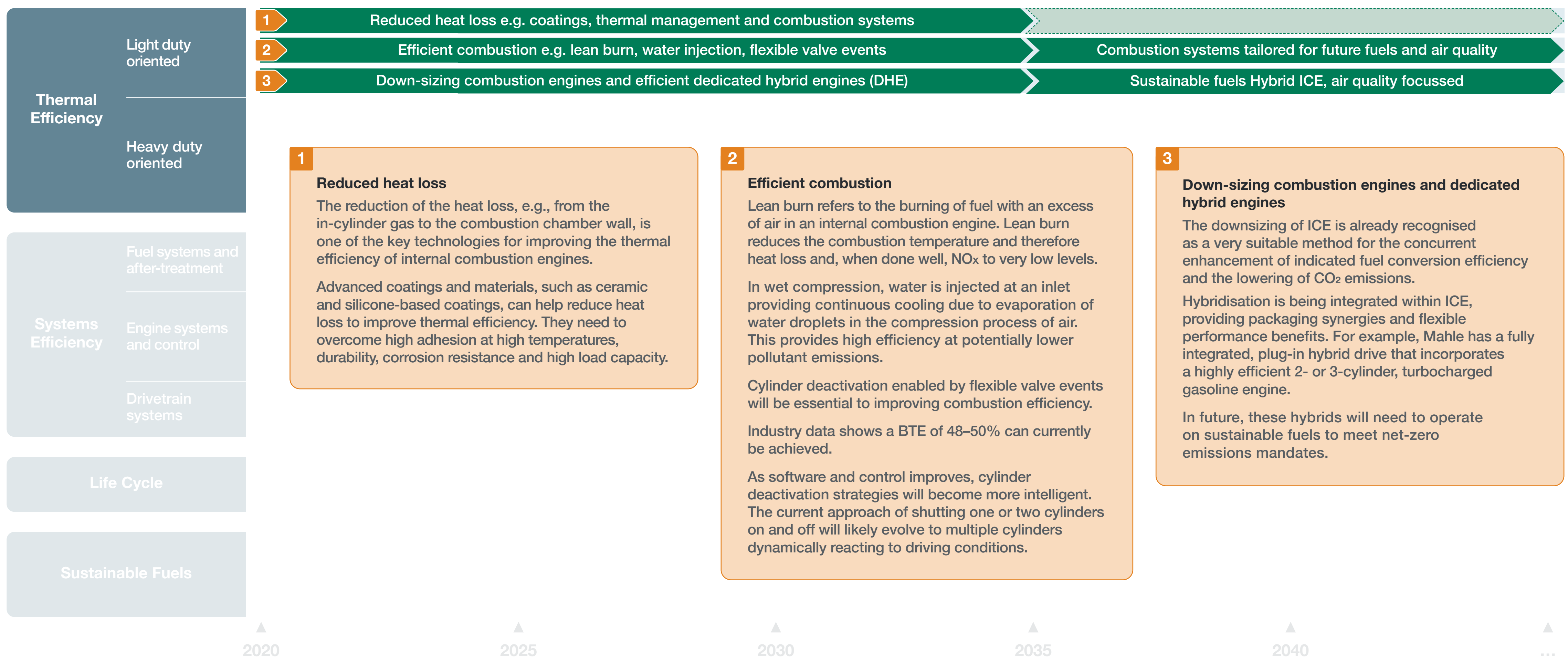
Life cycle includes the energy intensity, LCA impact, resource consumption and recyclability value chain for TPS components. Designing for disassembly, recycle and remanufacturing are current themes. Dedicated hybrid engines and new net-zero fuel combustion systems will need life-cycle principles embedded up-front.

Sustainable Fuels

Sustainable fuels: A brand new section on sustainable fuel has been added to the roadmap. Combustion engines are consumers of fuel, resulting in their related emission effects. Tackling fuels used in engines has a direct benefit to tail-pipe emissions and future net-zero ambitions. Three fuel themes are listed on the roadmap (Drop-in, non drop-in and future fuels), with examples of low and net-zero carbon options currently available or in development.

Thermal efficiency (light duty)

Reduced heat loss, efficient combustion and hybridisation are key strategies to increase performance and meet regulatory requirements, especially for inner-city vehicles.



