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European Roadmap

Future Light-duty Powertrain Technologies and Fuels

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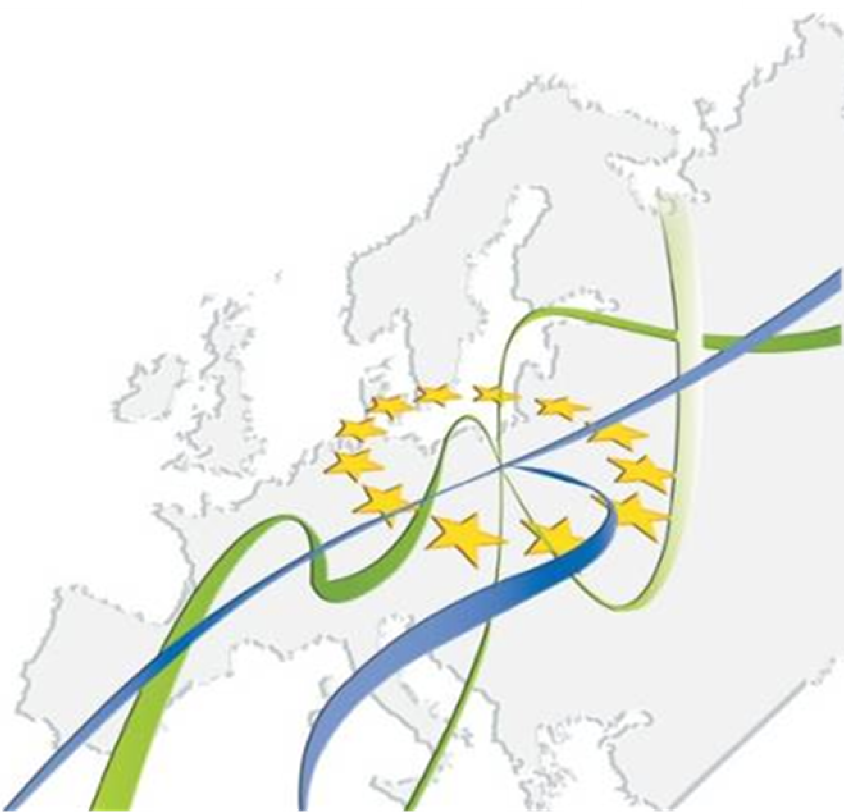
ERTRAC Working Group on Energy & Environment



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1. Executive Summary

Over the coming decades, Europe will require reliable and sustainably-produced energy for road and non-road transport as well as an energy infrastructure that efficiently utilizes and distributes this energy. Energy production must be combined with energy conservation in order to achieve ERTRAC's stated objectives for the 'decarbonisation of road transport'. In this paper, a research roadmap is presented for substantially improving the energy efficiency of road transport while increasing the share of renewable sources used by road transport.

The focus of this roadmap is future light-duty powertrain technologies based on advanced internal combustion engines (ICEs) as well as the fuels, processes, materials, and assessment tools that will be needed to enable them. Similar developments in heavy-duty powertrain technologies can be anticipated and will produce similar benefits in energy efficiency and in the decarbonisation of road transport. Meeting aggressive targets in this area will require a clear understanding of increasingly diversified energy demand and supply and the necessary innovation, research, development, and deployment activities that will be needed to meet these targets.

The advanced ICEs and fuels considered in this roadmap anticipate future demands for better transport energy efficiency, vehicle emissions, fuel flexibility, and flexible vehicle applications through:

- Light-weighting, by engine and vehicle downsizing and by structural improvements;
- Exhaust aftertreatment systems with lower impacts on engine efficiency;
- Flexible, adaptive, and predictive engine management systems for continuously optimizing engine parameters;
- Tailored operating modes, especially in hybrid and range-extended vehicle concepts;
- New demands on engine performance and competitiveness, especially in emerging markets;
- New fuels, both renewable and alternative, with consistent quality meeting market demand; and
- Scientifically-robust and reliable tools for evaluating environmental sustainability and performance.

2. Introduction

2.1 Background

A previous ERTRAC paper (ERTRAC (2010b)) presented a Future Transport Fuels Energy Pathway for Road Transport, describing an energy chain comprising primary energy, energy carrier, and application. This was a first step in describing energy scenarios for sustainable mobility that include energy demand from different road transport sectors and different transport and non-transport energy uses. A detailed view on energy production and distribution was considered beyond the scope of the previous paper and is the subject of this paper. In addition, important research needs related to the continuing development of advanced Internal Combustion Engines (ICEs) have not previously been addressed in ERTRAC Roadmaps and are included here.

Transport is a major consumer of energy. European consumers value their mobility and have a strong preference for personalized transport. Historical trends also show that there is a close relationship between the economic vitality of a country or region and its energy consumption. Without energy, a country or region will struggle to remain competitive in the world market and satisfy its consumers' demands for personal mobility.

For these reasons, the supply of energy and fuel required to meet these future demands will require a dynamic balance between aggressive energy conservation, sustainable energy production, and energy diversification. A broad range of technological and non-technological options will therefore be required, both to aggressively save energy and produce a greater fraction of energy from renewable sources in compliance with climate change and sustainable environmental expectations. At the same time, sustainable energy production must be coupled with developments in energy efficient vehicles that are attractive to consumers and can utilize a diversified energy mix while a reliable infrastructure must be in place to distribute this energy mix to where it is needed.

While the energy and fuel supply is expected to diversify in the future, advanced ICEs and powertrains will continue to play a major role for both light- and heavy-duty applications. The improvement potential for fuel consumption of advanced ICEs is still significant and continued improvements in regulated emissions performance and low overall cost are still feasible. For these reasons, advanced ICEs and powertrains will be important for meeting future consumer and regulatory demands over the near- and medium-term and they will be the pacesetter technology for alternatives like hybrid and battery electric vehicles. As such, they will be an important contributor to achieving ERTRAC's grand societal challenge for decarbonisation of transport.

Similar performance improvements can also be anticipated for heavy-duty ICEs and powertrains. In this document, similarities in research needs between light-duty and heavy-duty powertrains will be noted and differences will be the subject of additional roadmaps in the future.

2.2 Scope

This European Roadmap on Future Light-duty Powertrain Technologies and Fuels provides a perspective, including benefits, challenges, and milestones, related to the following topics:

- Advanced light-duty ICEs and powertrain technologies;
- Production and use of biofuels and advanced fuel products;
- Energy production and distribution for vehicle electrification (issues beyond those described in ERTRAC (2010b));
- Advanced materials and materials recycling for vehicles and infrastructure;
- Assessment tools (Well-to-Wheels (WTW), Life Cycle Analysis (LCA)).

2.3 Complementarities with other ERTRAC Roadmaps

This Roadmap is intended to complement other ERTRAC roadmaps focusing on Future Transport Energies, Hybridisation of Road Transport, and Sustainable Freight Transport.

2.4 Integrated approach

Increasing concerns for climate change and energy security are driving public policy while there is an ever-increasing consumer and business demand for transport and energy. Although advanced ICEs are expected to dominate road transport for several decades, especially in long-distance transport modes, the global competition for affordable energy and resources will lead to increasing diversification of energy sources, fuel types, and vehicles. This diversification will be greatest in urban environments where the transport and distance requirements are more compatible with diversified energy types and new energy distribution infrastructures. This roadmap, therefore, addresses the innovation, research, technology, and deployment needed to diversify the energy mix and infrastructure through the use of renewable fuels and advanced fuel products, including electricity, and improve the energy efficiency of vehicles and infrastructure especially through the use of advanced and lightweight materials. These changes must be accompanied by continuous improvements in road transport safety, noise, and emissions. Finally, continued development of models and assessment tools (WTW/LCA) will be needed to guide the evaluation of different fuel/vehicle combinations on a consistent and technically robust basis.

3. Contributions to the Grand Societal Challenges

The grand societal challenges addressed by the ERTRAC Strategic Research Agenda (ERTRAC (2010a)) are: 1) Decarbonisation, 2) Reliability, and 3) Safety. **Figure 1** summarizes the guiding objectives (corresponding to the main areas and indicators) of ERTRAC's 2010 SRA.

