Stirling machine as auxiliary power unit for range extender hybrid electric vehicles

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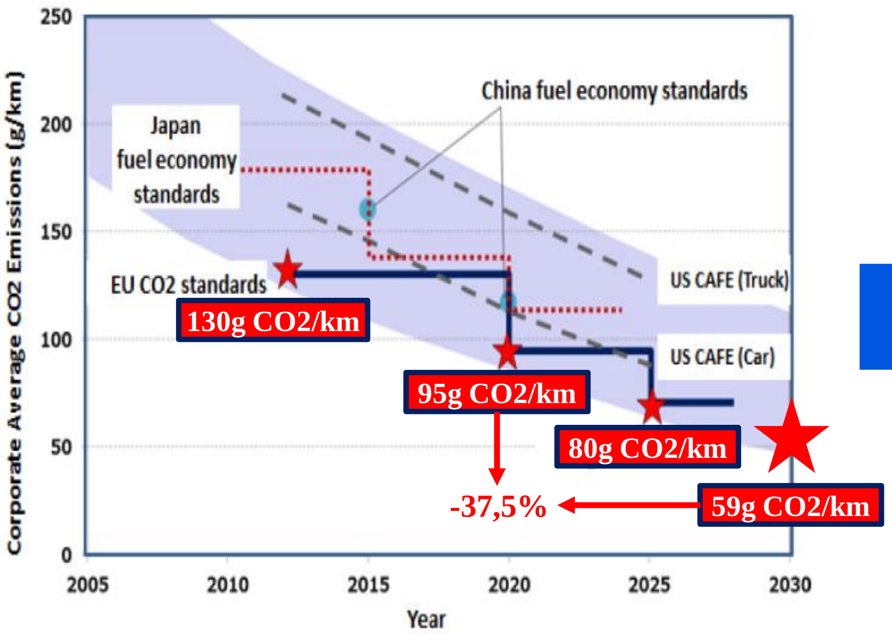
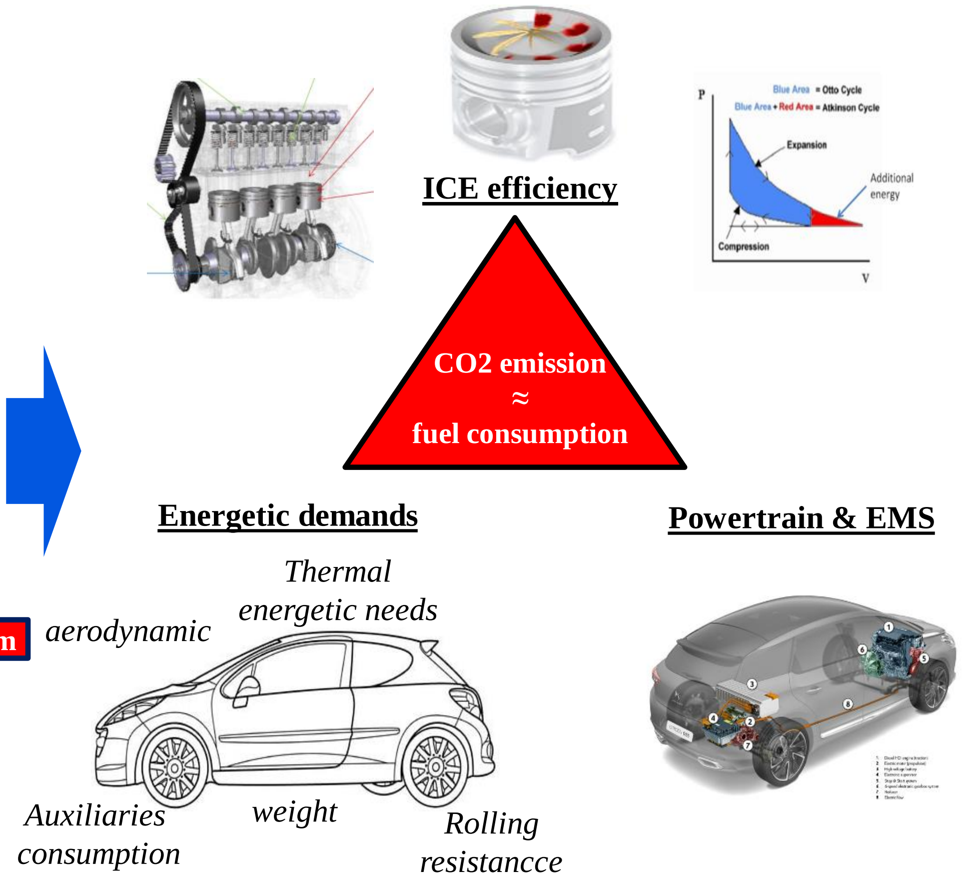
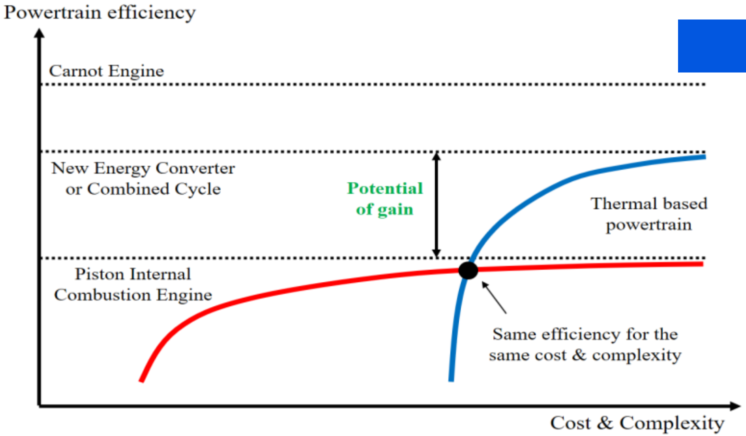
Wissam BOU NADER – Groupe PSA



