AIRCRAFT ENGINES

Emerging propulsion

ISAE Supaero – MsC MAE 2MAE006 Aviation and environment

Nicolas TANTOT
Safran Aircraft Engines, Preliminary design YXFO
nicolas.tantot@safrangroup.com

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Introduction

Nicolas TANTOT
Supaero graduate, 2002
Future concepts architect, preliminary design
Cycle performance lead expert

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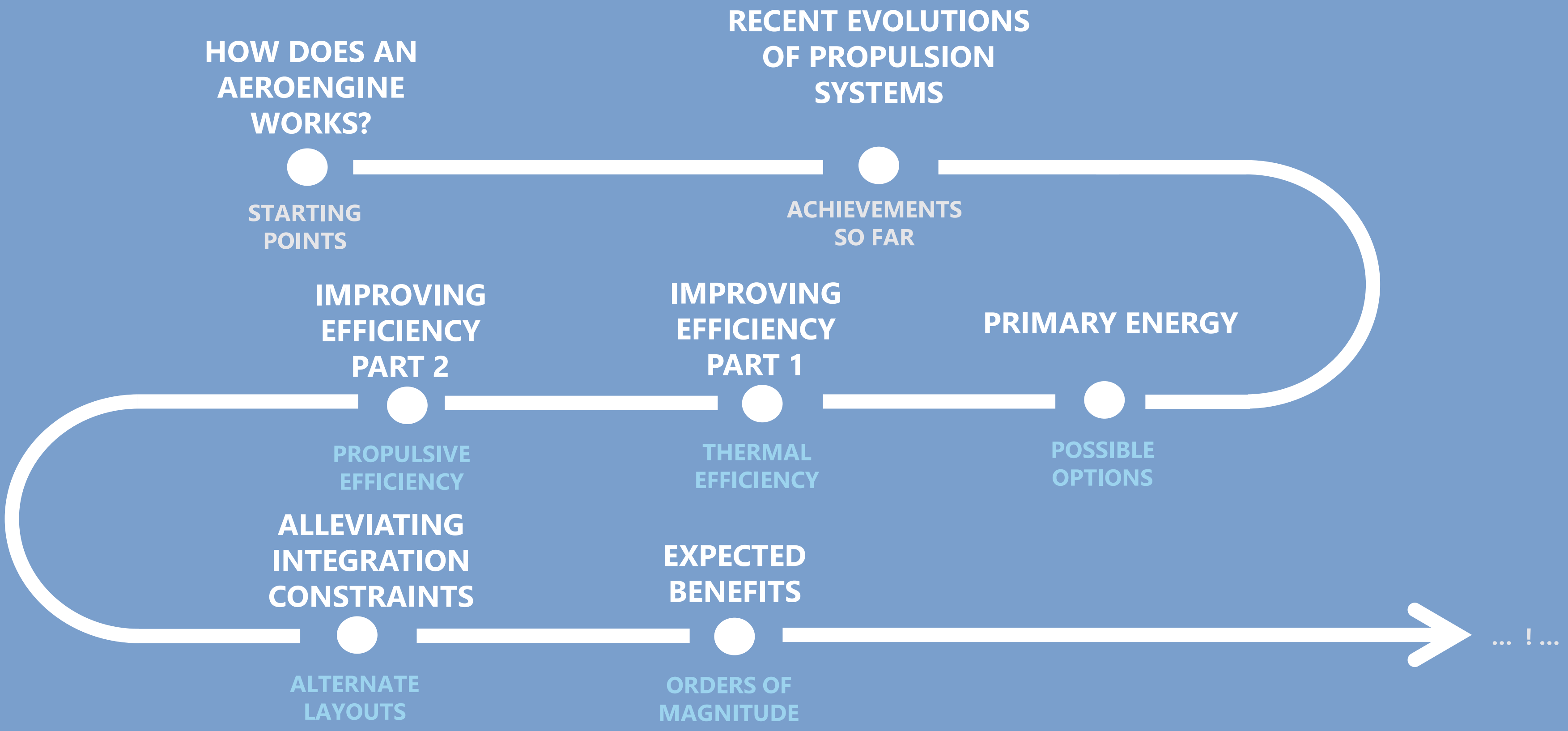
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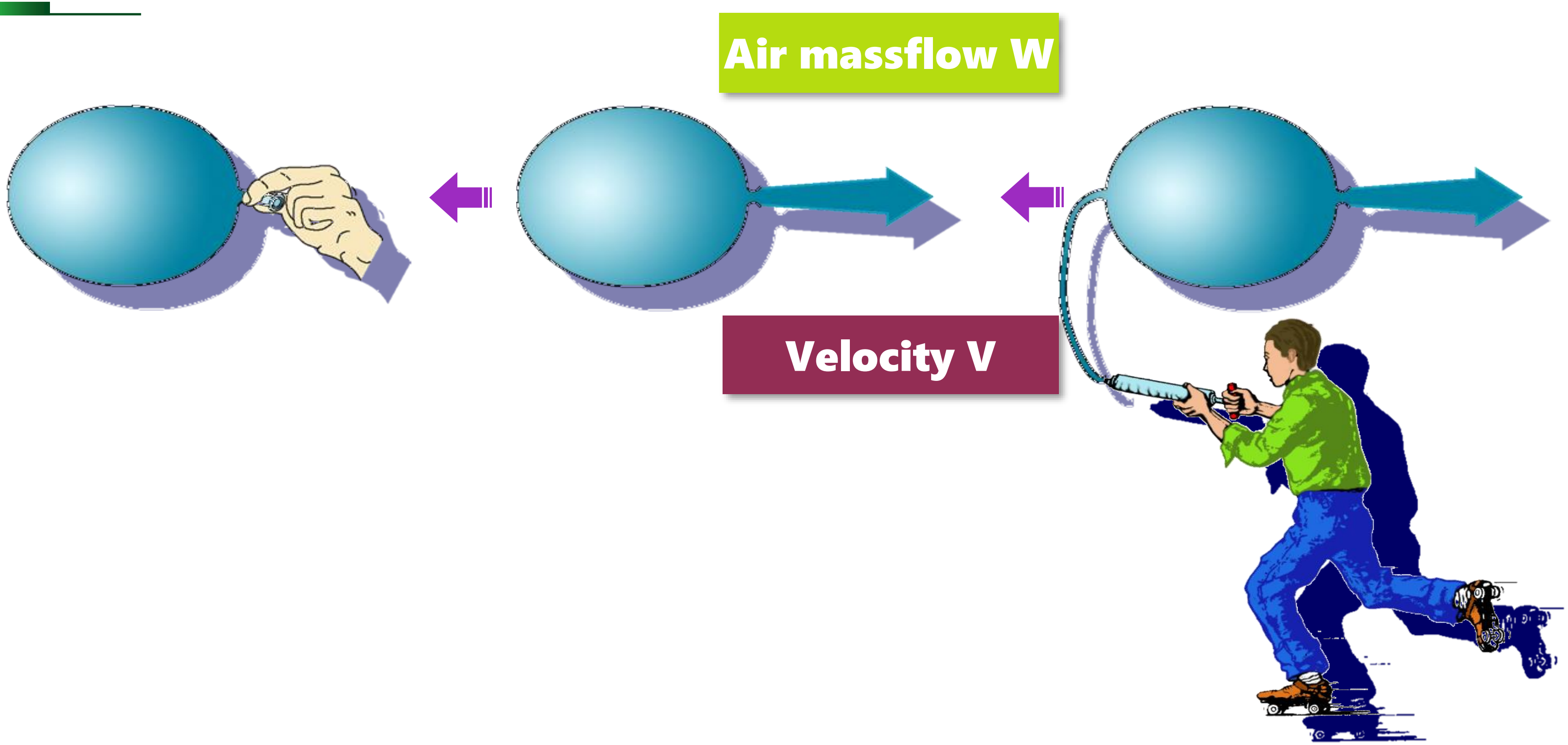
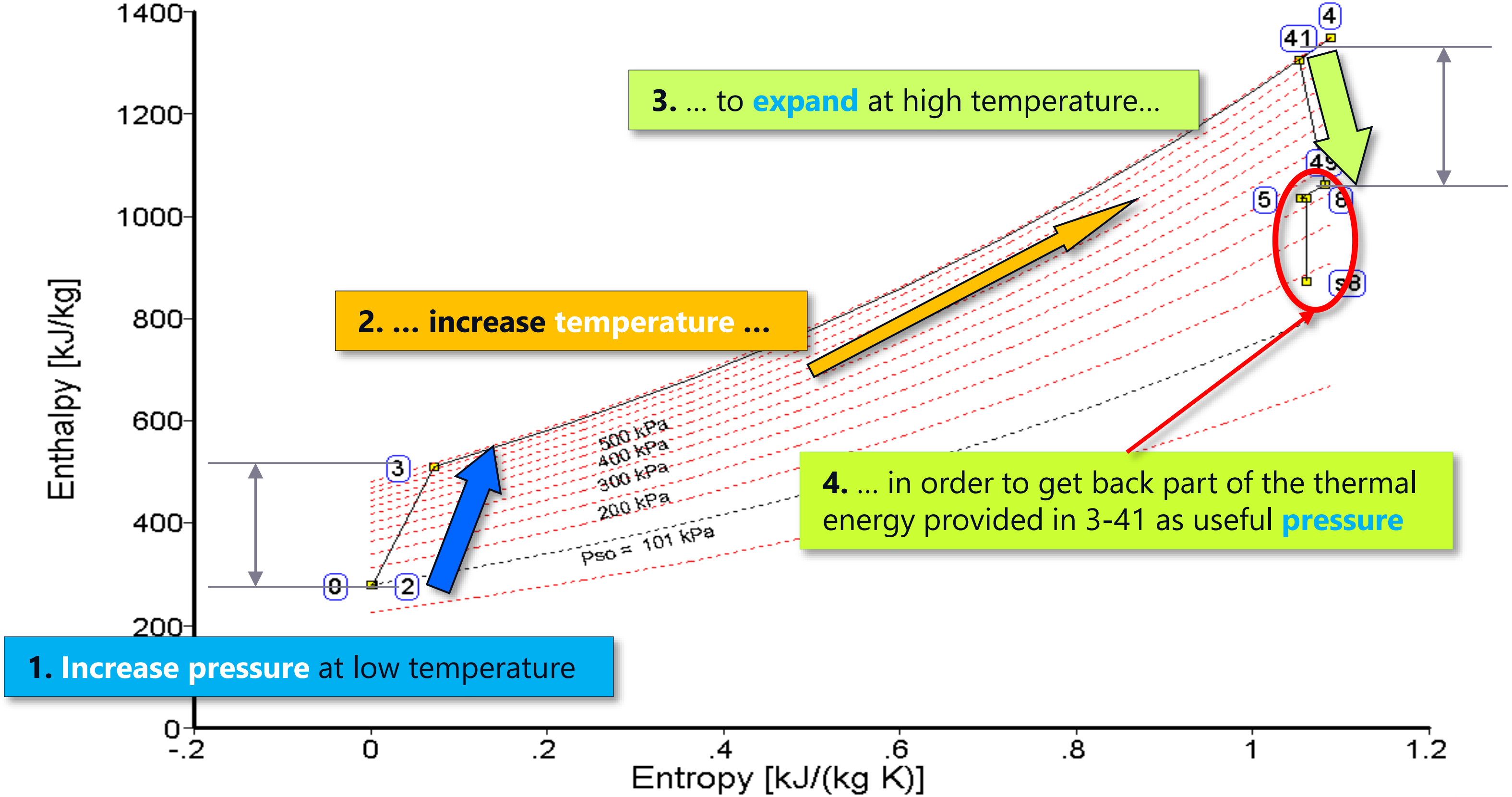
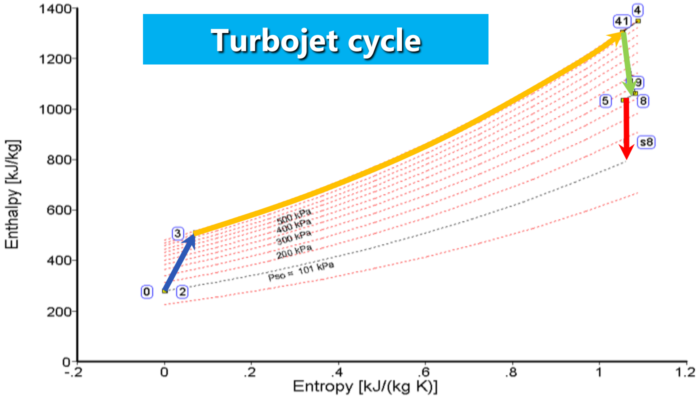
Thrust generation