Figure 1 Guiding objectives of ERTRAC's "A Strategic Research Agenda for a '50% more efficient Road Transport System by 2030' (ERTRAC (2010a))

By 2030 Road Transport is 50% more efficient than Today

	Indicator	Guiding objective for 2030
Decarbonisation	Energy Efficiency: Urban Passenger	**+80%**
	Energy Efficiency: Long Distance Freight	**+40%**
	Share of Renewables	Biofuels: **25%** Electricity: **5%**
Reliability	Reliability of transport times	**+50%**
	Urban Accessibility	Preserve Improve where possible
Safety	Accidents with fatalities and severe injuries	**-60%**
	Cargo Lost to Theft and Damage	**-70%**

Table 1. Clear guiding objectives for Decarbonisation, Reliability and Safety in Road Transport.
The mission of '50% more efficient Road Transport' is articulated in leading indicators on Decarbonisation (3), Reliability (2) and Safety (2). Each indictor is furnished by a guiding objective for 2030 either indicating the improvement versus a 2010 baseline, indicated with '+' or '-' sign or an absolute level as is the case with 'Share of Renewables'.

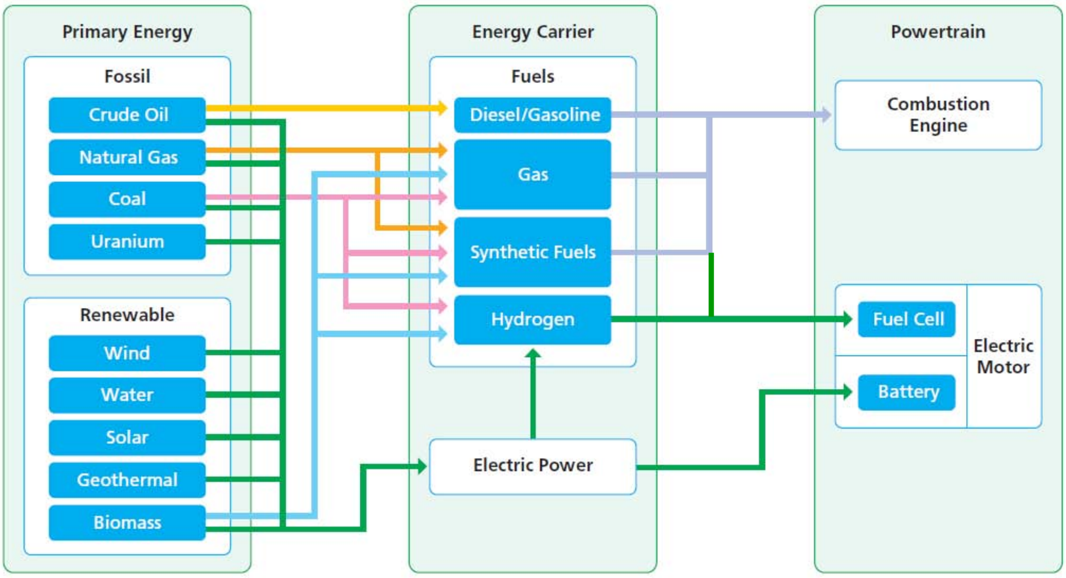
This roadmap on 'Future Light-duty Powertrains and Fuels' is specifically expected to impact the Grand Societal Challenge related to the 'Decarbonisation of Road Transport' by:

- Substantially improving the energy efficiency of road transport through an:
  - +80% improvement in the energy efficiency of urban transport;
  - +40% improvement in the energy efficiency of long-distance freight transport.
    - These will be achieved in large part through improvements in the fuel efficiency of engines, powertrains, and vehicles.
- Substantially increasing the share of renewables in road transport specifically:
  - 25% share of renewable fuels in road fuels;
  - 5% share of renewable electricity used for vehicle electrification.
    - The increasing share of renewable fuels in road fuels will require engines and vehicles that are fully compatible with the renewable fuels in the marketplace.
    - The increasing share of renewable electricity will also aid decarbonisation of road transport through the use of plug-in and battery electric vehicles which are covered in other ERTRAC roadmaps.

4. Research Lines

As was shown previously in ERTRAC's 'Future Transport Fuels' roadmap, **Figure 2** summarizes the diversification of energy pathways from primary energy, to energy carrier, to powertrain technology. Although future pathways may increasingly lead to electric motor options, internal combustion engines are likely to be the performance and cost favourite for the near- to medium-term for light-duty applications. For heavy-duty applications, there are even fewer good alternatives so that ICEs and liquid fuels consisting of fossil and renewable fuel products will be the mainstay for some time.

Figure 2 Energy pathways for liquid, gaseous, and electric energies



4.1 Research Areas

To address the grand societal challenge associated with transport decarbonisation, the following research areas have been identified. In large part, these areas follow two main lines: increased penetration of renewable energy in the transport system (i.e. via electrification and via biofuels and alternative fuels) and drastic improvement of energy – fuel consumption of existing powertrain systems. A major research effort has also to be directed towards guaranteeing that real world performance of all systems is at the same level as during certification, closing the gap that has emerged in some cases. The main research topics are explained below.

A1) Advanced Internal Combustion Engines (ICEs)

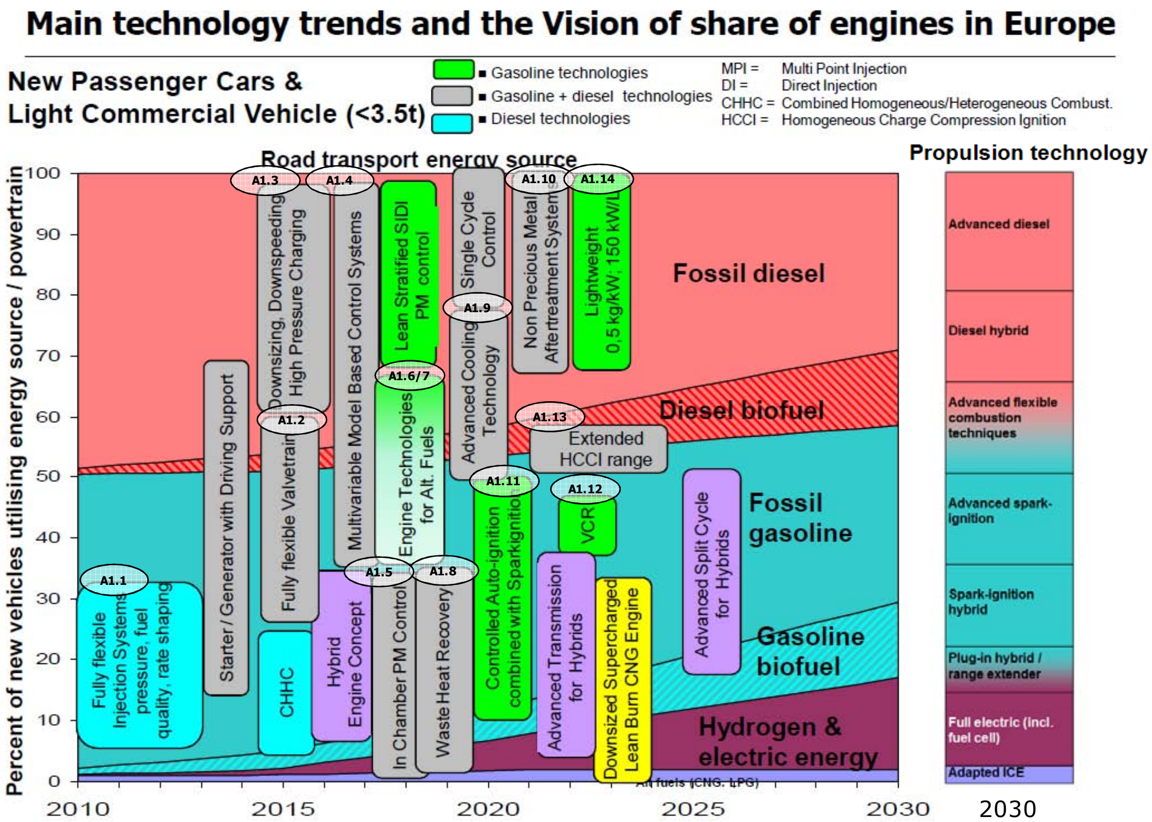
Electrification of the vehicle has already been identified as a future priority area for R&D and the research needs have been documented in another ERTRAC roadmap.

