Decarbonization Wedges Exercise

December 2015 – www.allianceenergie.fr

Thermal engines

1. State of the art and current development in different world regions

The main challenge for future internal combustion engine in the considered timeframe is to reduce greenhouse gas emissions —especially CO_2 emissions— while maintaining similar performance for the user —drivability, cost, etc. — and meeting even more stringent pollutant emissions.

Technology 1: High efficiency spark-ignited engines
This technology includes several evolutions —e.g. improvement in combustion efficiency, reduction of friction losses, downsizing, advanced design etc. High efficiency spark-ignited engines will emit 30% less CO_2 by 2025. This reduction could reach 50% by 2050. Engine platforms require high flexibility for local adaptations

Technology 2: Advanced Diesel engines
This technology is also experiencing several innovations: indeed advanced diesel engines should emit 20% less CO_2 in 2025.

Technology 3: Multi-fuel engines
Multi-fuel engines can run on several types of fuels. Second generation biofuels can be used to run multi-fuel: in that case CO_2 emissions reduction could amount to 10 to 20%; no significant cost increase is expected since same injection system is used. Another multi-fuel technique involves using different fuels at the same time (concomitant injections). Dual fuel engines include: [Ethanol + gasoline] or [CNG[1] + Diesel] or [gasoline + Diesel] or [CNG + gasoline].

Technology 4: Engines dedicated to hybrid powertrains
Thermal engines are not specifically developed for hybrid applications yet because of the low market share and of high development costs. The hybrid market increase by 2050 could be an opportunity to develop dedicated technologies adapted to this specific engine operating area and to fine-tuned engines for hybrid applications.

2. Maturity level and technological perspectives

Maturity of elementary technologies associated with thermal engines

Methodological information:

The maturity level is the TRL, reduced to 5 levels with market deployment enclosed in the higher TRL classes; maturity level scaling: 0 = none; 1 = fundamental research; 2 = R&D; 3 = demonstrator; 4 = low deployment; 5 = large deployment.

	2015	2020	2030	2040	2050
High efficiency gasoline engines	1-2	2-3	3-4	4-5	5
Advanced Diesel engine	2-3	3-4	4-5	5	5
Multi-fuel engines	2	3	4	5	5
Engines for hybrid applications	2	3-4	4-5	5	5

[1] CNG: Compressed Natural Gas

Potential development of technologies associated with thermal engines

Methodological information:

Potential development is measured as the percentage of the technology's contribution to environmental protection. This means evaluating, in terms of carbon emissions and of carbon emissions reduction, to what extent this new technology can contribute to limiting temperature increase to 2°C above pre-industrial level according to the time horizon considered in this study. Potential development scaling: 0 = not significant; 1 = significant (i.e. more than 1% of global emissions reduction) in some countries; 2 = significant on the global scale; 3 = very significant on the global scale (i.e. up to 3% of global emissions reduction); 4 = major technology vs. climate change (i.e. more than 3% of global emissions reduction).

	2020	2030	2040	2050
High efficiency gasoline engines	0	2	3	4
Advanced Diesel engine	0	2	3	4
Multi-fuel engines	0	0	1	1
Engines dedicated to hybrid applications	0	1	2	3

Technology 1: High efficiency spark-ignited engines
Many innovations pertain to downsizing and optimizing several components —turbocharger development, valve train technologies, combustion system, friction losses, etc. — and are still in developing stage. However their development will accelerate in the years to come and the outcomes will be observable only by 2030.

Technology 2: Advanced Diesel engines
Down speeding —and, to a lesser extent, downsizing— are two main technological trends in the timeframe of the decarbonization study. After-treatment should evolve as well thanks to SCR systems[2] and integration of Diesel Particulate Filter in a same technological brick to further reduce pollutants emissions.

Technology 3: Multi-fuel engines
Dual fuel engines are a *niche* market but it might be an opportunity to diversify energy resources and to further improve engine efficiency. Current R&D programs focus on ethanol and gasoline engines, and natural gas and Diesel engines. The main innovations involve fuel injection systems and combustion system but also after-treatment devices and engine control.

Technology 4: Engines dedicated to hybrid powertrains
This technology is currently subjected to R&D programs and its effects will be observable only by 2030.

By 2020 high efficiency sparke-ignited engines and advanced diesel engines will be the most present technologies on the market. Indeed multi-fuel engines will represent 5 to 10% of the market —with higher share on local market (as for Brazil) — and hybrid powertrains will represent 10 to 20% of the market.

In 2050, hybrid powertrains will become the most used of all four technologies, the others three technologies will share the rest of the market.

3. Technological, economic and social bottlenecks

Methodological information:

The following table ranks the bottlenecks according to their impact on the development of the technology. A bottleneck ranking at 6 on the scale will hinder or stall the deployment of the technology compared with bottlenecks ranking at 1; conversely, a bottleneck ranking at 1 will hinder the deployment of the technology much less than bottlenecks ranking at 6. Note that the ranking is relative, meaning that a bottleneck ranking at 6 is not necessarily hard to remove; conversely, a bottleneck ranking at 1 is not necessarily easy to remove. Technologies rank according to: research, finance, regulations, resources & environment, security and acceptability. The table also contains keywords associated with each bottleneck.