→ Problematic arises for post 2025 due to more stringent reglementation regarding CO2 emissions

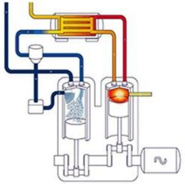


Internal Combustion Engine (ICE) powertrains main problematics

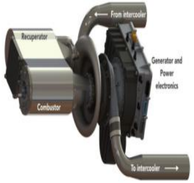


ICE Max efficiency

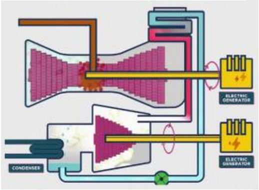
Stirling



Split cycle



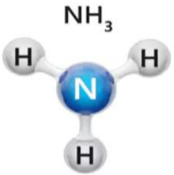
Gas-Turbine



Combined cycle

ICE multi-fuel compatibility

Solid combustion

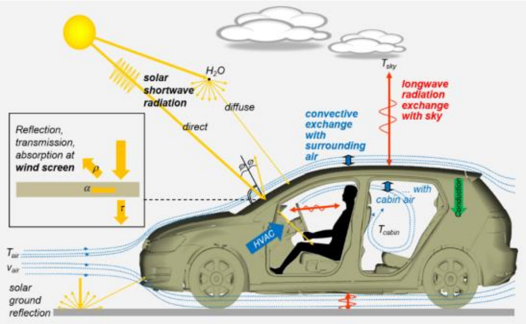


E-fuel

Hydrogen

Bio-fuel

Confort thermal energetic needs



On the other hand… ongoing development of Battery Electric Vehicles (BEV)

Tesla

Renault Zoe

Citroën C0

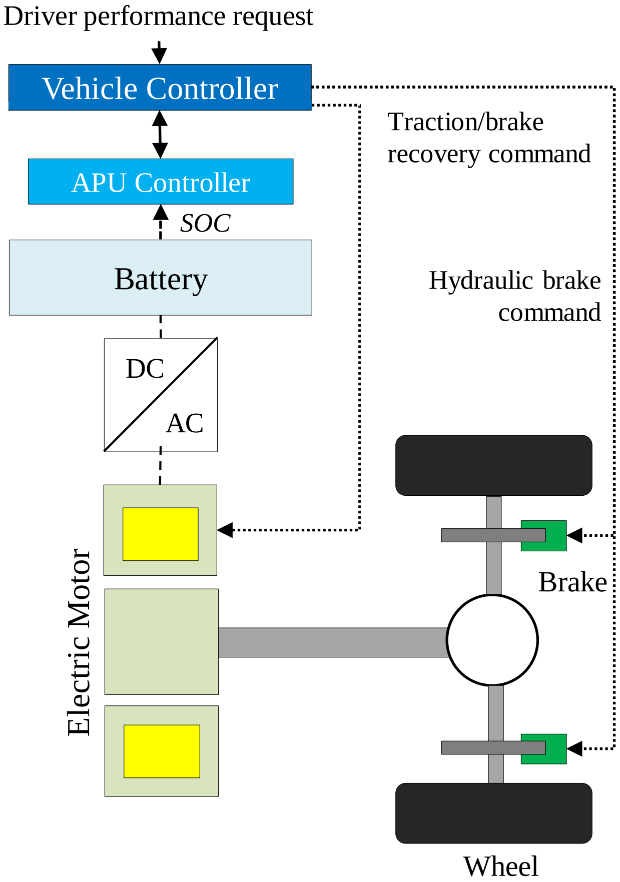
Benefit of Zero Vehicle Emission

(Tank to wheel emissions !!!)

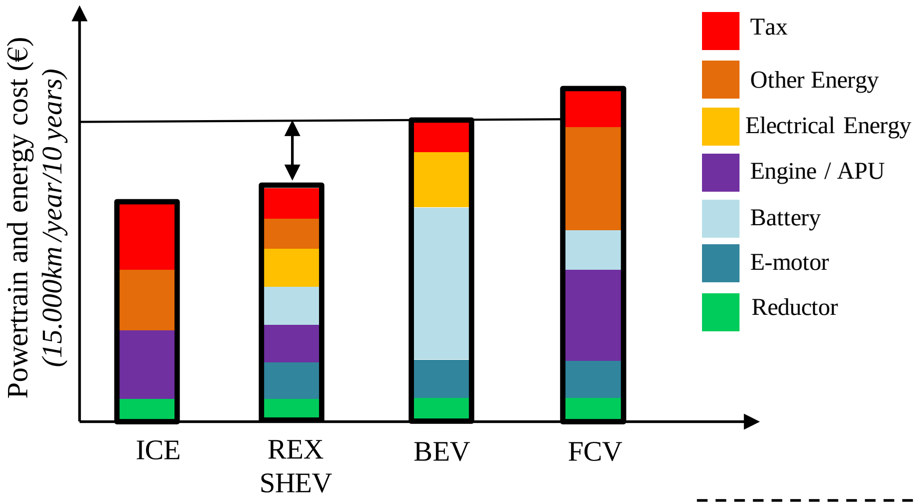
However, BEVs present many drawbacks

- Large battery capacities for long autonomy range: Additional weight
- Thermal confort such as heating is not free compared to thermal based powertrains
- CO_2 emission (well to wheel analysis) depends on the electricity production
- Geopolitical problematic for European automotive manufacturers
- Cost for the customer