Projections for the penetration of alternative powertrain technologies over the next decades suggest that a large proportion of new light-duty vehicles will continue to use an internal combustion engine equipped with advanced concepts and technologies. ERTRAC's Strategic Research Agenda 2010

(ERTRAC (2010a)) indicated that more than half of new light-duty vehicles in 2050 will still be powered by an advanced ICE. A substantial fraction of these can be expected to be vehicles with an ICE as the sole source of propulsion while, in others, ICEs will increasingly be integrated with electric motors and batteries in a range of hybrid powertrains as described above.

Figure 3 shows the main technology trends for the light-duty powertrain over the next 20 years. Thus, there is a real urgency to address the near-term research needs while considering the medium- and longer-term technologies for 2015 and beyond. Today's ICEs have reached a very high level of maturity but they still offer significant potential for further improvement and these refinements should be exploited in future research activities.

Figure 3 Technology trends and research needs for light-duty ICE powertrains to 2030



Note: The reference numbers in this chart refer to the research needs that are described in more detail in the following section.

It is essential therefore to maintain focus on improvements to the ICE for light- and heavy-duty vehicle application, while R&D is carried out in parallel on components and systems for electrification of the vehicle. This approach will ensure the contribution of ICE technologies to sustainable mobility. Decarbonisation of the ICE itself will be achieved through efficiency improvements and the use of low carbon fuels, particularly biofuels. To achieve these advancements, further research is needed now and in the future.

A1.1) Fully flexible injection systems, pressure, fuel quality, and rate shaping

Injection is one of the most crucial parameters in modern diesel engines. The injection itself can be varied either with respect to its hardware setup (e.g. type of nozzle, number of injection holes, hole shape, targeting direction, etc.) as well as in its operational parameters. These are injection pressure, temporal variation of the injection rate (rate shaping), multiple injections, fuel quality sensing, etc. Both, hardware- and operational- parameters are strongly linked and follow partly diverging routes. At low rpm and loads, an injection rate is required that has a small gradient at the beginning and then steepens quickly. At full load, very fast injections with immediate high rates are preferred. These different targets cannot be achieved by setting only hardware design parameters but rate shaping has to contribute. Thus enabling rate shaping in the engine map offers additional potential with respect to engine emissions as well as fuel consumption reduction. Especially for the emission of particulate matter (PM) the injection system plays a key role in direct injection engines. Also for a variety of fuels different rate shaping is required respectively in order to keep “injected energy” at constant levels for different lower calorific heat levels. Closed loop combustion control and self-diagnostic systems will also be important to enable the full potential of future fuel injection equipment and strategies.

A1.2) Fully flexible valvetrains

Variable valvetrains such as camphasers on the inlet and exhaust offer the possibility of a moderate de-throttling at part load conditions as well as an internal Exhaust Gas Recirculation (EGR) capability by increased valve overlap. At Wide Open Throttle (WOT), better exhaust gas scavenging can be achieved in both naturally aspirated and turbocharged/supercharged engine types. Increasing variabilities in the valvetrain such as variable lift and variable opening duration lead to load control at part load via the valvetrain rather than via the throttle. Additionally, the response time for load jumps can be decreased. As an additional example, fully flexible valvetrains, which are completely decoupled from the crankshaft allow turbulence levels inside the combustion chamber to be adapted closer to the needs of the combustion process, e.g. via multiple opening events, etc. The latter is the enabling technology for advanced low temperature combustion. Almost all of the above mentioned aspects can be addressed by systems with discrete lifts rather than fully flexible ones but only the latter will achieve full benefits.

A1.3) Downsizing, downspeeding, and high-pressure charging

A strong trend towards downsized passenger car gasoline engines is clearly visible in the industry. The current maximum brake mean effective pressure (BMEP) reaches levels between 22 and 25 bar. The question is how to further increase the BMEP without deteriorating too significantly the engine’s thermodynamic efficiency at high loads. Similar to diesel engines, transmission ratios can be increased if the maximum engine speed (RPM) is brought to a lower value, which in turn offers the possibility to optimize the gas exchange process for a lower rpm range (downspeeding). In combination with refined applications of Miller- or Atkinson-Cycles with appropriate compression ratios further potential is to be explored. Together with increased charge motion and hence turbulence levels, cooled EGR and high pressure charging, methods how to achieve very high (up to 30bar) BMEP have to be developed for smaller displacements. Another challenging task is the development of appropriate turbo- and/or superchargers. The tradeoff will be between pressure build-up (turbo lag) and appropriate air-throughput without deteriorating full-load thermodynamics too badly due to an increased rate of hot exhaust gas remaining in the cylinder from the previous cycle which can be caused by higher back pressures. Turbocharging systems must also overcome increasing power demands for charging if very high levels of EGR are used to enable low temperature combustion.

A1.4) Multivariable model-based control systems

Further improved combustion engine technologies are required to meet the future demands on fuel efficiency and emissions. As a consequence, the variety and complexity of controllers for both diesel and petrol engines will be increased more and more. This trend can be boosted by new sensors and increasingly powerful processors for automotive application, in particular multi core systems of high computing power. Model based controls are a potential alternative to avoid additional complexity and cost of sensors.

As vehicles are operated in a broad variety in terms of driving behaviour, road profile and operation purposes the conventional calibration based on a standardized operation pattern will not yield optimal performance concerning fuel consumption and emissions. In particular, the transient operation of combustion engines can be improved significantly.

A dedicated online-observation capability for analyzing engine combustion, powertrain and vehicle behaviour during the individual operation patterns would enable an on-road adaption of all components towards an optimized performance. Thus, individual demands from the driver on fuel efficiency or responsiveness could be accounted for as well as requirements resulting from cold start, warming-up or regeneration events of aftertreatment devices.

The real-time computing capability for engine control, e.g. via a predictive combustion model and an optimiser for the entire powertrain including electric motors and the use of route guidance systems, will maximize the benefit for both vehicle user and environment. This approach offers fuel consumption potentials up to 4% (max 2% for diesel).

A1.5) Particulate Matter (PM) control with focus on alternative fuels

New regulations related to particulate matter number assessment, in combination with the necessity to cope with a variety of biofuels, drive the need for greater understanding of processes related to particulate formation and consumption within the engine's internal combustion process. A more in-depth understanding is needed both within the diesel and gasoline engine development communities with particular emphasis on the direct injection gasoline engine. Areas that need further fundamental development include:

- Influence of fuel constituents, alternative fuels, and future fuels on combustion mechanisms related to PM;
- Influence of conventional and advanced combustion modes on PM emissions;
- Exploration of the potential of nanotechnology for development of insulating coatings of low heat capacity;
- Efficient experimental methods for characterizing PM formation and reduction during the combustion process;

- Improved computational models for combustion mechanisms related to the generation and decline of PM. Developments are needed both to predict PM levels throughout the combustion cycle and to improve the design and optimization of advanced combustion systems;

- Influence of injection system technology and specifications as well as influence of oil control on PM emissions;

- Development of charge system (boosting, EGR, and cooling) that support suitable boundary conditions for reduced PM generation;

- Maintain real life performance under varying operation conditions at the level of the vehicle certification cycle.

A1.6) Spark Ignition (SI) engine technology for alternative fuels (including downsizing)

The challenge for the development of technological solutions for a sustainable transportation system asks for high synergies between the evolution of the Internal Combustion Engine technologies and the use of low carbon alternative gaseous /renewable fuels. The innovative engine platforms based on downsizing/turbocharging/variable valve actuation enable a wide flexibility in adapting the combustion process to the specific characteristics of each fuel, thus maintaining the optimum conditions in terms of efficiency and pollutant reduction. Compared to a conventional naturally-aspirated SI engine, these new engines will provide a significant CO_2 reduction potential, close to 20%.