Thermal Efficiency
- Light duty oriented
- Heavy duty oriented

Systems Efficiency
- Fuel systems and after-treatment
- Engine systems and control
- Drivetrain systems

Life Cycle

Sustainable Fuels

1 Reduced heat loss e.g. coatings, thermal management and combustion systems

2 Efficient combustion e.g. lean burn, water injection, flexible valve events → Combustion systems tailored for future fuels and air quality

3 Down-sizing combustion engines and efficient dedicated hybrid engines (DHE) → Sustainable fuels Hybrid ICE, air quality focussed

1

Reduced heat loss

The reduction of the heat loss, e.g., from the in-cylinder gas to the combustion chamber wall, is one of the key technologies for improving the thermal efficiency of internal combustion engines.

Advanced coatings and materials, such as ceramic and silicone-based coatings, can help reduce heat loss to improve thermal efficiency. They need to overcome high adhesion at high temperatures, durability, corrosion resistance and high load capacity.

2

Efficient combustion

Lean burn refers to the burning of fuel with an excess of air in an internal combustion engine. Lean burn reduces the combustion temperature and therefore heat loss and, when done well, NO_x to very low levels.

In wet compression, water is injected at an inlet providing continuous cooling due to evaporation of water droplets in the compression process of air. This provides high efficiency at potentially lower pollutant emissions.

Cylinder deactivation enabled by flexible valve events will be essential to improving combustion efficiency.

Industry data shows a BTE of 48–50% can currently be achieved.

As software and control improves, cylinder deactivation strategies will become more intelligent. The current approach of shutting one or two cylinders on and off will likely evolve to multiple cylinders dynamically reacting to driving conditions.

3

Down-sizing combustion engines and dedicated hybrid engines

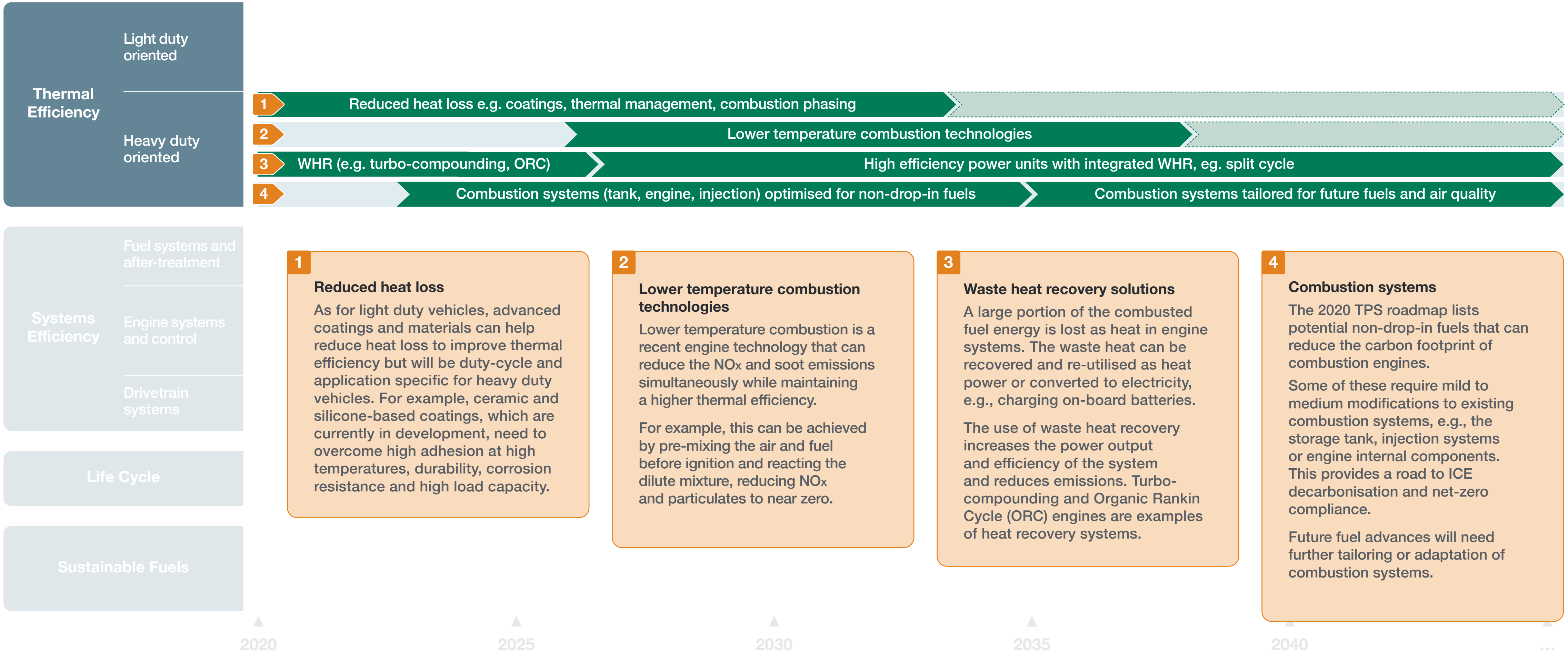
The downsizing of ICE is already recognised as a very suitable method for the concurrent enhancement of indicated fuel conversion efficiency and the lowering of CO_2 emissions.