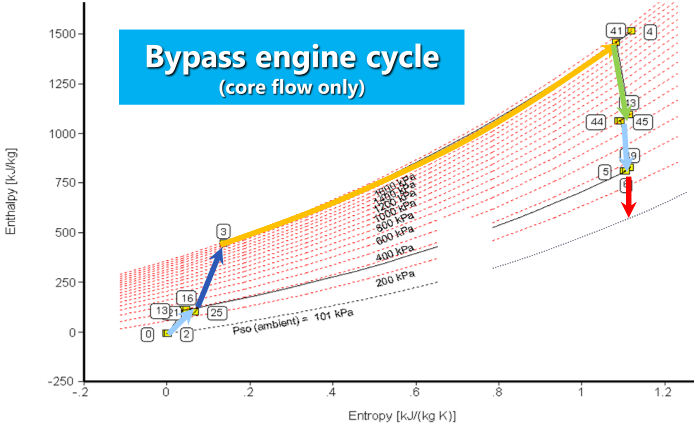


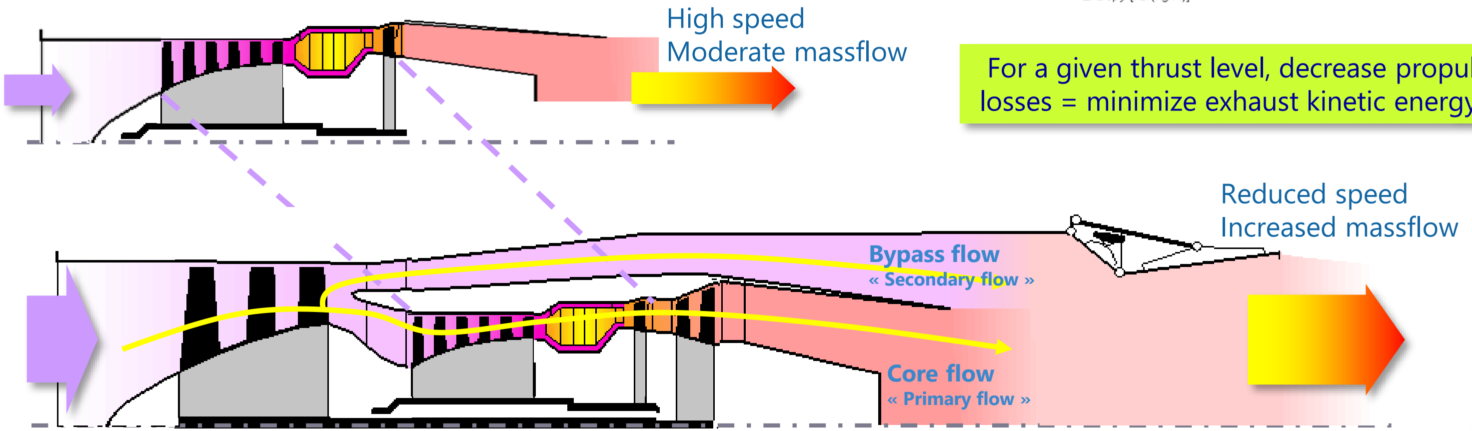
Thermodynamic cycle – Basic principles



From engine cycle to engine architecture (1/2)