This approach represents the ideal way to exploit the benefit coming from the use of Compressed Natural Gas (CNG) from both fossil and renewable sources (biomethane). Moreover, from the industrial point of view the availability of such a kind of flexible engine platform is a key factor considering that other alternative fuels such as bioethanol can be also used on SI engines, depending on the local availability of the fuel. At the same time, CNG engine technology is also able to improve the introduction of hydrogen, based on renewable energy sources production, in the transportation sector via the use of natural gas and hydrogen blends for captive fleets, while for long transportation sector, Liquefied Natural Gas (LNG) is of growing interest.

A1.7) Compression Ignition (CI) engine technology for alternative biofuels

The development of process technologies for synthetic diesel by Fischer-Tropsch (FT) technology and hydrogenated vegetable oils (HVO) (as well as hydrogenated animal fats) enables a wider panel of combustion approaches thanks to the specific fuel properties of these blend components, especially higher cetane number and low aromatics composition. The availability of advanced biodiesel products at industrial scale necessitates the analysis of their impact on the powertrain technologies both from the standpoint of the combustion process and system components adaptation. Together with the evolution of the biodiesel option, blending of diesel fuel with bioethanol could also represent an option for specific applications.

A1.8) Waste heat recovery

The waste heat re-use represents a great opportunity to improve the internal combustion engine efficiency, in particular at high load operation and at heavy duty vehicle applications. Up to 70% of the combustion energy is converted to heat that is rejected in the exhaust and by the engine cooling. So, being able to re-use a considerable part of this heat means a significant overall efficiency increase of the powertrain, evidently accounting for the passenger car constraints (dimensions, weight, and reliability) and based on technologies with a low environmental impact.

Since there are different technological solutions allowing the re-use of the waste heat, the challenge is the identification of the best solutions in terms of technology, sustainability and efficiency for small and medium passenger cars that represent the major part of the sold vehicle in Europe. To achieve these goals, it is required to develop new generation of components, systems and of powertrain able to take the maximum benefit from the waste heat re-use.

A1.9) Advanced cooling technology

Although the efficiency of modern internal combustion engines is increasing, the cooling requirements are rising due to higher demands on power output. Unlike naturally aspirated engines that eliminate heat to the environment through the exhaust gas, more rejected heat in modern ICEs will be transported into the underhood environment from heat exchangers, especially intercoolers and EGR coolers. With the underhood space already limited by passive safety and styling constraints, thermal interactions between hot parts will need to be taken into account and used more efficiently. Due to the increasing number of auxiliary systems, the cooling circuit is becoming more and more complex. This makes it very difficult to integrate and control the different components like radiator shutter and thermostat while different coolant temperatures are necessary to operate in the specified temperature range (e.g. gear box, high voltage battery, charge air cooler). Therefore research is necessary on the one hand to reduce the complexity of the coolant circuits, while on the other hand to enable advanced cooling strategies via integration of prediction tools regarding driving pattern and routing to forecast engine operating conditions.

A1.10) Non-precious metal aftertreatment systems for biofuels and alternative fuels

Global vehicle market growth and strengthened emission legislation will put a growing premium on the limited supply of platinum group metals (PGM) used in engine aftertreatment systems. Therefore, cost effective material alternatives will be needed to sustain the substantial improvements that advances in aftertreatment technology have provided in prior years. Aftertreatment technology based on close to zero or even PGM-less content will benefit from advances made in calibration and engine hardware but also from improved fuel quality as enhanced PM replacing materials gain feasibility. Areas of focus might be found specifically in PGM-less lean NOx aftertreatment technology and/or base metal only catalyzed filters. Close to zero PGM washcoat technology and/or significant platinum group metal shifts between individual PGM on oxidation catalysts and three-way catalysts will remain in focus within the industry for many years to come. PGM usage reduction in exhaust aftertreatment technologies is one enabler for other PGM consuming technologies, such as fuel cells. Finally a major challenge in this research topic is to achieve real life performance under varying operation conditions at the level of the certification cycle.

A1.11) Controlled Auto-Ignition (CAI) combined with spark ignition

A combined combustion mode, i.e. auto-ignition at low load conditions and spark ignition at high load conditions, is a promising option to reduce CO_2 while significantly reducing pollutant emissions. Advanced technologies, such as air dilution loop or EGR dilution loop, should be developed to better control the auto-ignition mode and optimising the spark ignition mode to reduce pollutant emissions.

These developments should be also combined with advanced strategies for engine control, based on technical breakthroughs on sensors or actuators.

A1.12) Variable Compression Ratio (VCR)

VCR technology allows a slight increase in overall engine efficiency and represents an opportunity to enable extreme downsizing of gasoline engines. The research target enabled by these benefits is a 15-20% improvement in overall fuel consumption and lower CO_2 emissions. Unfortunately, all of the available technologies to implement VCR on light-duty engines result in one or more drawbacks such as highly specific overall engine architecture, increased mass, higher engine friction, lower reliability, insufficient control, or difficulty in vehicle integration. There is a strong interest in pursuing research to design a reliable and efficient VCR technology that could be used as an add-on to conventional piston engine architecture.

A1.13) Extended range Homogeneous Charge Compression Ignition (HCCI)

HCCI is a combustion mode that ignites throughout the cylinder charge after activating the fresh injected fuel charge by exhaust gases that remain in the cylinder from a previous cycle. Under HCCI operation, engine-out NOx emissions may be one or two orders of magnitude lower than in a conventional engine, with an improvement in fuel consumption due to less throttling. HCCI currently suffers most from restrictions in the engine map area where it can be applied. The research target is to extend HCCI operation to a wider range, in particular low load modes. Coping with low temperatures and catalytic converter operation at low load and keeping HCCI going at low loads are other substantial tasks.

A1.14) Engine lightweighting

This is strongly interlinked with the downsizing topic. Lightweight and ultrahigh power-to-weight ratios contradict each other. The higher the specific power output of an engine will be the more demand for alternative fuels exists. Only with ethanol- or methanol-blends can the required high cylinder pressures be achieved through acceptable spark advances. This in turn requires very high strength of the components such as crankcase, connecting rod, piston, bearings, etc. which currently do not exist in conventional turbocharged engines. In diesel engines, the same problems are already being faced today. Cylinder pressures of around 200bar require special designs which in turn increase weight. The challenge is to make a step-out improvement compared to today's engine. The use of exotic materials and very smart design layouts which are considerably different from today is inevitable. Lightweighting will be especially important in hybrid and range-extended vehicles to offset additional battery weight.

A2) Production, distribution, and storage of biofuels and advanced fuel products

The demand for cleaner more energy efficient road transport is inevitable linked to the fuels employed and their properties. Advanced fuels and biofuels can and will play a very important role in achieving a more environmentally friendly and energy efficient profile. Fuel technology evolution is highly related to vehicle engine technology and exhaust aftertreatment systems development. Greater use of biofuels for transport forms an important part of the package of measures required if the EU is to comply with CO_2 reduction targets set for the near future as well as of any policy packages set up to meet further commitments in this respect. Advanced fuels and biofuels may play an important supplementary role in vehicle electrification and the vehicle-grid integration envisaged for the next decade.

A2.1) Improve process and catalyst technology in order to improve WTT efficiency of fuel production

Biofuel production today in the large volumes required to meet ambitious EC targets is not fully sustainable because of limited availability of raw materials, high costs of production, and uncertainties about indirect land use change. New technologies should focus on fully exploiting biofuels benefits (GHG reduction, reducing dependency on oil products) while facing challenges such as widening the raw materials base towards waste products and waste biomass, developing new production processes, and reducing manufacturing costs. Process and catalyst technology improve can make a substantial contribution to making advanced biofuels socially and economically sustainable in the long term.