Hybridisation is being integrated within ICE, providing packaging synergies and flexible performance benefits. For example, Mahle has a fully integrated, plug-in hybrid drive that incorporates a highly efficient 2- or 3-cylinder, turbocharged gasoline engine.

In future, these hybrids will need to operate on sustainable fuels to meet net-zero emissions mandates.

Thermal efficiency (heavy duty)

With their unique duty cycles and powertrain architectures, waste-heat recovery, low-temperature combustion and adaptations for future fuels provide opportunities for ICE technology.



1

Reduced heat loss

As for light duty vehicles, advanced coatings and materials can help reduce heat loss to improve thermal efficiency but will be duty-cycle and application specific for heavy duty vehicles. For example, ceramic and silicone-based coatings, which are currently in development, need to overcome high adhesion at high temperatures, durability, corrosion resistance and high load capacity.

2

Lower temperature combustion technologies

Lower temperature combustion is a recent engine technology that can reduce the NO_x and soot emissions simultaneously while maintaining a higher thermal efficiency.

For example, this can be achieved by pre-mixing the air and fuel before ignition and reacting the dilute mixture, reducing NO_x and particulates to near zero.

3

Waste heat recovery solutions

A large portion of the combusted fuel energy is lost as heat in engine systems. The waste heat can be recovered and re-utilised as heat power or converted to electricity, e.g., charging on-board batteries.

The use of waste heat recovery increases the power output and efficiency of the system and reduces emissions. Turbo-compounding and Organic Rankin Cycle (ORC) engines are examples of heat recovery systems.

4

Combustion systems

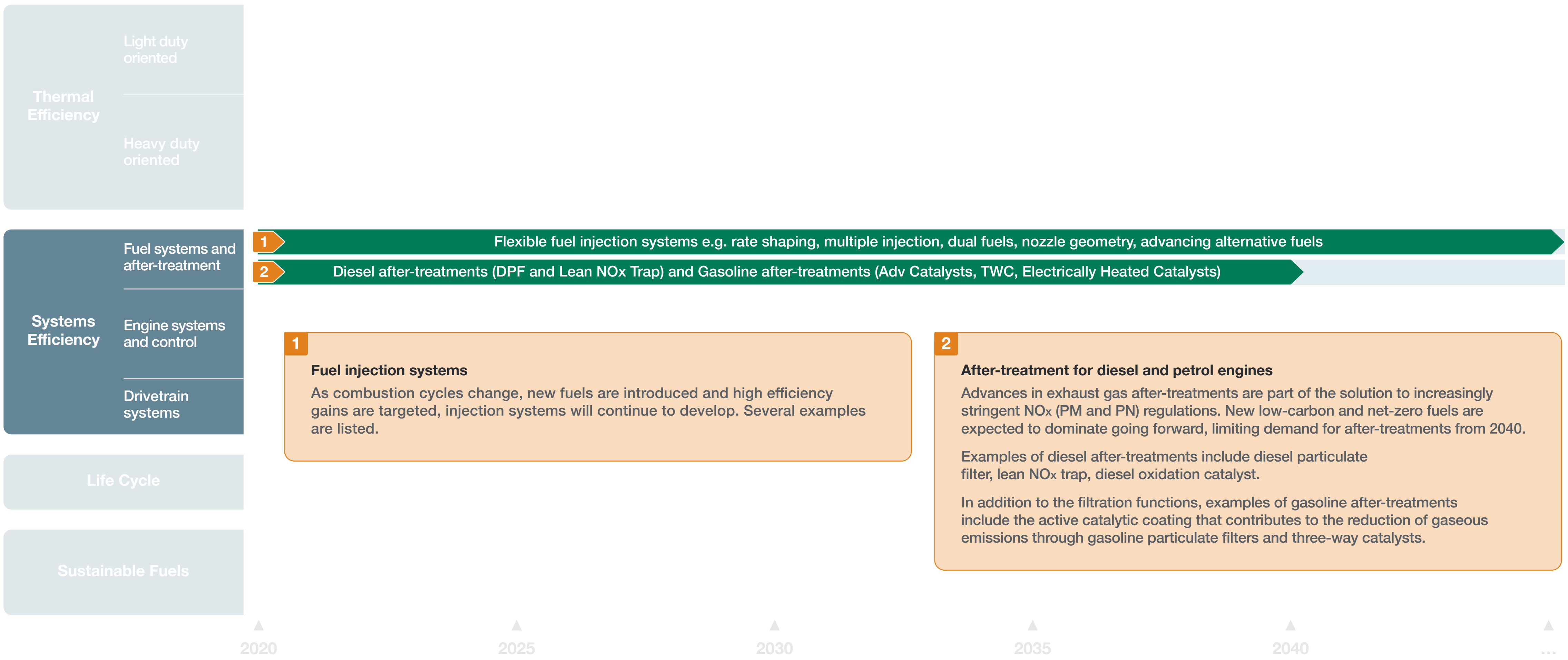
The 2020 TPS roadmap lists potential non-drop-in fuels that can reduce the carbon footprint of combustion engines.