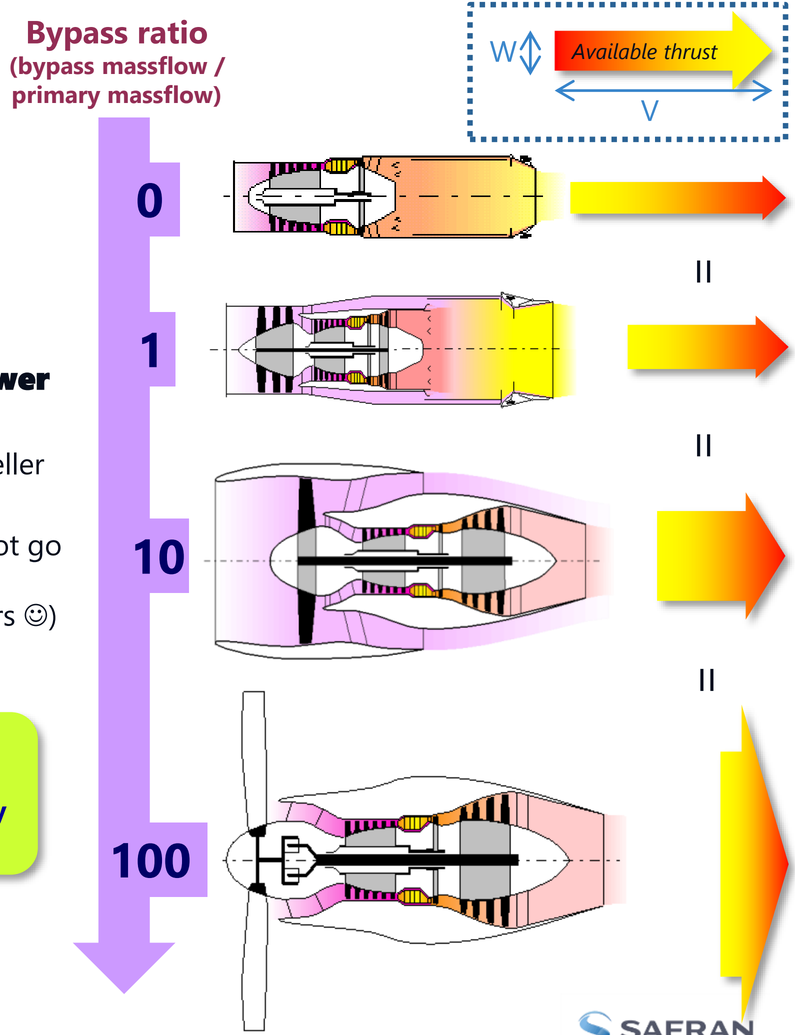
For a given thrust level, decrease propulsive losses = minimize exhaust kinetic energy (V^2)

From engine cycle to engine architecture(2/2)

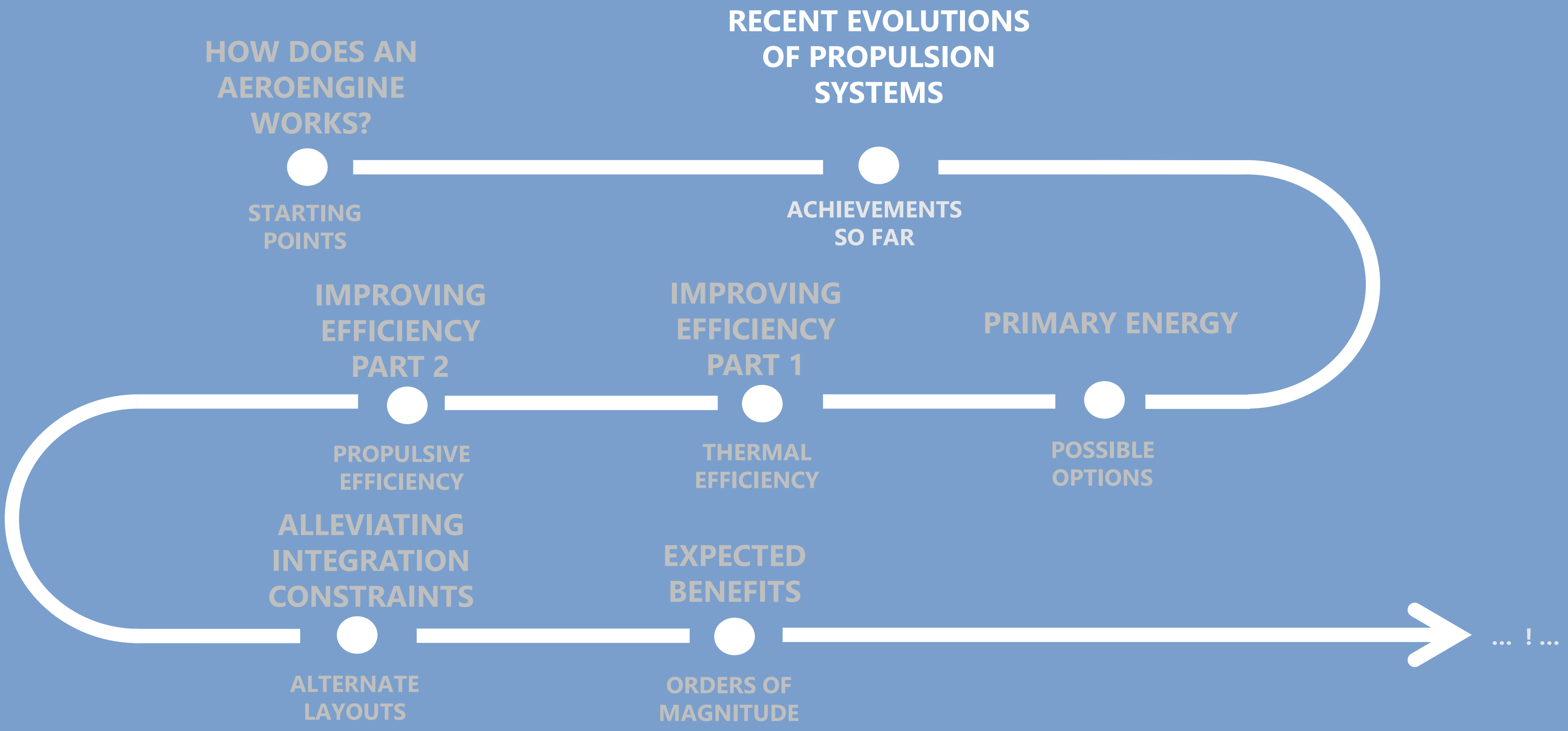
- **Available pressure can be used:**
  - **<u>Directly</u>: expansion into a nozzle**
    - Exhaust velocity increase → thrust generation
    - → Turbojet architecture
  - **<u>Indirectly</u>: expansion into a turbine, then use of mechanical power generated to drive a thrust generating device**
    - Use of a 2nd turbine, driving an upstream compressor (turbofan) or a propeller (turbopropeller)
    - This second compressor / propeller deals with an air massflow that does not go into the combustor
      → bypass airflow (« secondary » airflow for broken English french engineers ☺)
    - Bypass massflow / primary massflow = bypass ratio (BPR)

To provide a given level of **thrust**, there are infinite combinations between **incoming air massflow** and **gas exhaust speed**
Selecting one combination will be mostly based on the **compromise between energy efficiency and engine size**, visible through **bypass ratio** value.

$$FN \approx W\,(V_{out} - V_{in})$$



Most common engine architecture : Bypass turbofan with 2 shafts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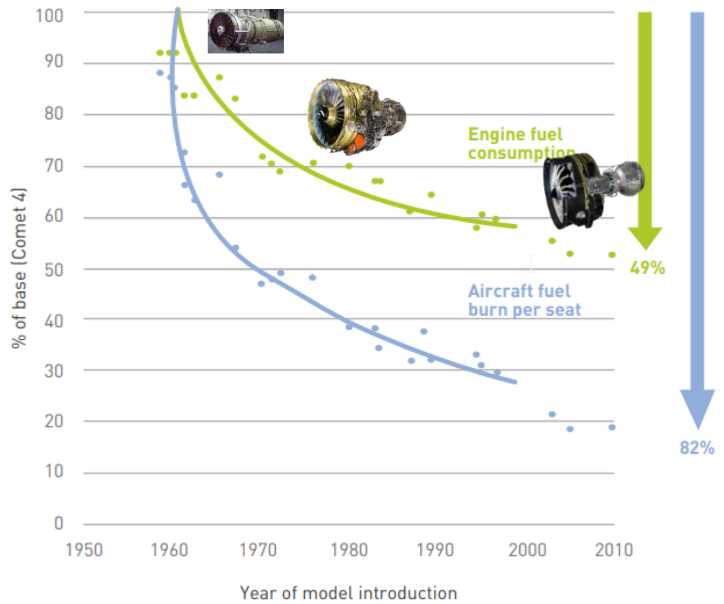
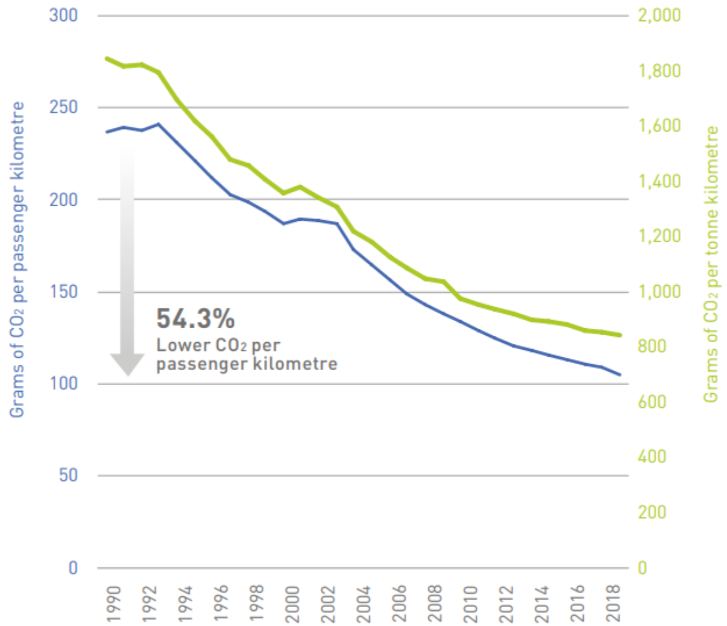
Fuel consumption reduction - *a long path already achieved*