A2.2) Meet current fossil fuel properties using advanced biofuel products (HVO, BTL, LC Ethanol, Biomethane, DME, Hydrogen) and adapt engine technology to meet regulated limits

The main research question under this heading is: 'how do we promote the parallel development of future powertrain systems and fuels, integrating research in both fields, in order to achieve optimal performance both as regards conventional pollutants and the corresponding emission standrads as well as CO_2 emissions requirements on a WTW basis?' In this context, the following topics need to be addressed: targeted fuels for efficient ICEs having near-zero engine-out emissions, the impact of biofuel blending on combustion, the combustion characteristics of alternative fuels, adaptability of engine performance to changes in fuel quality, on-board fuel quality sensing systems, exhaust aftertreatment systems for biofuel-powered engines, powertrain calibrations for multiple fuel operating schemes, etc.

A2.3) Long-term biofuel storage systems

The development of technologies and networks for the effective promotion of new fuels and biofuels and the creation of fuel blends of custom properties and characteristics are important challenges both from a technical and a logistics and fuels distribution point of view. In this context research is required to address the following topics: In-pump blending, fuel distribution and refuelling infrastructures for long-range applications, establish conditions for compatibility of biofuels and biofuel blends with existing logistics, and the development of full biomass supply chains. From today's point of view issues related to the long term storage of current biofuels (biodiesel and bioethanol) such as microbial growth and degradation need to be specifically researched.

A2.4) Additive technology for enabling enhanced performance

Additives, added to the fuel in small amounts, are necessary to perform several functions. Among others, additives can (1) reduce emissions; (2) improve fluid stability over a wider range of conditions; (3) improve viscosity, reducing the rate of viscosity change with temperature; (4) improve ignition by reducing its delay time, flash point, and so forth; and (5) reduce wear with agents that adsorb onto metal surfaces and sacrificially provide chemical-to-chemical contact rather than metal-to-metal contact under high-load conditions. For conventional fuels and biofuel blends of low concentrations there is a wide knowledge basis of metal based additives, oxygenated additives, depressants and wax dispersants and ignition promoters. However, research is needed to further expand fuel additives as indispensable tools not only to decrease drawbacks but also to produce specified products that meet international and regional standards, allowing the fuels trade to take place.

A2.5) Competition from other transport modes for renewable fuel products

Not all alternative fuels are equally suited for all modes of transport, and also not for all sectors within a specific mode. The needs of the different modes and the possibilities of the different fuels therefore need to be analysed for each mode separately. The suitability of a fuel for a specific transport mode depends on energy density of the fuel, vehicle compatibility and emissions performance, cost and market availability, safety during production, distribution, storage, vehicle refuelling, and use. The EC's Future Transport Fuels Report (COM (2011c)) has a suggestion with respect to the coverage of the different transport modes by the different alternative fuels. Research needs to concentrate on the specific aspects raised by each mode separately, e.g. biomass derived kerosene for aviation and biofuels for railways.

A3) Energy production and distribution for vehicle electrification

A3.1) CCS and energy production

In the EC's Strategic Energy Technology (SET) plan, the EC outlined an objective to demonstrate the commercial viability of Carbon Capture and Storage (CCS) technologies in an economic environment driven by the Emissions Trading Scheme, in particular, to enable cost-competitive deployment of CCS in coal-fired power plants by 2020 or soon after. The same technology could be used in selected refineries where the CO_2 sources support the added investment and the CO_2 transport and sequestration facilities are available. A large reduction in cost as well as an improved efficiency is necessary. The steps cover capture (pre- or post-combustion, chemical looping) and CO_2 transport and sequestration. In response to these challenges, a portfolio of demonstration projects is expected within the next five years, to test existing CCS technologies and demonstrate their long term operational availability and reliability.

A3.2) Marginal electricity production

A change of all passenger cars to electric vehicles would require a power generation corresponding to 10-20% range of current power generation (reference). An analysis of how this electricity will be generated is necessary to estimate the Well-to-Wheels (WTW) emissions of CO_2 for electrical vehicles. Some examples can be found in the electricity roadmap (ERTRAC 2009) generally indicating a positive contribution for different generation mixes while a pure fossil scenario may increase the CO_2 emissions. Most studies indicate that the marginal power will be dominated by fossil fuel until 2030. Extended studies of different scenarios for power generation are needed including an analysis of the dynamic aspects of this transition. The results of such studies depend on the size and timing of the change in supply of electricity. On the longer term it is likely that the so called "dynamic margin" consists of both fossil and renewable energy. For example the 450ppm scenario from the International Energy Agency expects significant reductions of CO_2 from EU electricity production (from ~535g/kWh in 2010 to 130 g/kWh in 2030).

The traditional definition of marginal electricity is most likely not applicable to a large fleet of electric vehicles in the future. What is of interest is the impact from a large fleet of electric vehicles and how additional electricity demand should be allocated to consumers, not the impact from limited numbers of vehicles in an introduction phase. Given the current costs and benefits of electric vehicles, it is expected that many years will be required to reach high market shares and, during this growth period, electricity production will change in a dynamic process depending on the overall demand for electricity, regulations, pricing, taxation, etc. In the introduction phase, when there are only limited amounts of renewable electricity available, the CO_2 savings from electric vehicles will be small. However, this early introduction will facilitate a larger fleet which will operate using electricity having much lower CO_2 emissions.

A3.3) Smart Grid management (city level energy and transport demand management)

Electricity generation and distribution are likely to change in near to mid-term and trends point towards more renewable and more local power generation. Larger proportions of wind and solar power will require more balancing, and possibly also energy storage, in the grid. Information and Communication Technology (ICT) is an integral part of the Smart Grid and developments offer new opportunities for load management and communication between the users (households and other users) and the grid operators. Several European countries are enforcing new metering demands supporting this development. The increasing need for charging of electrical vehicles will benefit from this development. The power industry has accepted the cap on CO_2 as a part of the trading system and transport electrification will move transport energy within the cap. More research is needed on many levels to identify an optimised overall energy system. This includes business models, roles of different stakeholders and integration of charging infrastructure. Electricity providers are expected to play an active role here to integrate smart grids with local power generation and distribution.

A3.4) Standardisation of recharging technology and infrastructure

Standardisation of the interfaces between charging infrastructure and vehicles is essential to keep cost down and facilitate a mass market introduction of plug-in vehicles. The standardisation needs to cover the physical interface with the vehicle as well as the communication protocols and procedures related to the information flow between vehicle and grid. The significant consequences on battery ageing from different charging strategies will most likely require that the main control is governed by the vehicle management unit within the limits set by the grid. New standards are needed in all charging areas including intelligent home charging, fast charging and wireless charging. It is important that the standards developed also take more long term requirements for Smart Grid implementation (such as demand side management, time-controlled charging, and vehicle-to-grid (V2G) technology) into account.

A3.5) Continuous charging capabilities

New technologies for continuous charging (inductive and conductive) through Electric Road Systems (ERS) are emerging. The ability to pick up electric power from the road system will have a significant positive impact on the high level system cost of transportation electrification and in particular on the size of the battery required onboard the vehicle. Synergies with bus and freight distribution truck market in urban areas are of interest. In the long run, also technologies for continuous charging of long distance freight distribution are possible. Primary research areas for ERS are power pick-up systems, safety solutions and how to overcome institutional barriers.

A4) Advanced materials and materials recycling for vehicles and infrastructure

A4.1) Vehicle redesign for efficient materials recycling

In order to provide an efficient use of recycled materials as well as an optimised handling of recyclable parts, it is important to include these aspects as early as possible in the design process. Recyclable items, or parts including such, need to be mounted and assembled so that they can be easily disassembled. This needs to be taken into account when choosing joining and fastening methods. It is also important to have the correct set of requirements on materials, avoiding unnecessarily strong requirements and thereby disqualifying recycled materials.

A4.2) Infrastructure redesign for efficient materials recycling

The logistic chains as well as the complete setup of suppliers need to take into account the handling of recycled materials in the flow. This covers inbound/outbound logistics as well as in-plant material handling. From a research point of view, this increases the complexity of an already very complex system and must be investigated in order to make correct cost estimates and optimisation of the complete flow.