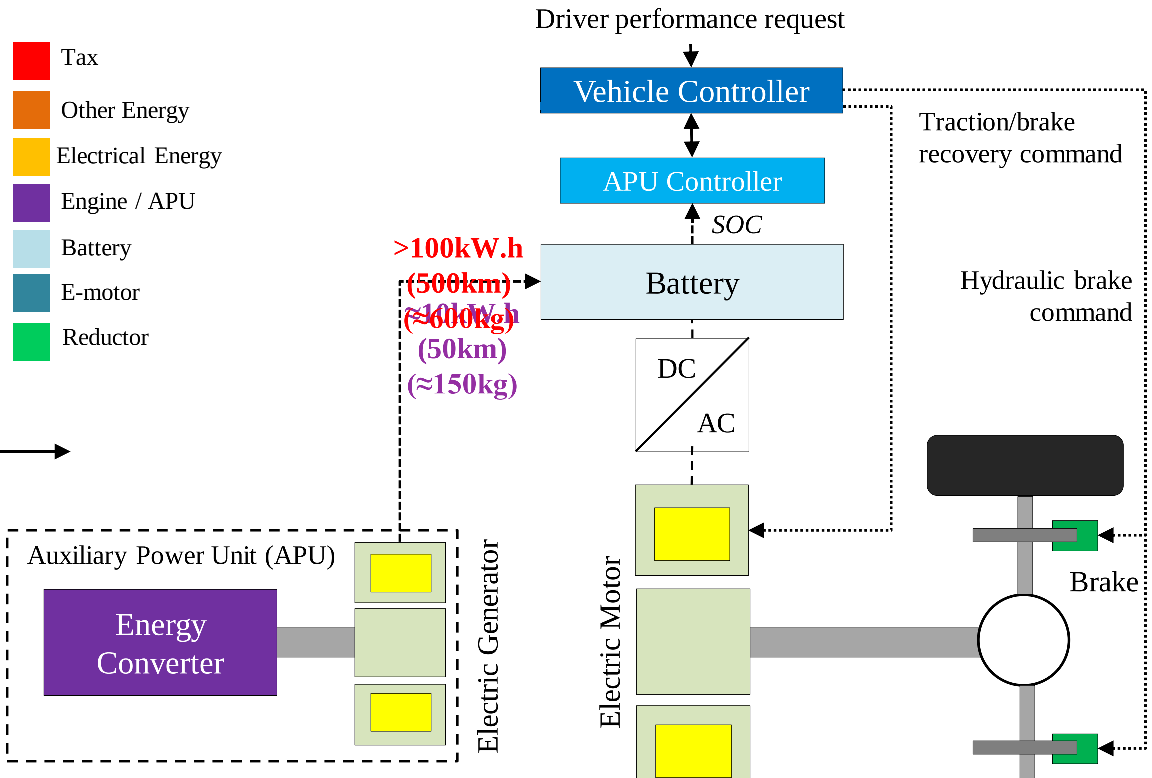
>100kW.h
(500km)
(≈600kg)



Range Extender powertrain seems to be a comprimise



- ZEV mode compared to ICE
- Low emission compared to ICE
- Cost compared to BEV and FCV
- Vehicle weight compared to BEV
- Fun to drive (such as BEV)



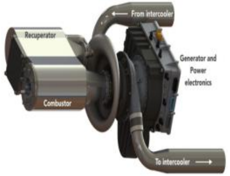
Different energy converters with different thermodynamic configurations can be envisaged

Conventional

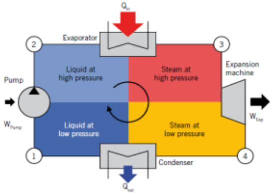
Non Conventional

ICE

Gas Turbine

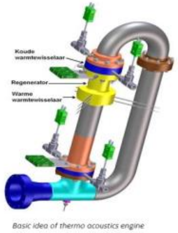


Rankine



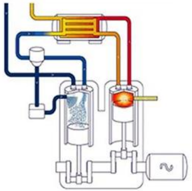
Stirling

TA

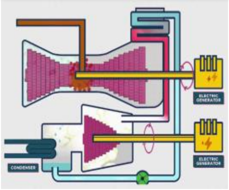


PEM Fuel Cell

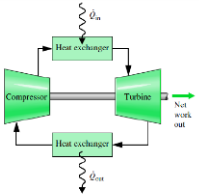
Split Cycle



CCGT

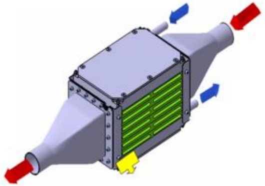


ECGT

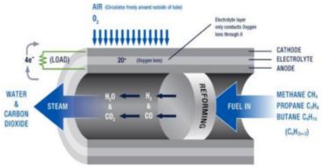


Ericsson

TEG



SOFC



Internal Combustion | **External Combustion** | **Electro Chemical**

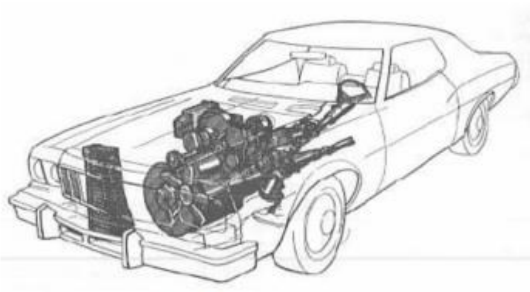
Mature technology for automotive applications