Source : ATAG Waypoint 2050 report, 09/2020



Between 1960 and 2000, engines architectures evolution enabled reducing fuel consumption (i.e. CO2 emissions) by **80%**

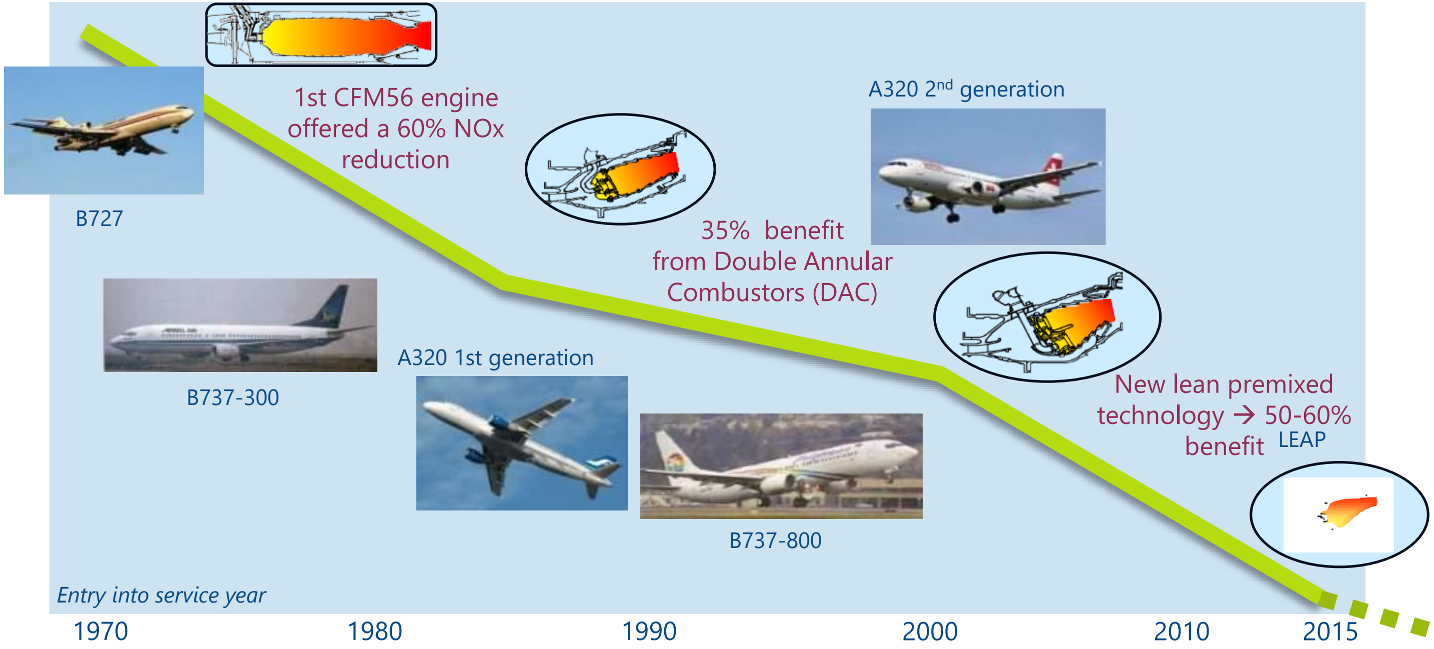
Modern aircraft fuel consumption is around **3.4 L/100 km/passenger**, i.e 86g CO2/km/passenger (*) ; it was halved since 1990

ACARE target is a further 25 % reduction per aircraft in 2050

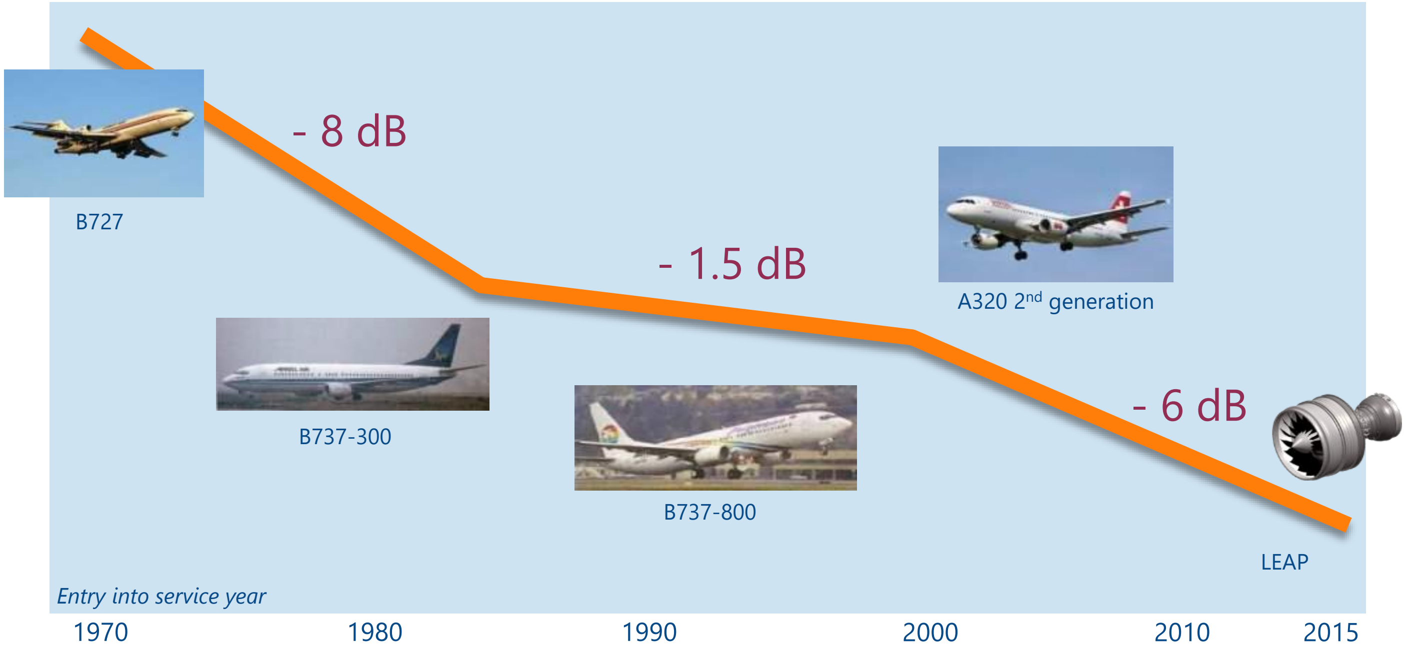
ATAG target is a 50 % global further reduction of all CO2 emissions since 2050