A4.3) Catalyst manufacturing and recycling processes

Catalysts derived from rare earth materials are regularly used in many transport-related applications, including fuel production and aftertreatment technologies. The recycling and reuse of these limited resources will be increasingly important while high-performing alternatives are identified that can be manufactured from more abundant components.

A4.4) Component technologies, such as electric machines, including lower-cost alternatives, availability of raw materials, optimised design, material demands, low-cost options

A large source of uncertainty is related to the availability of reliable and diversified supply of metals, e.g. copper and permanent magnets that are necessary to assure high efficiency and high power density (compact) electrical motors. While at a research level several solutions are pursued, it seems there is no viable industrial alternative to NdFeB for at least another decade. The move from few and critical sources of oil to a likely even more critical single source of permanent magnets should urgently address the development of both new high efficiency motors using limited weight of permanent magnets and completely new motor designs. Advanced materials are therefore required for permanent magnets and magnetic cores. This incorporates development of highly integrated motors (on-axle, in-wheel) and controls using aggressive cooling and optimized (or even non-) magnetic materials.

A4.5) Policy issues related to sustainable vehicle production

Sustainability is already at the centre of automotive R&D. Environmental challenges such as climate change and resource scarcity are the source of both constraints and opportunities for technological development. Research has to satisfy both environmental and customer needs, generating high added-value products, related processes and technologies to meet functionality requirements as well as growth conditions, public health, occupational safety and environmental protection concerns. This means that public policies and regulations need to take into account all these aspects in a proper balance.

A4.6) Affordable technologies for producing easily recycled batteries, magnets, etc.

Cathode materials such as Lithium Iron Phosphate ($LiFePO_4$), Lithium Manganese Spinelle ($LiMn_2O_4$), are currently considered promising "new generation" electrode materials. Together with reference cobalt- and nickel-based materials, such as $Li(NiMnCo)O_2$ and $Li(NiCoAl)O_2$, these cathodes cover the main technological trends for the near future. The disposal of end-of-life batteries is a fundamental issue for all automotive application involving advances batteries. While the absence of Co- and Ni-based compounds should have a positive effect on the initial cost of the battery, it is still unclear if the recycling process for alternative chemistries is technically feasible and economically viable.

The total cost of the cell should be evaluated, for an expensive process to enhance conductivity can compensate the apparent low cost of the cell's raw components (case of $LiFePO_4$). Of course, the general performances of the cell (in terms of energy and power capability) should stand up to the car makers requirements.

A5) Assessment tools (Well-to-Wheels (WTW), Life Cycle Analysis (LCA))

A5.1) Robust WTW/LCA tools for valuing alternative fuel/vehicle pathways and further development and routine applications of LCA methodologies

Environmental sustainability will be a key driver for future technological improvements. In order to achieve this outcome, future technological innovations must be evaluated in a scientifically-robust and consistent way for their environmental impact and sustainability. LCA is a recognised approach, following guidance contained in the International Reference Life Cycle Data System (ILCD) Handbook, to achieve robust and reproducible results. Although much progress has been made on LCA methodologies in recent years, a more robust LCA methodology and software tool for vehicle design should be developed to facilitate industry decisions and enable quick and reliable 'eco-scans' that can be used to guide the environmental aspects of vehicle design. Such an LCA tool for vehicles should consider the extraction of raw materials, the manufacturing of components, vehicle assembly, and use phase (on a WTW basis) as well as maintenance, end-of-life (EoL) treatment, and recycling. A coherent framework is needed in order to compare different drive train technologies (ICEs, hybrids, battery electrics, etc.) and different fuel technologies (gasoline, diesel, compressed gases, etc.). Awareness must also be drawn to related topics such as typical vehicle utilization and associated drive cycles, interactions between electricity storage systems and the power generation grid, and the manufacturing and EoL treatment of batteries.

A5.2) LCA for vehicle materials options

The important question to address here is how to develop advanced, lightweight, cheap and eco-friendly materials from abundant resources in order to adequately fill the demands of future vehicle development and improve vehicle safety, reliability and environmental performance. In this context, it is necessary to carry out LCA of common and alternative materials, multi-fuel compatible materials including non-precious metals and catalysts, and advanced alloys aimed at the identification of materials with favorable environmental profiles.

A5.3) Models for economic and business evaluation

Economic modeling for efficient resources and production management is a key point for achieving optimal reliability and efficiency. In addition is the factor that will reveal the interactions between phenomenally unrelated technologies and practices and in the end define the viability of each technological option investigated. Modeling in this field should aim at generating and collecting data for sustainability assessment of existing and potential promising production chains and analyse possible impacts of technologies introduction in vehicle and fuels market. In addition customer behavioral analysis as well as marketable products development should also be addressed by appropriate modeling tools.

A5.4) Models for evaluation of policy alternatives

Similarly to the models for economic evaluation, models for the coherent long term policy evaluation and harmonisation are needed, capable to address topics such as investigation of joint public/private financing for R&D for biofuels introduction and vehicle-grid integration as well as demonstration of new production routes and end-use applications. Modelling can also play an important role in the development of certification systems to assure environmental sustainability of different technologies as well towards the development of indicators and coherent methodologies to assess and monitor the three dimensions of sustainability.

A5.5) Simulation tools for production design

The vehicle integration should be kept in mind from the very start of the vehicle concept design, and guaranteed throughout the development cycle. Currently, this 'vehicle integration focus' is typically not implemented from the very start, but instead sub-optimally synchronized during the development cycle. This brings along the risk that developed solutions and physical prototypes will remain at the level of fancy add-ons, rather than becoming integrated solutions to improve the overall vehicle performance. In future R&D, the 'integrated vehicle design' focus should be implemented from the very start. Modeling & simulation can play a key role in this, and novel R&D actions are needed to develop the necessary methodologies to achieve this.

5. Milestones

The objective of the next twenty years is to develop the following milestones related to Future Light-duty Powertrain Technologies and Fuels.

- **Milestone 1: (2015):**

The first milestone is intended to adapt existing technologies to increasingly impact the decarbonisation challenges. The timescale for market introduction is approximately 2020-2025.

- **Milestone 2: (2020):**

The second milestone is intended to integrate implemented technologies to increasingly impact the decarbonisation challenges. The timescale for market introduction is approximately 2025-2030.

- **Milestone 3**: **(2030):**

The third milestone is intended to achieve optimised performance from implemented technologies in order to sustainably impact the decarbonisation challenges. The timescale for market introduction is approximately 2030+.

Table 1 Milestones for Light-duty Powertrain Technologies and Fuels

	Milestone 1 (2015) Market 2020-2025	**Milestone 2 (2020) Market 2025-2030**	**Milestone 3 (2030) Market 2030+**
Milestone Concept	**Adapting**	**Integrating**	**Sustaining**
A1) Advanced ICEs			
A1.1) Fully flexible injection systems, pressure, fuel quality, and rate shaping	Increasing utilisation of advanced fuel injection system technologies	Increasing integration of system technologies to enhance performance	Full integration of system technologies to achieve optimised performance
A1.2) Fully flexible powertrains	Increasing utilisation of fully flexible powertrains	Full utilisation of fully flexible powertrains to enhance performance	Full utilisation of fully flexible powertrains to achieve optimised performance
A1.3) Downsizing, downspeeding, and high-pressure charging	Increasing utilisation of best options to evaluate commercial potential	Increasing integration of best options to enhance performance	Full integration of best options to achieve optimised performance
A1.4) Multivariable model-based control systems	Increasing utilisation of model-based control systems	Increasing integration of model-based control systems to enhance performance	Full integration of model-based control systems to optimise performance
A1.5) Particulate Matter (PM) control with focus on alternative fuels	Increasing utilisation of PM control strategies	Increasing integration of PM control strategies to enhance performance	Full integration of PM control strategies to achieve optimised performance
A1.6) Spark Ignition (SI) engine technology for alternative fuels (including downsizing)	Increasing utilisation of advanced SI technologies	Increasing integration of advanced SI engine technologies to enhance performance	Full integration of advanced SI engine technologies to achieve optimised performance
A1.7) Compression Ignition (CI) engine technology for alternative fuels	Increasing utilisation of advanced CI technologies	Increasing integration of advanced CI engine technologies to enhance performance	Full integration of advanced CI engine technologies to achieve optimised performance
A1.8) Waste heat recovery	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies	Increasing utilisation of most promising technologies
A1.9) Advanced cooling technology	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies	Increasing utilisation of most promising technologies