Mature technology for non-automotive applications

Non-mature technology

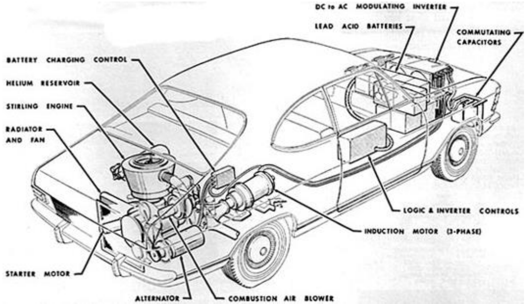
CCGT = Combined cycle Gas Turbine
TA = Thermoacoustic
TEG = Thermoelectric Generator

ECGT=External Combustion Gas-Turbine
PEM = Proton Exchange Membrane
SOFC = Solid Oxide Fuel Cell



Ford Torino

Chevrolet Celebrity



Opel Kadet

Automotive intrinstic benefits: Multi-fuel capability, good thermal efficiency, high torque at low speed, silent operation, low vibration.

Many reasons hindered their deployments: Leakage, controllability, Investment costs, and particularly the simplicity and price of the ICE at that time

Today with CO2 and emissions topics, Stirling for automotive applications gain interest

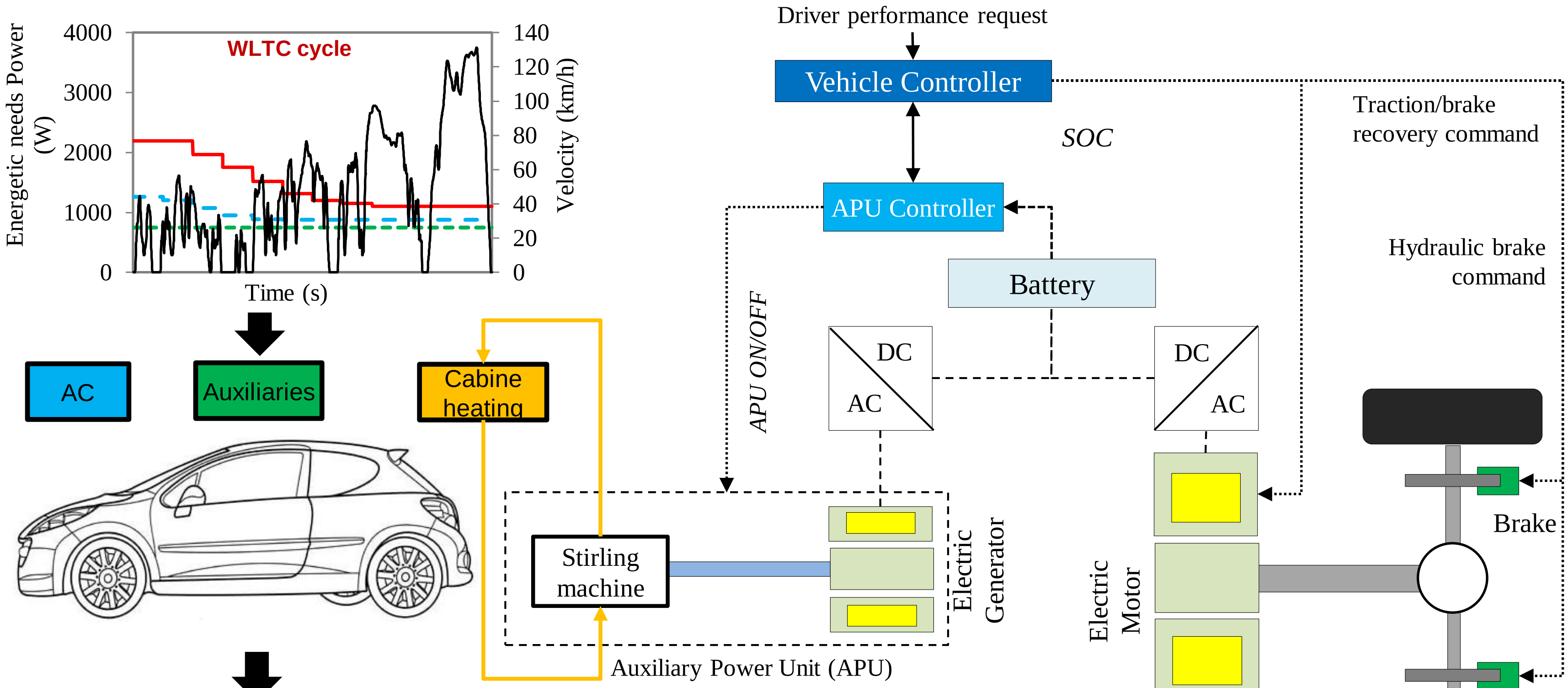
- Development of Series Hybrid Electric Vehicles (SHEV) :
  - efficiently operation under all driving cycle
  - quasi-stable operating state: reduce control complexity

- **External combustion machine - Emission reduction through:**
  - Choice of fuel and continuous combustion

- **Development of magnetic coupling systems:**
  - Complete sealing to avoid working fluid leakages

- **Material advancement to reach higher temperature and pressure:**
  - Higher thermodynamic cycle efficiency and higher power density