(*) in Europe, in 2019 ; source EASA European aviation environmental report

NOx reduction – *a constant progress*



More silent aircraft



A 3rd generation advanced turbofan : the CFM LEAP engine

15% Reduction in fuel consumption and CO_2 emissions versus today's engines

50% Margin on NOx emissions versus CAEP/6 standards

99.98% Dispatch reliability

Aircraft compliance with future Chapter 14 **noise regulation**

Maintenance costs comparable to today's industry-leading CFM56 engines

1. **High bypass ratio**
   Optimum propulsive efficiency
2. **3D woven carbon fiber composites**
   Lightweight, increased durability
3. **Debris rejection system**
   Airfoils protection against erosion
4. **High tech compressor**
   Optimum thermal efficiency
5. **New generation combustor**
   Lean burn low temperature
6. **Ceramic composites, new cooling & 3D aerodynamics**
   Reduced weight, cooling optimization
7. **Lightweight materials & 3D aerodynamics**
   Reduced weight, increased efficiency

A step further made possible thanks to continuous R&T effort

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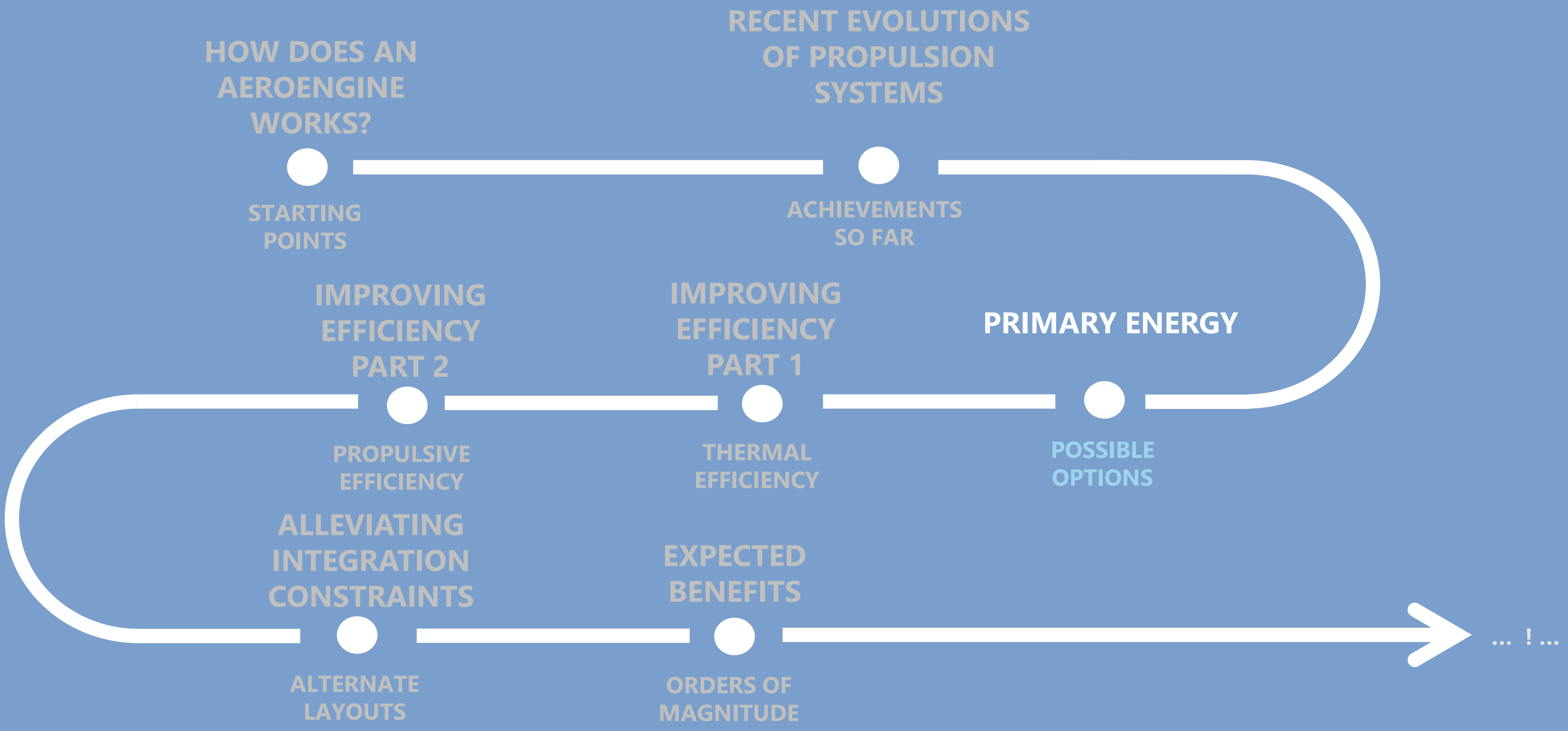
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Going further in reducing carbon emissions …

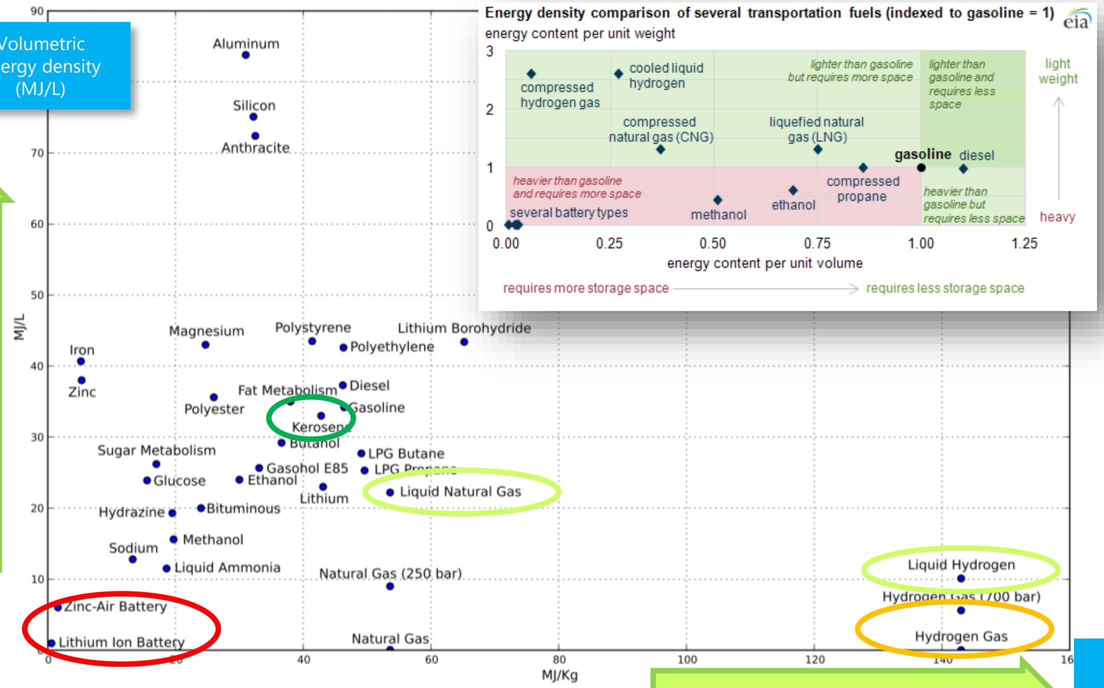
Low carbon primary energy

Alternative fuels enabling combustion

Electricity

Volumetric energy density (MJ/L)

DESIRABLE for a flying platform



ESSENTIAL for a flying platform

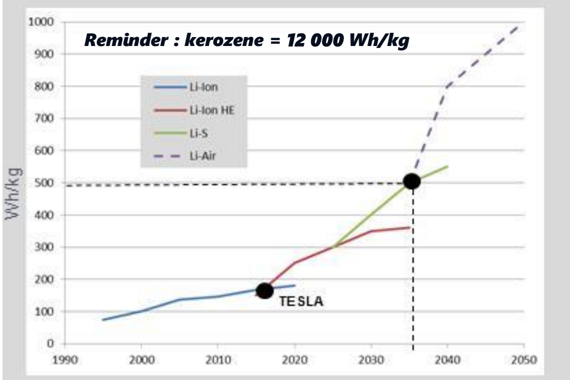
Gravitometric energy density (MJ/kg)

- **Electricity is not an option to provide the whole primary energy** for a medium/high size flying platform
- Alternate fuels not similar to kerozene require **significant geometrical/volumetric modifications on the airframe**