A1.10) Non-precious metal aftertreatment systems for biofuels and alternative fuels	R&D to evaluate potential for non-precious metal technologies	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies
A1.11) Controlled Auto-Ignition combined with Spark Ignition	Scale-up of best options to evaluate commercial potential	Commercial application over limited speed/load range	Commercial application over full speed/load range
A1.12) Variable Compression Ratio	Scale-up of best options to evaluate commercial potential	Commercial application over limited speed/load range	Commercial application over full speed/load range
A1.13) Extended range HCCI	Scale-up of best options to evaluate commercial potential	Commercial application over limited speed/load range	Commercial application over full speed/load range
A1.14) Engine lightweighting	R&D to evaluate material options for engine lightweighting	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies
A2) Production, distribution, and storage of biofuels & advanced fuel products			
A2.1) Process and catalyst technology to improve WTT efficiency of fuel production	R&D to evaluate technical options	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies
A2.2) Advanced biofuel products and adapted engine technology to meet regulated limits	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies	Commercial development of most promising technologies
A2.3) Long-term biofuel storage systems	R&D to evaluate technical options	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies
A2.4) Additive technology for enabling enhanced performance	R&D to evaluate technical options	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies

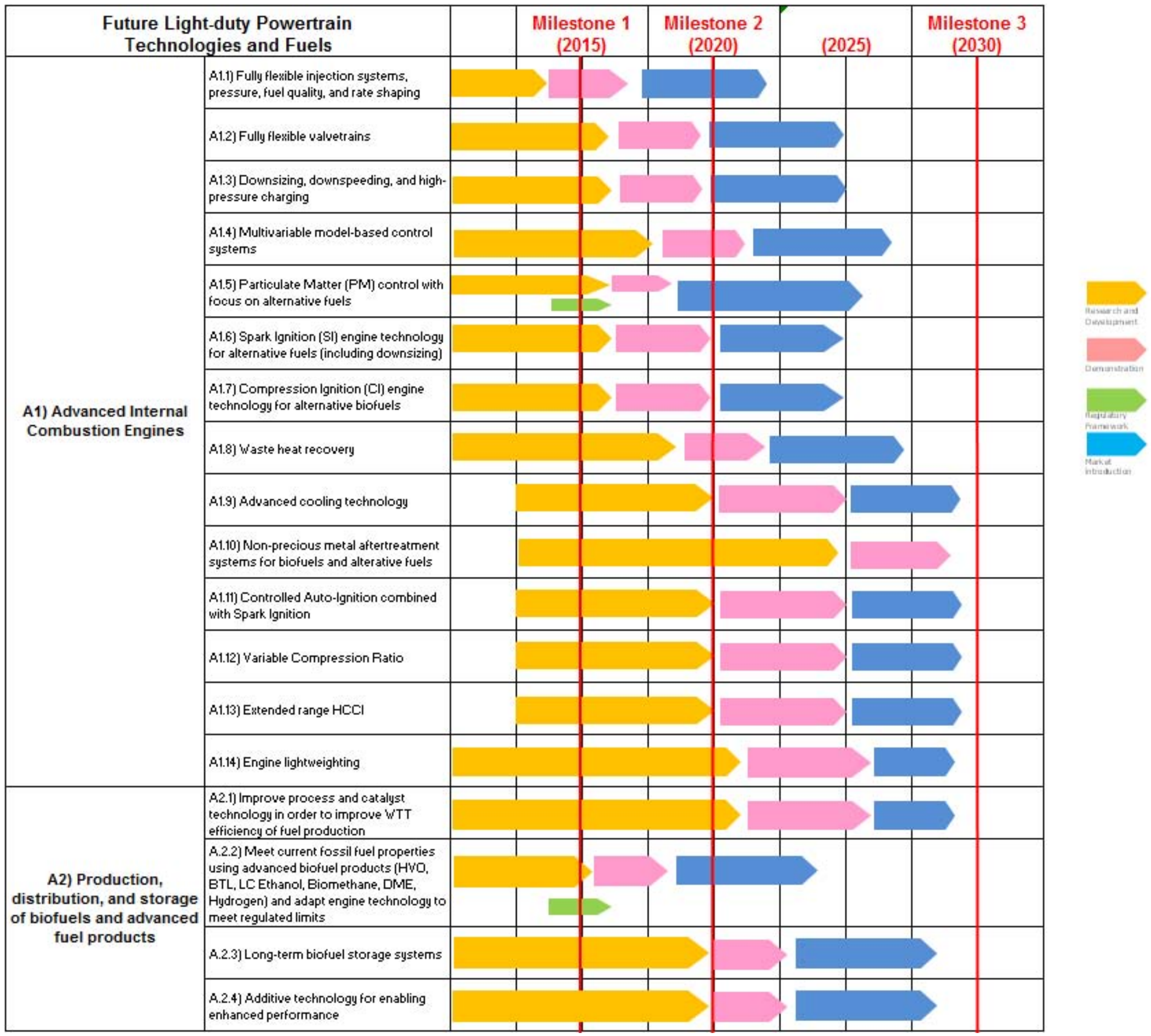
A3) Energy production & distribution for vehicle electrification			
A3.1) CCS and energy production	R&D to evaluate technical options	Pilot scale to test technical options	Scale-up of best options to evaluate commercial potential
A3.2) Smart Grid management	R&D to evaluate technical options	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies
A3.3) Standardisation of recharging technology and infrastructure	Agreement on best options for commercial applications	Commercial implementation on limited scale	Commercial application on large scale
A3.4) Continuous recharging capabilities	R&D to evaluate technical options	Scale-up of best options to evaluate commercial potential	Commercial development of most promising technologies
A4) Advanced materials & materials recycling for vehicles and infrastructure			
A4.1) Vehicle redesign for efficient materials recycling	R&D to evaluate vehicle redesign options	Scale-up of best options to evaluate commercial potential	Commercial development of most promising approaches
A4.2) Infrastructure redesign for efficient materials recycling	R&D to evaluate infrastructure redesign options	Scale-up of best options to evaluate commercial potential	Commercial development of most promising approaches
A4.3) Catalyst production processes	Scale-up of best options to evaluate commercial potential	Commercial development of most promising approaches	Full implementation, refinement and optimisation
A4.4) Component technologies	Scale-up of best options to evaluate commercial potential	Commercial development of most promising approaches	Full implementation, refinement and optimisation
A4.5) Policy issues related to sustainable vehicle production	Small scale evaluation of best approaches to determine potential	Broader evaluation to determine potential	Full implementation, refinement and optimisation
A4.6) Affordable technologies for producing easily recycled batteries, magnets, etc.	R&D to evaluate potential for affordable technologies	Scale-up of best options to evaluate commercial potential	Commercial development of most promising and affordable technologies