Some of these require mild to medium modifications to existing combustion systems, e.g., the storage tank, injection systems or engine internal components. This provides a road to ICE decarbonisation and net-zero compliance.

Future fuel advances will need further tailoring or adaptation of combustion systems.

Fuel systems and after-treatment

After-treatments continue to develop to mitigate particulate and NO_x emissions but will transition to managing new fuels of the future.



1 Flexible fuel injection systems e.g. rate shaping, multiple injection, dual fuels, nozzle geometry, advancing alternative fuels

2 Diesel after-treatments (DPF and Lean NOx Trap) and Gasoline after-treatments (Adv Catalysts, TWC, Electrically Heated Catalysts)

1

Fuel injection systems

As combustion cycles change, new fuels are introduced and high efficiency gains are targeted, injection systems will continue to develop. Several examples are listed.

2

After-treatment for diesel and petrol engines

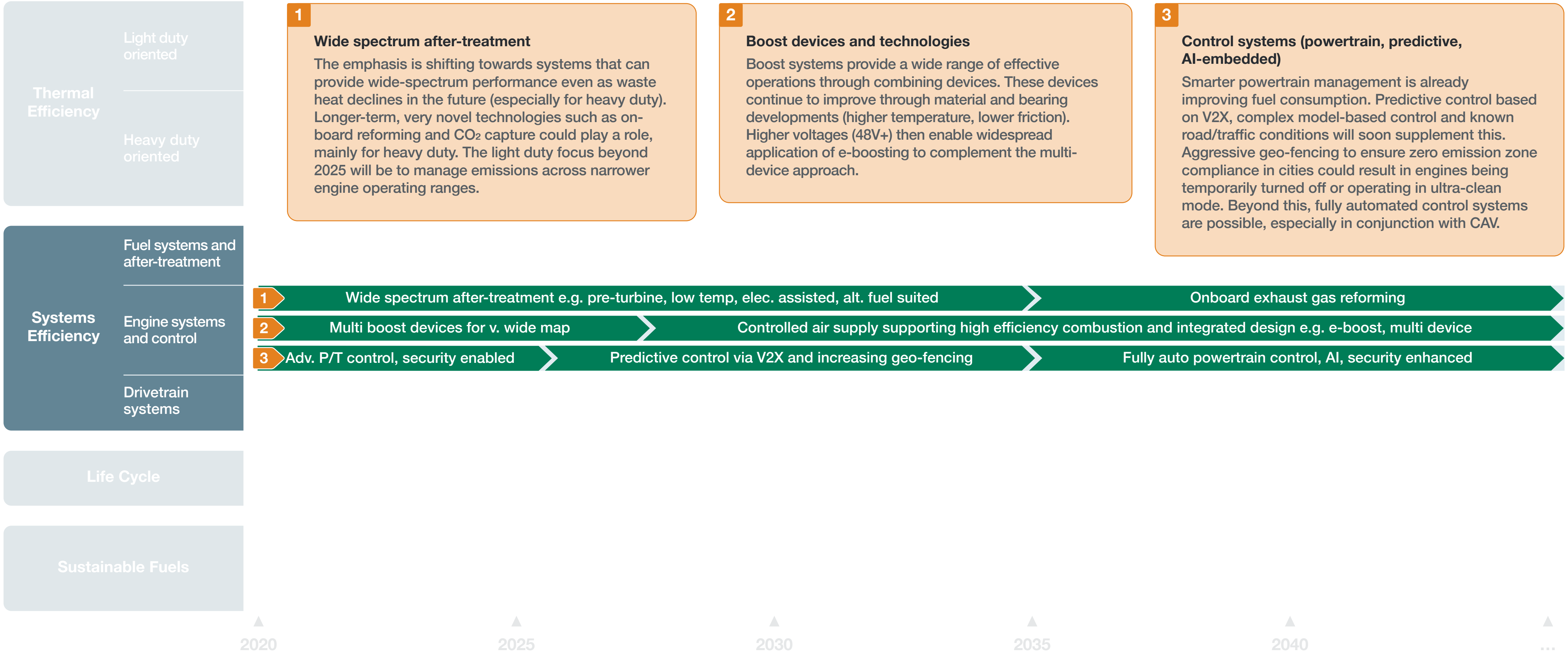
Advances in exhaust gas after-treatments are part of the solution to increasingly stringent NO_x (PM and PN) regulations. New low-carbon and net-zero fuels are expected to dominate going forward, limiting demand for after-treatments from 2040.

Examples of diesel after-treatments include diesel particulate filter, lean NO_x trap, diesel oxidation catalyst.

In addition to the filtration functions, examples of gasoline after-treatments include the active catalytic coating that contributes to the reduction of gaseous emissions through gasoline particulate filters and three-way catalysts.

Engine systems and control

A wide range of improvements in engine systems and control will support developments in existing engines and the emergence of more novel designs.