It must be stressed that the ranking of such different factors must be considered with caution; as an expert's judgement, not a quantitative assessment.

[2] SCR: Selective Non-Catalytic Reduction

Technology		Research & technological bottlenecks	Economy and financial bottlenecks (investment, risks)	Regulation & institutional environment	Resources & environmental impacts (including scarcity of raw materials, water, land, climate)	Safety & security (impacts on health, people and security assets)	Socio-technical feasibility
High efficiency gasoline engines	Rank	4	6	5	3	2	1
	Key-words	Optimization of technologies	Initial investment for production	Soot emissions for direct injection applications			
Advanced Diesel engine	Rank	3	5	6	2	4	1
	Key-words	Optimization of technologies	Initial investment for production	NOx/PM emissions	Materials for after-treatment devices	Health impacts of local emissions (NOx[3], PM[4])	
Multi-fuel engines	Rank	5 (for ICE[5])	6	4	2	1	3
	Key-words	Flexfuel ICE durability (in addition to processes and logistics) Combustion system and fuel injection for dual fuel	Initial investment for production and infrastructure	Local incentives	Biofuels	Non-regulated pollutants emissions	Infra-structures, refueling network
Engines dedicated to hybrid applications	Rank	5	6	4	2	1	3
	Key-words	R&D investment and design specifications	Initial investment for production	Incentives for hybrid applications			Grid adaptation, reverse energy concept

Global comments:

- Fuel price can be a bottleneck, notably for investment —because of CO_2 cost per gram. Incentives, taxes and regulations are crucial elements to develop of a technology;
- Diversifying resources could be strategic for a country or a regional hub;
- Electrified powertrains are also an essential aspect and will lead to different priorities for thermal engines development for manufacturers.

Technology 1: High efficiency spark-ignited engines

Initial investment is very high for new production lines.

Technology 2: Advanced Diesel engines

Initial investment is not only high for high efficiency spark-ignited engines: indeed, for new production lines for advanced Diesel engines also require high investment. Furthermore wholesale cost on post-treatment NOx / PM and Diesel in some cities can hinder the development of the technology.

[3] NOx : Nitrogen Oxide
[4] PM : Particulate Matter
[5] ICE: Internal Combustion Engine

Technology 3: Multi-fuel engines
Gaseous fuels (CNG, LNG, H2,…) or biofuels stations availability increase the security of supply FlexFuel engine durability. Design constraints should also be mentioned for this technology.

Technology 4: Engines dedicated to hybrid powertrains
Many hybrid applications involve different levels of electrification: this leads to various engine specifications. This is why there is a need for strong flexibility in the design and integration of engines to drivetrains. For reverse-energy concept, the vehicles are considered as energy providers on the grid.

4. Potential radical and incremental innovations

Methodological information:

The following table lists the nature of innovations needed to overcome the bottlenecks mentioned earlier. There are two types of innovations: I stands for 'incremental innovation' (i.e. improving existing products and processes) and R stands for 'radical innovation' (i.e. developing new products and processes).

Technology		**Research & technological innovations**	**Economy and Financial innovations** (investment, risk)	**Regulation & institutional environment**	**Resources & environmental impacts** (including scarcity of raw materials, water, land, climate)	**Safety & security** (impacts on health, people and security assets)	**Socio-technical feasibility**
High efficiency gasoline engines	I or R	I	I	I	I	I	I
	Key-words	Engine components					
Advanced Diesel engine	I or R	I	I	I	I	I	I
	Key-words	Engine components					
Multi-fuel engines	I or R	R	R	I	I	I/R	R
	Key-words	Management of several fuels in the engine	Market share and production costs (economies of scale)				New fuel stations infrastructure
Engines dedicated to hybrid applications	I or R	I	R	I	I	I	R
	Key-words		Market share and production costs (economies of scale)				Electric charging stations

Technologies 1 & 2:
There should be incremental innovations on different components of the engine, but no radical evolutions before 2030 because there are already industrial facilities.

Technology 3:
Radical innovations should help to manage the use of several fuels in the engine. Innovations will also pertain to refueling stations infrastructure in order to manage several fuels at the worldwide level. However economies of scale imply a financial risk. This technology involves multi-platforms and a versatile product, but a worldwide base engine should be created for different functions —i.e. turbocharging, EGR, etc. Currently development costs are limited for manufacturers —wholesale cost of adaptation by regional areas is due to heterogeneous regulations and heterogeneous customer demand.

Technology 4:
There is a financial risk linked to economies of scale. This is why it is important to increase the hybrid vehicles market share and also to use similar engines regardless of hybridization levels.