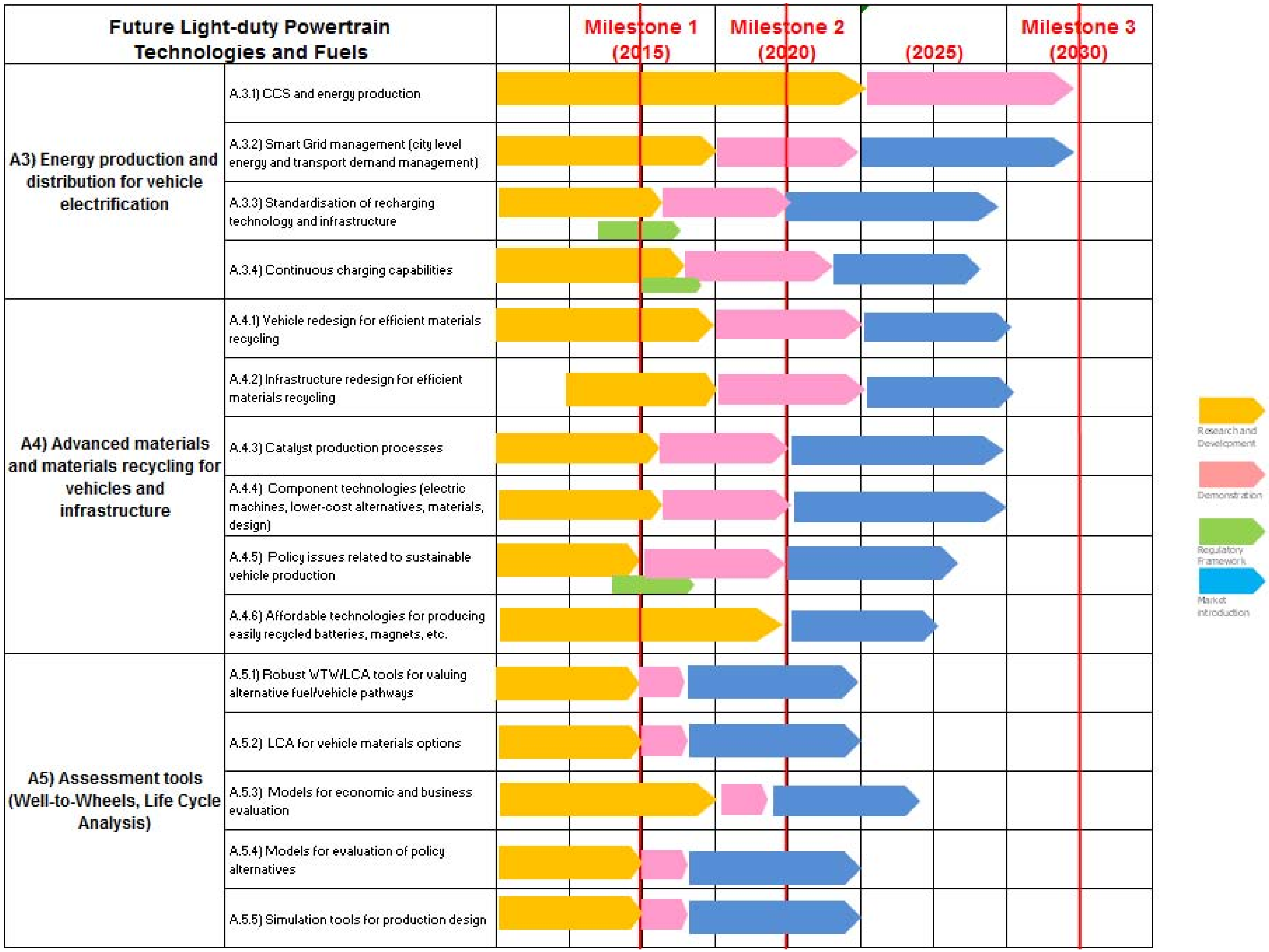
A5) Assessment Tools (WTW, LCA)			
A5.1) Robust WTW/LCA tools for valuing alternative vehicle/fuel pathways	Development of approaches to evaluate commercial applications	Implementation, refinement and optimisation to enhance performance	
A5.2) LCA for vehicle materials options	R&D to evaluate approaches for vehicle applications	Development of approaches for commercial applications	Implementation, refinement and optimisation to enhance performance
A5.3) Models for economic and business evaluation	Development of approaches to evaluate commercial applications	Implementation, refinement and optimisation to enhance performance	
A5.4) Models for evaluation of policy alternatives	Development of approaches to evaluate commercial applications	Implementation, refinement and optimisation to enhance performance	
A5.5) Simulation tools for production design	Development of approaches to evaluate commercial applications	Implementation, refinement and optimisation to enhance performance	

6. Roadmap phases and their milestones

Following the definition of milestones, this section defines the roadmap corresponding to the research needed to achieve the stated objectives. The roadmap indicates the main tasks leading to these milestones.

The framework document of the roadmap elaborated in the ERTRAC Strategic Research Agenda (ERTRAC (2010a)) defines four steps for the implementation of the actions for each roadmap. The following arrows summarize the steps that have been used in the diagrams below:


Future Light-duty Powertrain Technologies and Fuels
Milestone 1 (2015)
Milestone 2 (2020)
(2025)
Milestone 3 (2030)
A1) Advanced Internal Combustion Engines
A1.1) Fully flexible injection systems, pressure, fuel quality, and rate shaping
A1.2) Fully flexible valvetrains
A1.3) Downsizing, downspeeding, and high-pressure charging
A1.4) Multivariable model-based control systems
A1.5) Particulate Matter (PM) control with focus on alternative fuels
A1.6) Spark Ignition (SI) engine technology for alternative fuels (including downsizing)
A1.7) Compression Ignition (CI) engine technology for alternative biofuels
A1.8) Waste heat recovery
A1.9) Advanced cooling technology
A1.10) Non-precious metal aftertreatment systems for biofuels and alterative fuels
A1.11) Controlled Auto-Ignition combined with Spark Ignition
A1.12) Variable Compression Ratio
A1.13) Extended range HCCI
A1.14) Engine lightweighting
A2) Production, distribution, and storage of biofuels and advanced fuel products
A2.1) Improve process and catalyst technology in order to improve WTT efficiency of fuel production
A.2.2) Meet current fossil fuel properties using advanced biofuel products (HVO, BTL, LC Ethanol, Biomethane, DME, Hydrogen) and adapt engine technology to meet regulated limits
A.2.3) Long-term biofuel storage systems
A.2.4) Additive technology for enabling enhanced performance


Future Light-duty Powertrain Technologies and Fuels
Milestone 1 (2015)
Milestone 2 (2020)
(2025)
Milestone 3 (2030)
A3) Energy production and distribution for vehicle electrification
A.3.1) CCS and energy production
A.3.2) Smart Grid management (city level energy and transport demand management)
A.3.3) Standardisation of recharging technology and infrastructure
A.3.4) Continuous charging capabilities
A4) Advanced materials and materials recycling for vehicles and infrastructure
A.4.1) Vehicle redesign for efficient materials recycling
A.4.2) Infrastructure redesign for efficient materials recycling
A.4.3) Catalyst production processes
A.4.4) Component technologies (electric machines, lower-cost alternatives, materials, design)
A.4.5) Policy issues related to sustainable vehicle production
A.4.6) Affordable technologies for producing easily recycled batteries, magnets, etc.
A5) Assessment tools (Well-to-Wheels, Life Cycle Analysis)
A.5.1) Robust WTW/LCA tools for valuing alternative fuel/vehicle pathways
A.5.2) LCA for vehicle materials options
A.5.3) Models for economic and business evaluation
A.5.4) Models for evaluation of policy alternatives
A.5.5) Simulation tools for production design
Research and Development
Demonstration
Regulatory Framework
Market introduction

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9. Glossary

BMEP	Brake Mean Effective Pressure
CAI	Controlled Auto Ignition
CCS	Carbon (or CO_2) Capture and Storage
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DME	Di Methyl Ether
EC	European Commission
EGR	Exhaust Gas Recirculation

EoL	End of Life
ERS	Electric Road System
FT	Fischer Tropsch (Process)
GHG	Greenhouse Gas or Gases
H_2	Hydrogen
HCCI	Homogeneous Charge Compression Ignition
HVO	Hydrogenated Vegetable Oil
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
ILCD	International Reference Life Cycle Data (System Handbook)
LC	Ligno Cellulose
LCA	Life Cycle Analysis
LNG	Liquefied Natural Gas
NG	Natural Gas
NOx	Nitrogen Oxides
PM	Particulate Matter
R&D	Research & Development
RPM	Revolutions Per Minute
SET	Strategic Energy Technology (Plan)
SI	Spark Ignition
STTP	Strategic Transport Technology Plan
TTW	Tank-to-Wheels
V2G	Vehicle-to-Grid
WOT	Wide Open Throttle
WTT	Well-to-Tank
WTW	Well-to-Wheels
XTL	X-to-Liquids (where X can be B (biomass), C (coal), G (gas), or W (waste))