Thermal Efficiency

Light duty oriented

Heavy duty oriented

1

Wide spectrum after-treatment

The emphasis is shifting towards systems that can provide wide-spectrum performance even as waste heat declines in the future (especially for heavy duty). Longer-term, very novel technologies such as on-board reforming and CO_2 capture could play a role, mainly for heavy duty. The light duty focus beyond 2025 will be to manage emissions across narrower engine operating ranges.

2

Boost devices and technologies

Boost systems provide a wide range of effective operations through combining devices. These devices continue to improve through material and bearing developments (higher temperature, lower friction). Higher voltages (48V+) then enable widespread application of e-boosting to complement the multi-device approach.

3

Control systems (powertrain, predictive, AI-embedded)

Smarter powertrain management is already improving fuel consumption. Predictive control based on V2X, complex model-based control and known road/traffic conditions will soon supplement this. Aggressive geo-fencing to ensure zero emission zone compliance in cities could result in engines being temporarily turned off or operating in ultra-clean mode. Beyond this, fully automated control systems are possible, especially in conjunction with CAV.

Systems Efficiency

Fuel systems and after-treatment

Engine systems and control

Drivetrain systems

1 Wide spectrum after-treatment e.g. pre-turbine, low temp, elec. assisted, alt. fuel suited › Onboard exhaust gas reforming

2 Multi boost devices for v. wide map › Controlled air supply supporting high efficiency combustion and integrated design e.g. e-boost, multi device