Zoom : impact of alternate primary energy sources on the airframe

Electricity

System-Level Battery Energy Density



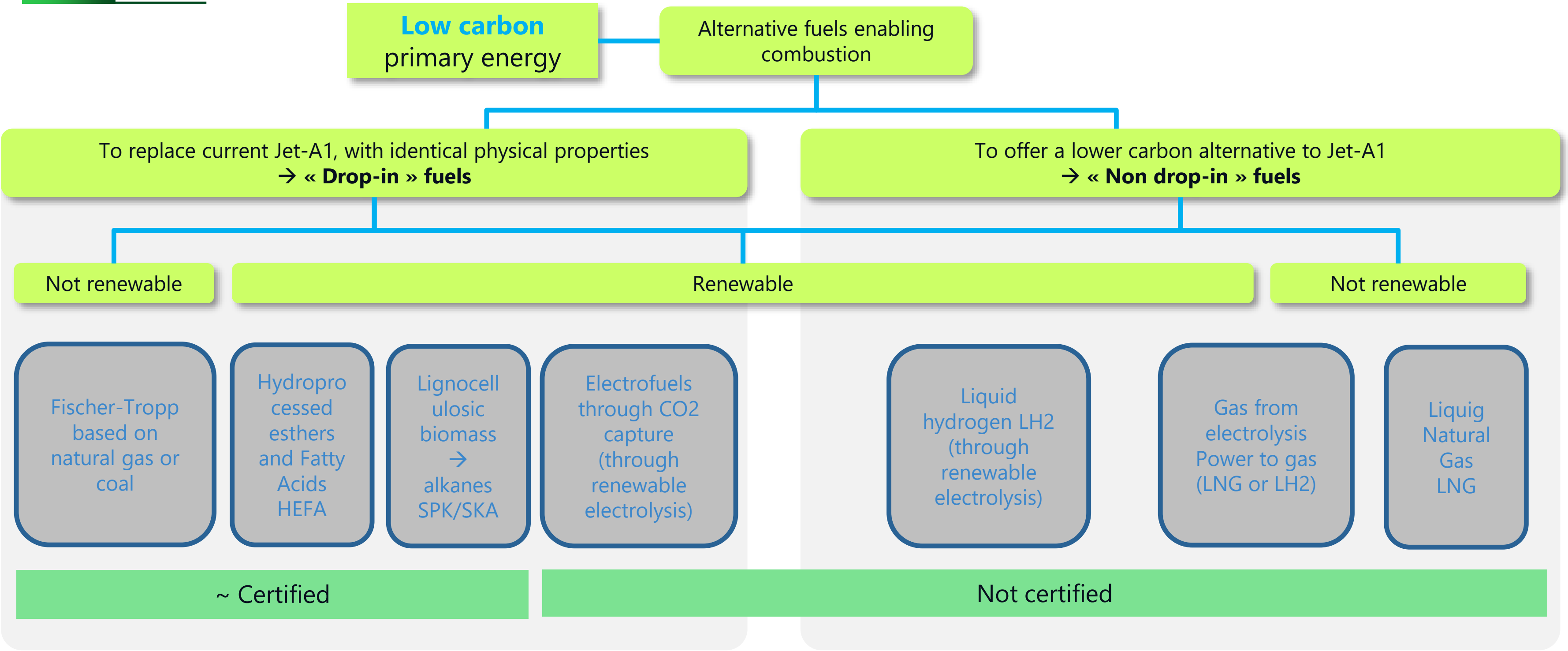
Even @1000 Wh/kg, an All-Electric Airbus A320 would require 170 t of batteries

Alternate fuels

LNG (liquid natural gaz), H2 :

- Low volumetric density
  → mandatory liquid state storage
- Cryogenic subsystem required to maintain liquid state
  → impacting airframe weight / volume / drag
- Numerous challenges regarding logistics (fill-in time, safety …)

Adapting to scarce fossile energies …



- **Limitations to such a classification:**
  - Complex combinations between direct emissions / indirect emissions / blend of renewable energy at stake in the process
  - Classification limited to process, not showing the various **energy quality expected** for an aeronautical use

Going further in front of fossile fuel increasing scarcity …

Low carbon primary energy

Alternate fuels enabling combustion

Substituting current Jet-A1 fuel → « Drop-in fuel », based on renewable primary source

Constituting a lower carbon alternate to Jet-A1, with different physical properties → « Non drop-in fuel »

- **Use properties**
  - Liquid state storage during whole flight
  - No deposit in pipes
  - Safety and predictable behavior in case of catastrophic event
  - Standardized fuel available worldwide
  - Ability to act as cold source for secondary functions
  - Mixing capability with Jet-A1
- **Availability and cost properties**
  - Capability to synthetize this fuel from primary material easily available, with minimum energy expense during transformation process, logistics, distribution and storage
- **Renewable**
  - Based on renewable material
  - Not conflicting with basic mankind needs
    - Biomass rather than dedicated crops …

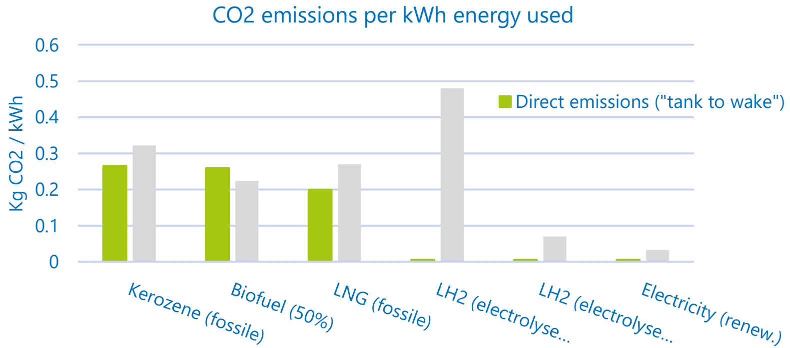
Energy properties

2 essential factors :

- High Fuel Heating Value (FHV)
- Low volume (or high volumetric density) to limit the weight of tanks and airframe structures

- To be compared to Jet-A1: FGHV = 43 MJ/kg and 35 MJ/m3)

Low carbon properties, considering the whole production chain :



Going further in front of fossile fuel increasing scarcity …

- Many **non technical factors** to consider as well:

Availability of primary material

- Biomass is not limiting for aviation (ressources >> need)
- Regarding low carbon electricity, needs towards 2050 can be fulfilled. Beyond …?

Competing use of ressources

- Available ressource… but not necessarily for everyone worldwide !
- Need to prioritize use of ressources (not competing with human food crops, etc …)

Logistics

- Still a lot to invent:
  - Logistics for biofuels raw material
  - Logistics for last production stage hydrogen

Finance

- Massive investments required:
  - Drop in : \$30B to 120B/y (Malina (MIT / ICAO)
  - Hydrogen : brand new complete chain : production, logistics, airport, airframe…

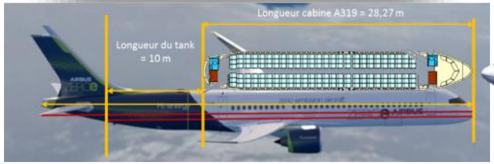
Existence of an alternate fuel marketplace

- More expensive than fossile fuels (long term target : 2 to 3times higher price)
- No clear incentive to use alternate fuels so far

Need :
~ 500 Mt fuel/year
= 21 EJ in 2050
1 EJ = exajoule = 10^{18} J

Zoom – Hydrogen-fueled aircraft

- **Hydrogen : an interesting gravitometric energy density, but …**
- **How to use it ?**
  - In a <u>fuel cell</u>
    - Energy conversion efficiency : ~ 60 % … → better than a turbofan engine, but much lower than a battery
  - In a <u>conventional turbofan burner</u>
    - Energy conversion efficiency : same as kerosene (~ 50 %) → no interest in terms of energy efficiency (in spite of other benefits such as reduced pollutants, availability, potential sustainability)
- **How to operate it ?**
  - Stored under liquid form (very low volumetric density)
  - Requires cryogenic storage (-250 °C) → additional complex and heavy fuel system (~ 10 times the weight of stored H2)
  - Calls for a significant volume to store : useful storage volume + consideration of leakages
  - Significantly modifies logistics during refueling : 2-3hrs to fill a SMR aircraft tank …