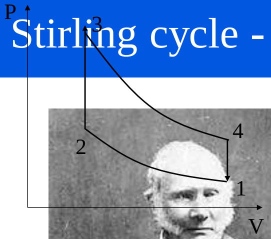
Target of this work

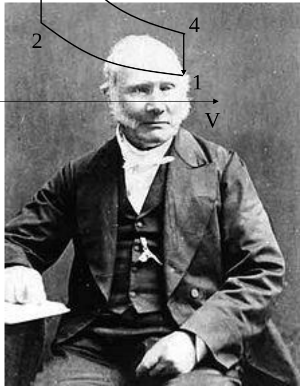


Vehicle Criteria: fuel consumption
Requirements: Acceleration, Max speed, gradability
Constraints: Weight, Size, Frontal surface

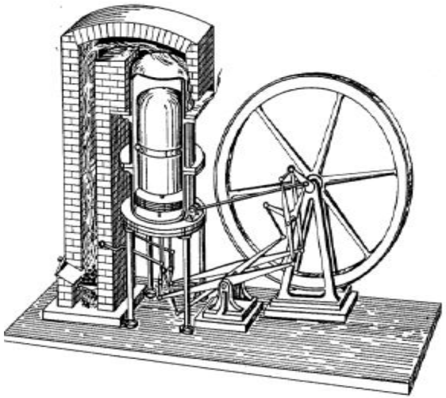
Cogeneration machine for automotive applications

Stirling cycle - Theory

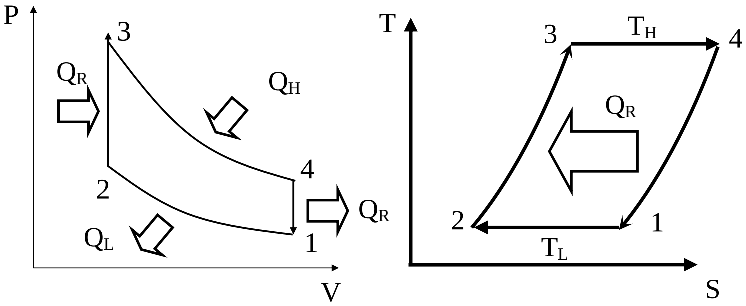




Robert Stirling (1816)



Hot air engine



Stirling engines

- External heat supply
- Closed cycle
- Regenerative engine

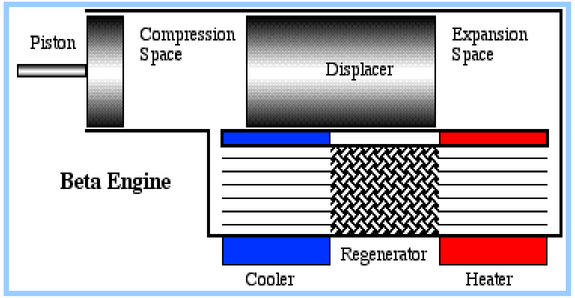
Ideal Stirling Cycle

- 2 isothermal transformations
  - Expansion 3-4
  - Compression 1-2
- 2 isochoric transfromations
  - Heating 2-3
  - Cooling 4-1

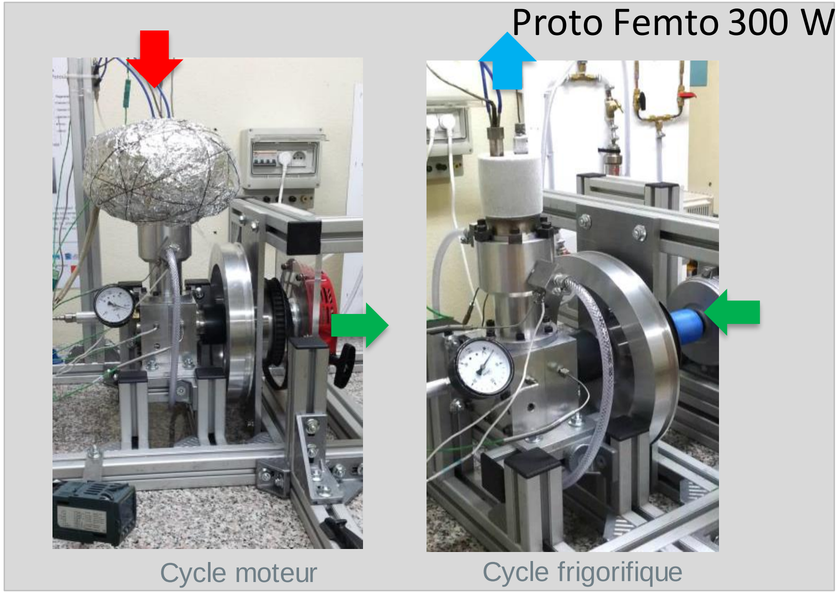
Configuration

Mechanical configuration : Beta

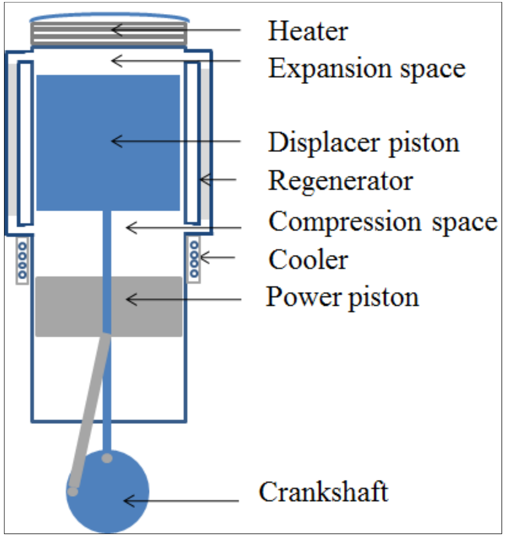
- One cylinder with 2 pistons
- Work piston : compression and expansion
- Displacer piston : no work done, moves the gas from the expansion space to the compression space