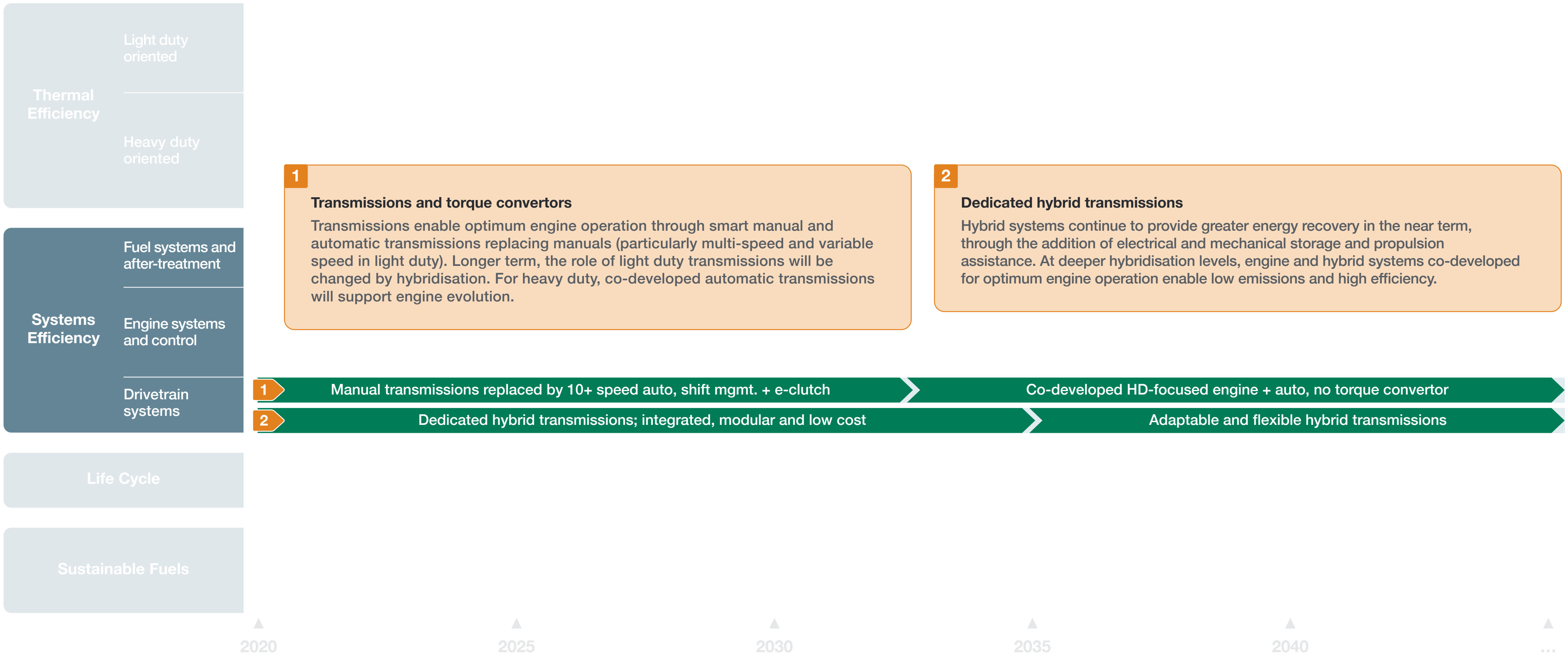
3 Adv. P/T control, security enabled › Predictive control via V2X and increasing geo-fencing › Fully auto powertrain control, AI, security enhanced

Life Cycle

Sustainable Fuels

Drivetrain systems

Transmissions and hybridisation are vital enablers for propulsion system efficiency; co-development will allow them to be operated closer to peak efficiency.



1

Transmissions and torque convertors

Transmissions enable optimum engine operation through smart manual and automatic transmissions replacing manuals (particularly multi-speed and variable speed in light duty). Longer term, the role of light duty transmissions will be changed by hybridisation. For heavy duty, co-developed automatic transmissions will support engine evolution.