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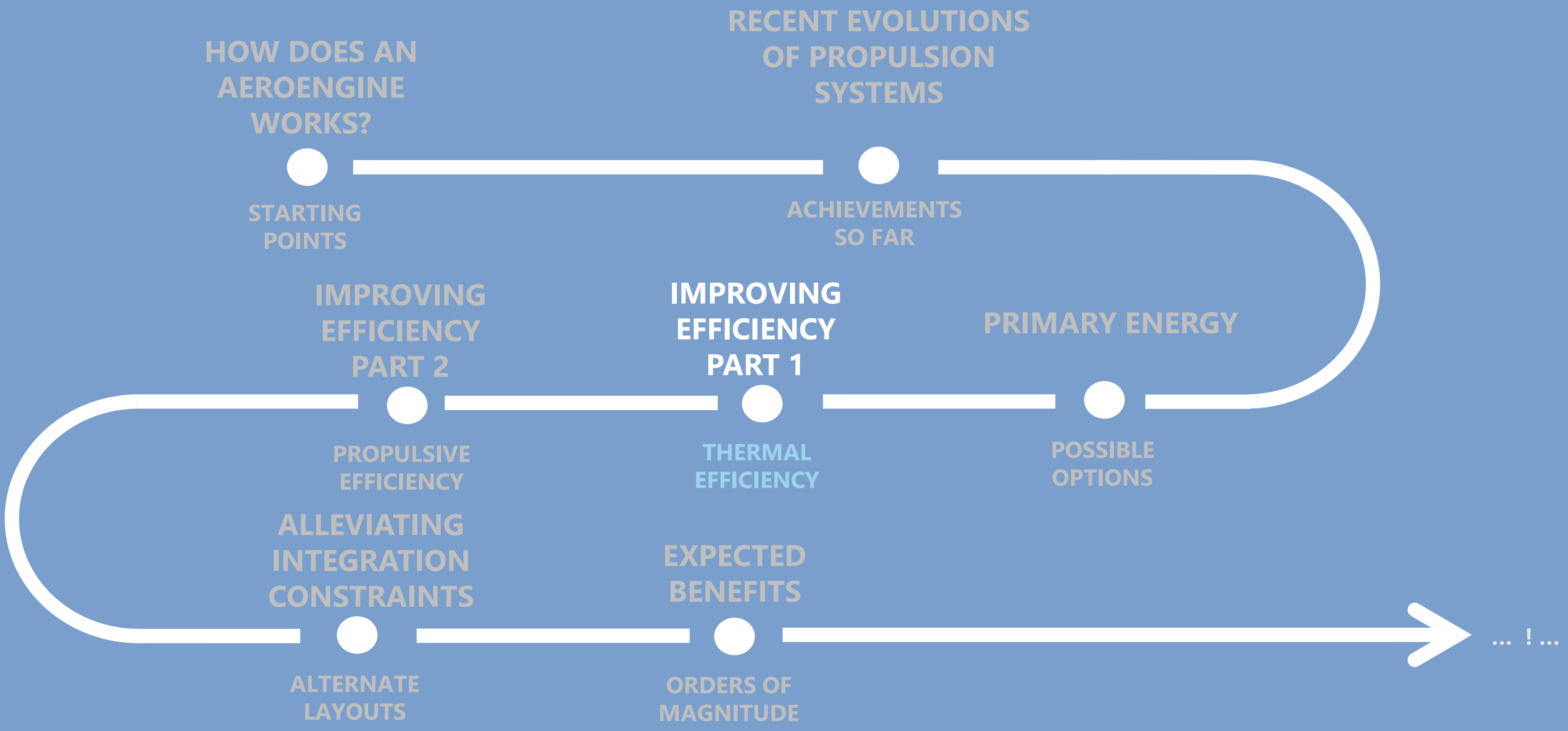
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Going further in energy efficiency and reduced environmental impact …

Thermopropulsive efficiency = Thermal efficiency X Propulsive efficiency

$$\eta_{thp} = \frac{PW_{aircraft}}{PW_{fuel}}$$

$$\eta_{th} = \frac{PW_{airflow}}{PW_{fuel}}$$

$$\eta_{th} = \frac{\frac{1}{2} W_{out} V_{out}^2 - \frac{1}{2} W_{in} V_{in}^2}{Wf.FHV}$$

$$\boxed{\eta_{th} = 1 - \frac{1}{OPR^{\frac{\gamma - 1}{\gamma}} \left(1 + \frac{\gamma - 1}{2} M_0^2\right)}}$$

$$\eta_{pr} = \frac{PW_{aircraft}}{PW_{airflow}}$$

$$\eta_{pr} = \frac{FN.V_0}{\frac{1}{2} W_{out} V_{out}^2 - \frac{1}{2} W_{in} V_{in}^2}$$

$$\boxed{\eta_{pr} = \frac{2}{1 + \frac{V_{out}}{V_{in}}}}$$

→ Increase OPR

→ Modify burner operation

→ Decrease exhaust speed (*→ decrease fan pressure ratio)*

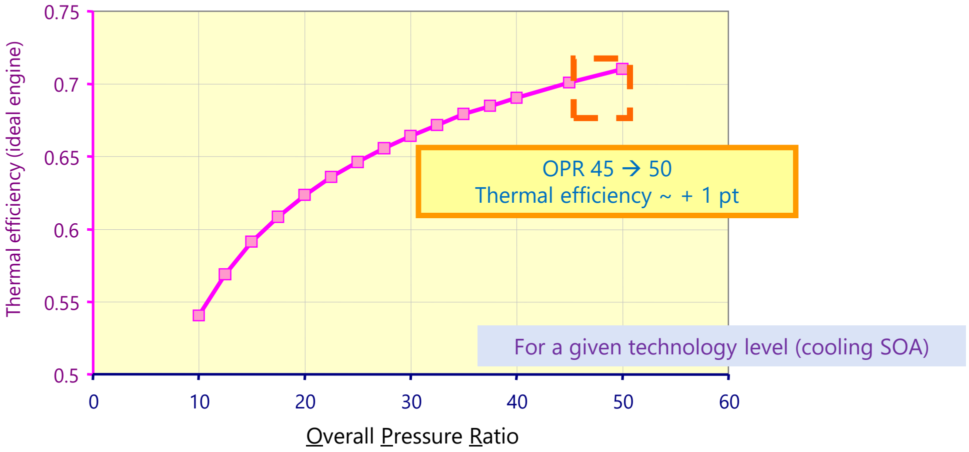
→ Decrease inlet flow speed seen by the engine

→ Alleviate constraints on engine installation

→ Combine various energy sources

Improve thermal efficiency – High OPR engine

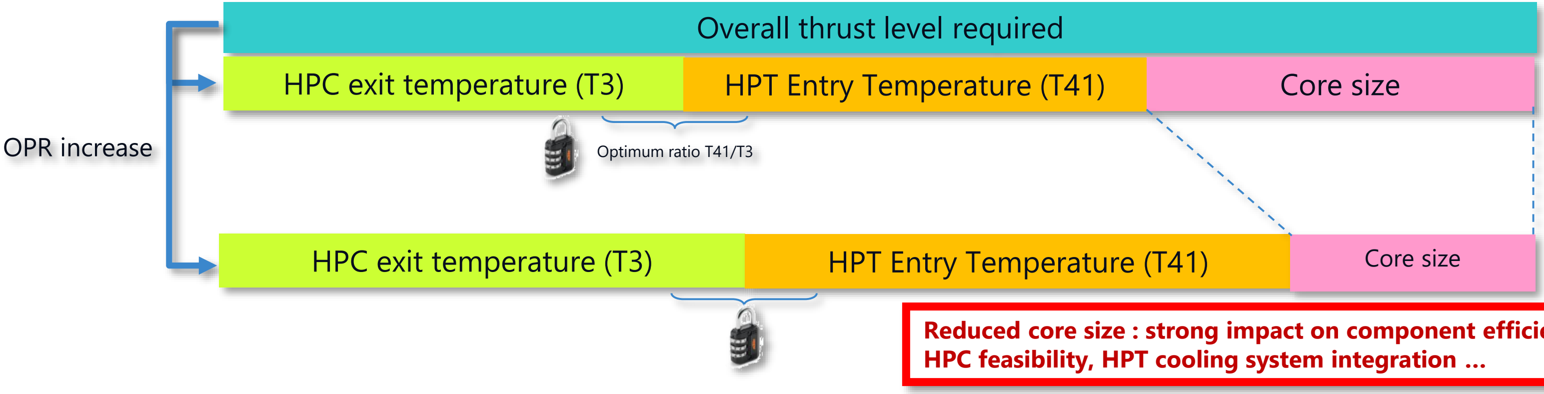
- Increasing OPR results in better thermal efficiency …



- … at the expense of increasing technology constraints :
  - Core size decrease → threats on HP core feasibility, LP shaft integration
  - T3 increase → need for advanced materials for last HPC rows
  - Increased compressor stage count → weight, length, dynamics
  - Hotter air offtakes → detrimental to cooling efficiency