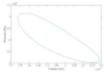
Beta



Designed prototype characteristics

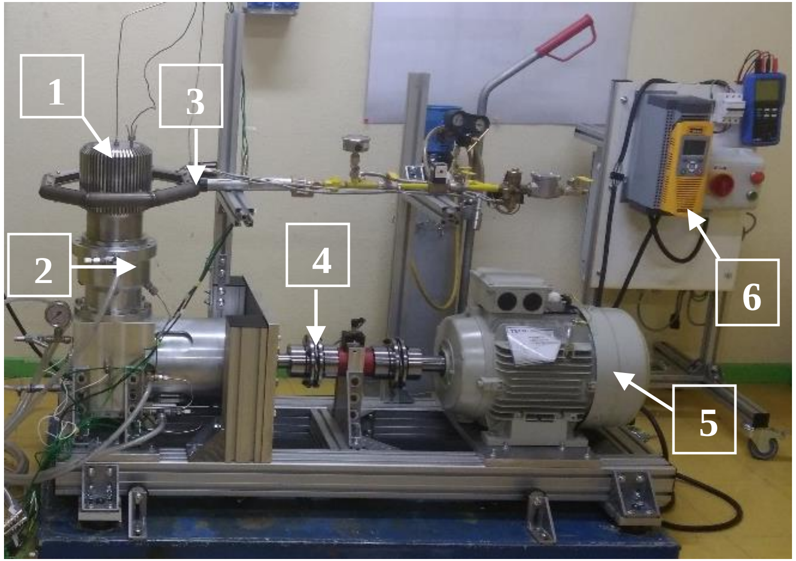


Engine characteristics	
Beta type	Single cylinder
Working gas	Nitrogen
Pressure	60×10^5 Pa
Power	12 kW
Generator	3 phase
Power piston diameter	10^{-1} m
Compression swept volume	4.5×10^{-4} m^3
Hot temperature	937 K
Cold temperature	337 K
Efficiency (target)	39 %
Frequency	35 Hz



PV Diagram from isothermal analysis (Schmidt)

Designed prototype characteristics

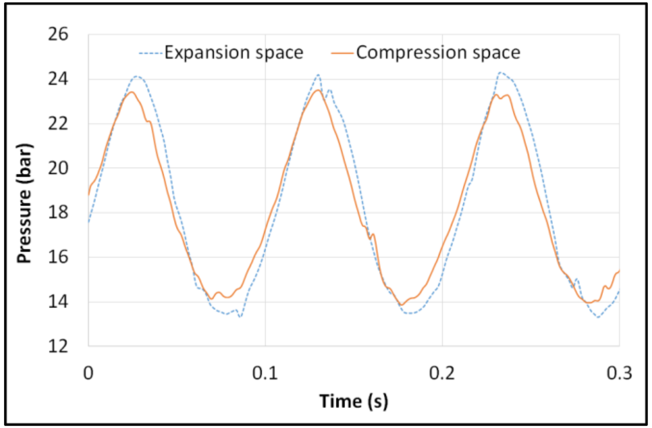


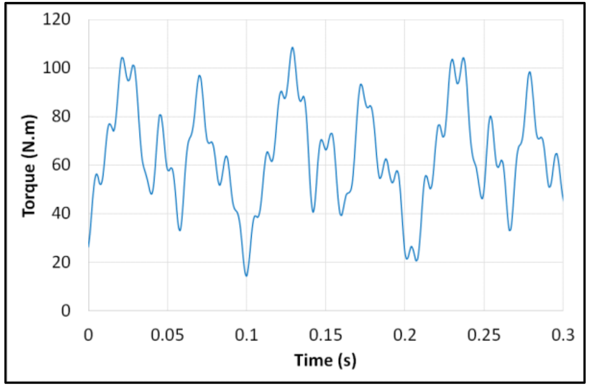
1: hot exchanger, 2: cold exchanger,
3: gas burner, 4: torquemeter,
5: electrical engine,
6: power electronics converter.

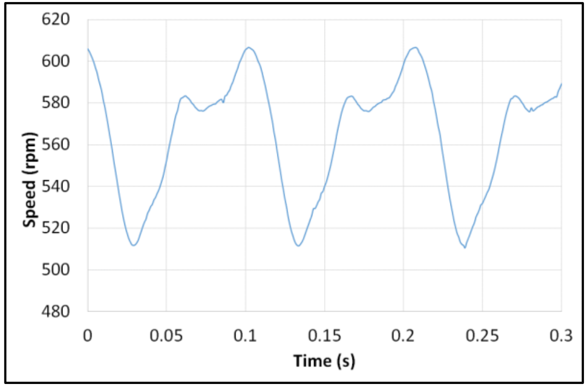
First tests :

- engine is driven by an electric drive
  - ➢ asynchronous engine
  - ➢ Inverter
- Reduced pressure 15 bar instead of 60 bar
- Reversed cycle : heat pump or refrigerating cycle