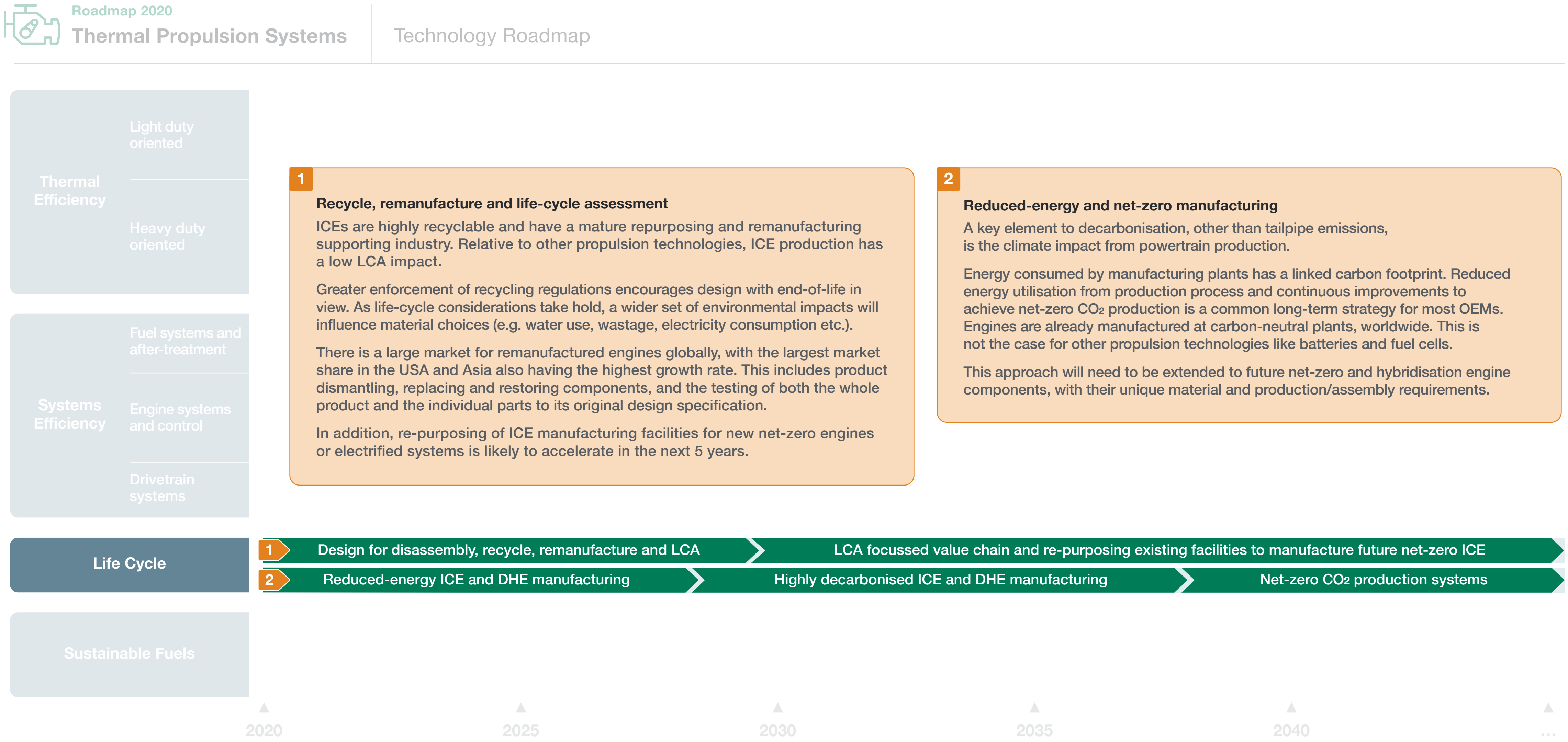
2

Dedicated hybrid transmissions

Hybrid systems continue to provide greater energy recovery in the near term, through the addition of electrical and mechanical storage and propulsion assistance. At deeper hybridisation levels, engine and hybrid systems co-developed for optimum engine operation enable low emissions and high efficiency.

Life cycle

Environmentally sustainable manufacturing is crucial for net impact assessment of all production processes, raw materials and plant operations.



Roadmap 2020

Thermal Propulsion Systems

Technology Roadmap

1

Recycle, remanufacture and life-cycle assessment

ICEs are highly recyclable and have a mature repurposing and remanufacturing supporting industry. Relative to other propulsion technologies, ICE production has a low LCA impact.

Greater enforcement of recycling regulations encourages design with end-of-life in view. As life-cycle considerations take hold, a wider set of environmental impacts will influence material choices (e.g. water use, wastage, electricity consumption etc.).

There is a large market for remanufactured engines globally, with the largest market share in the USA and Asia also having the highest growth rate. This includes product dismantling, replacing and restoring components, and the testing of both the whole product and the individual parts to its original design specification.

In addition, re-purposing of ICE manufacturing facilities for new net-zero engines or electrified systems is likely to accelerate in the next 5 years.