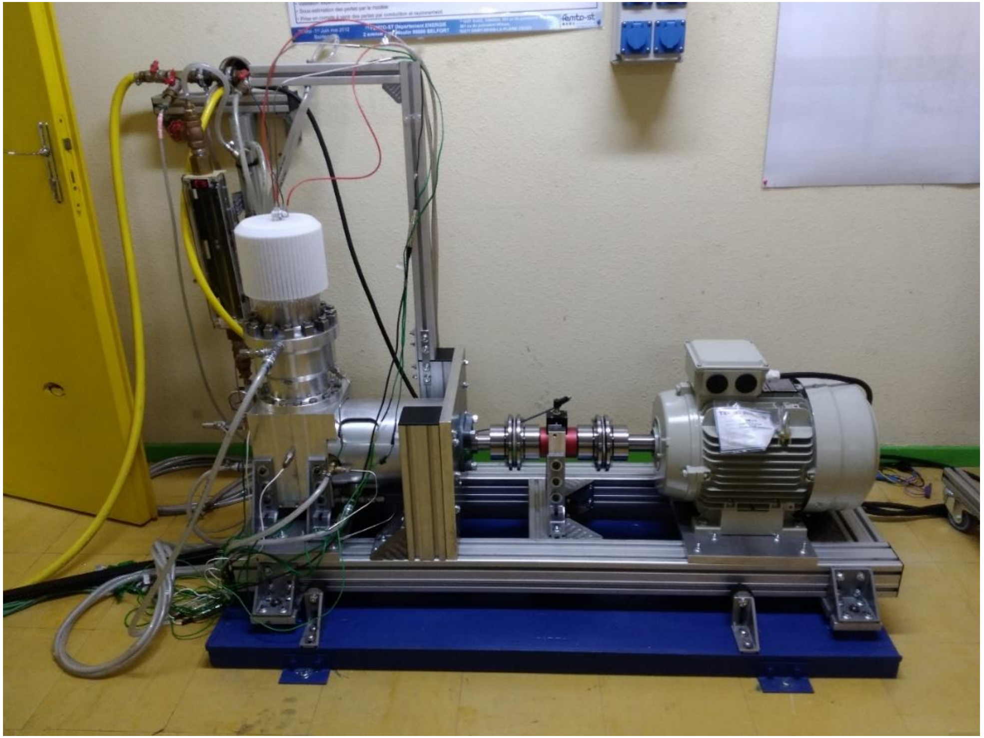
Results: pressure, torque, rotational speed for a few cycles