2

Reduced-energy and net-zero manufacturing

A key element to decarbonisation, other than tailpipe emissions, is the climate impact from powertrain production.

Energy consumed by manufacturing plants has a linked carbon footprint. Reduced energy utilisation from production process and continuous improvements to achieve net-zero CO_2 production is a common long-term strategy for most OEMs. Engines are already manufactured at carbon-neutral plants, worldwide. This is not the case for other propulsion technologies like batteries and fuel cells.

This approach will need to be extended to future net-zero and hybridisation engine components, with their unique material and production/assembly requirements.

1 Design for disassembly, recycle, remanufacture and LCA

LCA focussed value chain and re-purposing existing facilities to manufacture future net-zero ICE

2 Reduced-energy ICE and DHE manufacturing

Highly decarbonised ICE and DHE manufacturing

Net-zero CO_2 production systems

Sustainable fuels

Net-zero carbon drop-in, non-drop-in and developing future fuels are increasing in focus to deliver performance and cost-competitive solutions to transition from existing fossil fuels.

1

Drop-in fuels

These are low and net-zero carbon fuels that can be added to or replace existing fuels and work in existing engine systems.

Some known examples are listed, ranging from e-fuels (generated from the use of electricity) to fuels from living waste materials. Bio-fuels (e.g. bio-methane) used for agricultural vehicles currently come from a biomass source, but a sustainable food and heat supply needs to be developed. Synthetic fuels and e-fuel are a viable alternative but need to focus on renewable energy sources for their production.

2

Non drop-in fuels

These cannot be directly substituted into current ICE systems as they need equipment modification. This could range from a simple modification to the storage tank or injection system to a full change to the ICE components.

Net-zero-carbon non-drop-in fuels offer a further range of fuel options, including dimethyl ether (DME), a gaseous fuel made from methanol, hydrogen (gaseous or liquid) and several other synthetic or e-fuels.

3

Future fuels

These are predominantly new fuels resulting in zero-carbon emissions that are not currently in widespread use.

In a drive to look for new combustion engine fuels, significant research is underway to find alternatives to fossil fuels that take advantage of well-known production systems, established materials supply and low-cost manufacturing of ICE.

Glossary

Abbreviation	Explanation
AI	Artificial intelligence. Smart machines and algorithms capable of performing tasks that usually require human intelligence.
BEV	Battery electric vehicle
BTE	Brake thermal efficiency represents, in percentage terms, the amount of energy converted into useful mechanical work by a base engine at the crankshaft (excludes transmission and driveline losses).
CAVs	Connected and autonomous vehicles is an umbrella term to capture the varying levels of autonomy and technologies relating to self-driving vehicles.
GhG	Greenhouse gases trap heat in the atmosphere. Include carbon dioxide, methane, nitrous oxide and fluorinated gases.
HDV	Heavy-duty vehicle
ICE	Internal combustion engine
LCA	Life-cycle assessment. Assessing environmental impacts over all stages of the life-cycle of a product (for instance from raw material extraction, through processing, to manufacture, use and ultimately recycling/disposal).
ORC	Organic Rankine Cycle. Generating additional power from waste heat. The principle is similar to a traditional steam turbine but using an organic fluid rather than water vapour offers several performance benefits.
PM	Particulate matter is the term for the complex mixture of solid and liquid particles of organics and inorganic substances suspended in air. Limits relate to the concentration of pollutants.
PN	Particulate number captures the number of particles of different sizes, reflecting evidence that particle size is important in observed health effects.
TPS	Thermal propulsion systems. A device that integrates an engine or fuel cell with thermal and / or electrical systems to manage power delivery to the wheels and recover waste energy to improved performance and efficiency. The key feature of a TPS is that the primary energy is stored chemically (rather than electrochemically like in a battery).
V2X	Vehicle-to-X refers to an intelligent transport system where all vehicles and infrastructure systems are interconnected with each other.

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This is an industry consensus roadmap facilitated by the APC

Summary of engagements during the 2020 roadmap refresh

Spread of companies that participated in the refresh

109 industry organisations participated in Workshops and Interviews

38 additional industry organisations participated via the Online Survey

Total engagements 147 Industry Organisations

A global view with international participation

- Austria
- Belgium
- England
- Germany
- Netherlands
- Scotland
- Singapore
- Sweden
- Switzerland
- United States
- Wales
- Japan