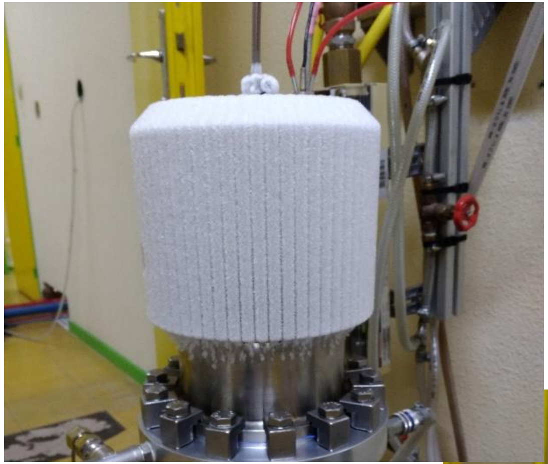


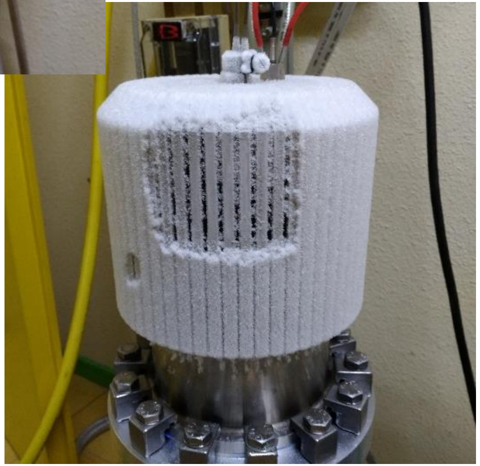




Results: as a refrigerating machine



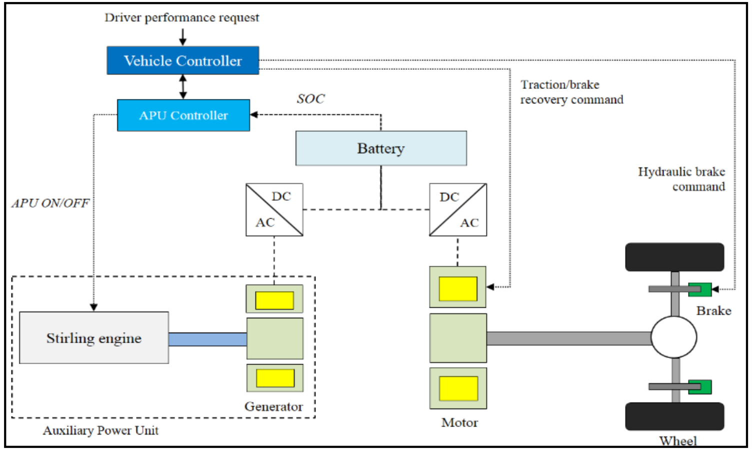




-30°C dans le volume de détente

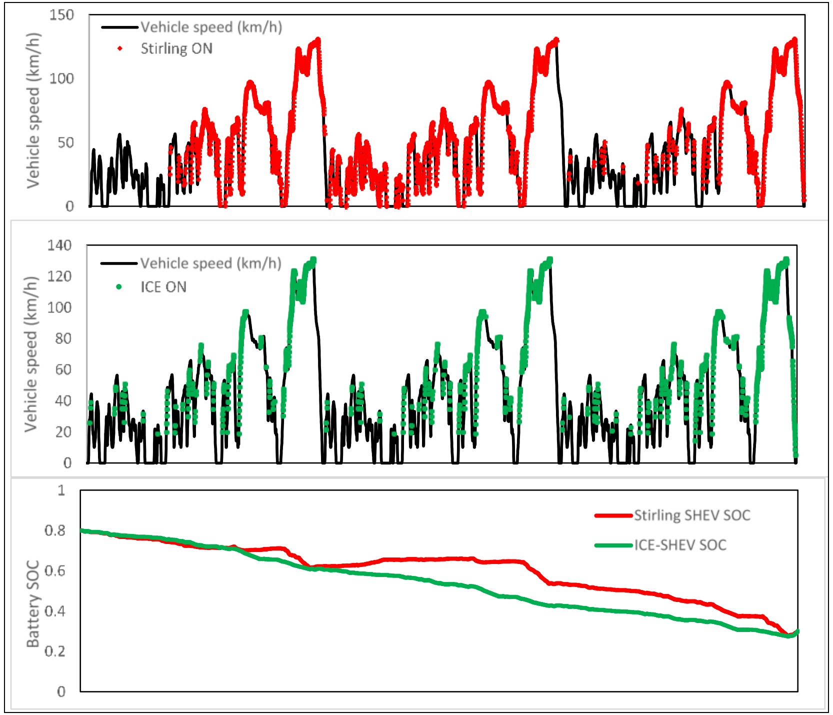
Vehicle model including an APU with ICE or Stirling engine

Vehicle specifications	
Vehicle mass (+ driver)	1210 kg
Wheel friction coefficient	0.0106
Air density	1.205 kg/m^3
Wheel radius	0.307 m
Auxiliaries consumption	750 W
Battery max. power	78 kW
Battery capacity	[5, 10, 20] kWh
Battery mass	[188, 259, 356] kg
Battery state of charge	[0.4, 0.6, 0.8, 1]
Stirling system	12 kW
Stirling efficiency	39 %
ICE power	97 kW
ICE max. efficiency	36 %



Vehicle specifications	
Generator max. power	12 kW
Generator max. efficiency	95 %
Motor max. power	80 kW
Motor max. efficiency	93 %
Transmission ratio	5.4
Transmission efficiency	97 %
Fuel heating value	42.5 MJ/kg

Model results

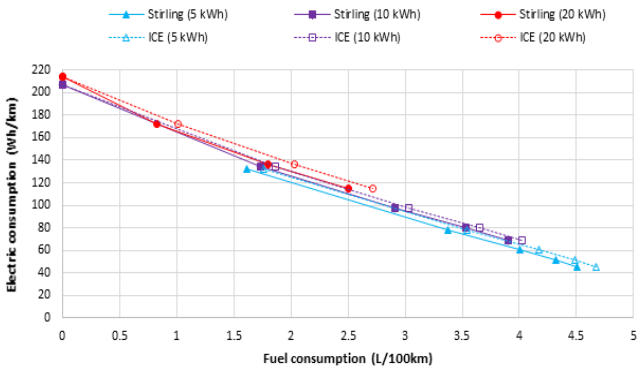


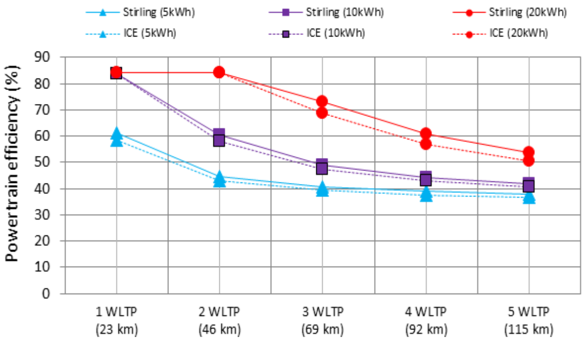
Energy converters operation

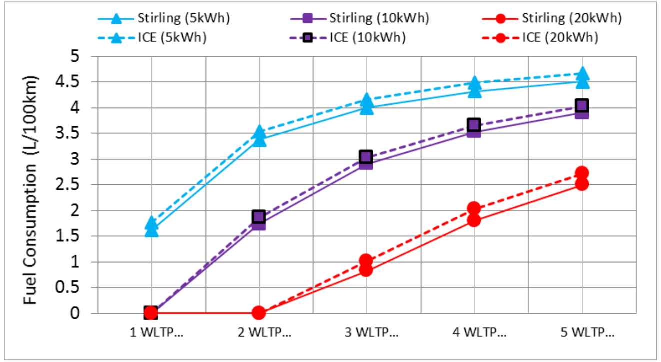
- for both Stirling and ICE on plug-In SHEVs powertrains
- three repeated WLTP
- 10kWh battery capacity

- Stirling engine operates at a lower power and more continuously than ICE

Model results







Battery and fuel energy trade-off for the plug-in configuration on one to five-repeated WLTP, under the three investigated battery capacities.

Powertrain efficiency of the plug-in configuration, on one to five-repeated WLTP, under the three investigated battery capacities.a

Fuel consumption results between Stirling-system and ICE of the plug-in on one to five-repeated WLTP, under the three investigated battery capacities.

Conclusion

- Alternative automobile powertrains are needed
- Series Hybrid Vehicles including a Stirling engine as APU is a good candidate
- Powertrain efficiencies and fuel consumption present good performances when compared to a conventional ICE APU
- A 10 kW Stirling engine prototype has been developed and is currently under tests