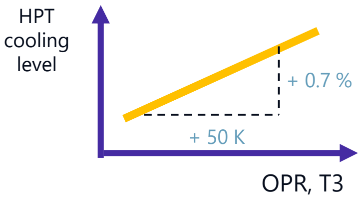
High OPR : related challenges

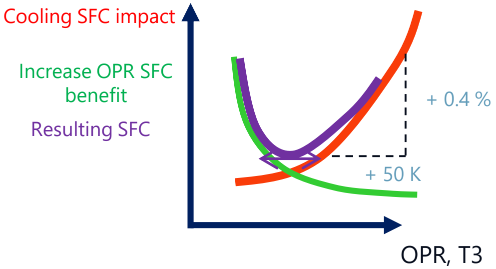
- 1) OPR increase directly affects **core size :**



Reduced core size : strong impact on component efficiencies, HPC feasibility, HPT cooling system integration …

- 2) OPR increase directly impacts HPT required cooling levels :



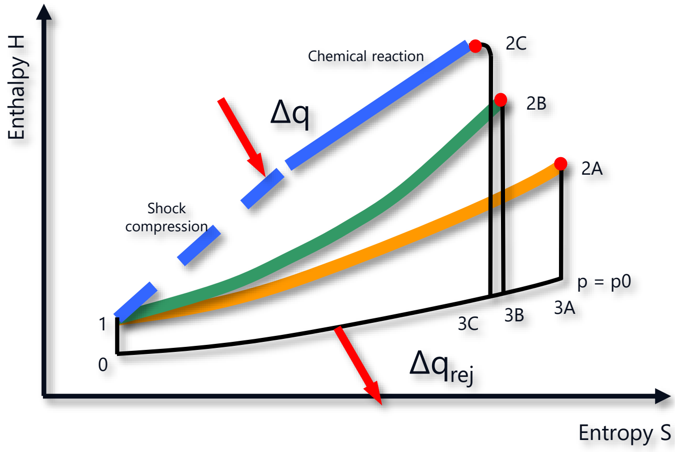


Increased engine temperatures → need for higher cooling amount → Partially offsets / annihilates SFC improvement through thermal efficiency

Improve thermal efficiency : modify burner operation

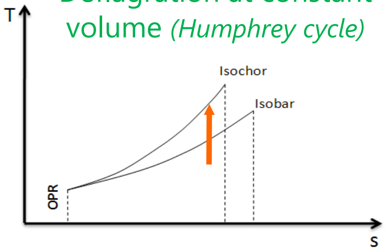
- **Deflagration (« subsonic heat propagation »)**
  - At constant pressure (isobaric) – CYCLE A → Brayton
  - At constant volume (isochoric) – CYCLE B → Humphrey

- **Detonation (« shock wave propagation »)**
  - CYCLE C

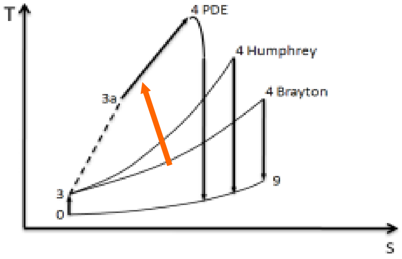


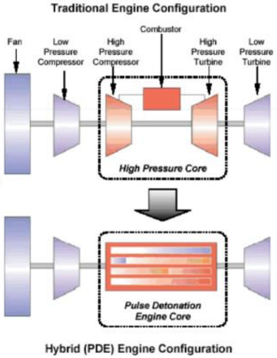
Various technologies for various burner operation modes

Deflagration at constant volume *(Humphrey cycle)*

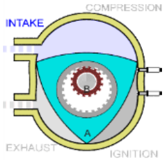


Detonation

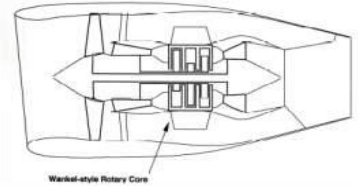




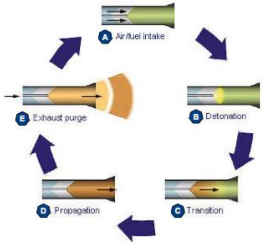
- Rotating piston (Wankel type)



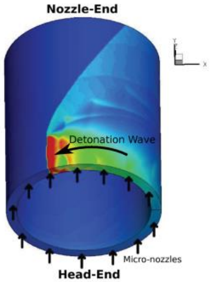
- Compound Cycle Engine

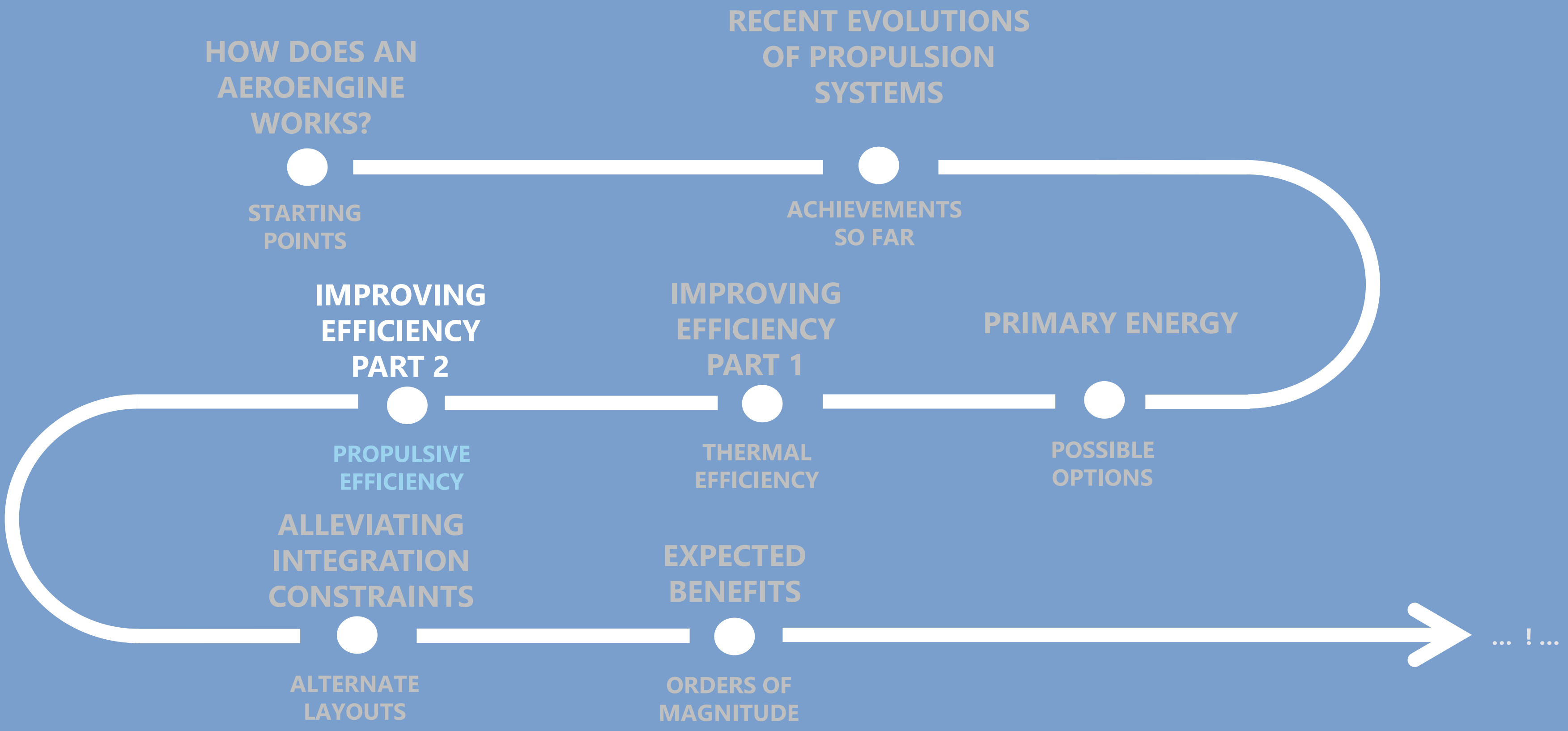


- Pulse Detonation Combustor



- Continuous Rotating Detonation Wave Engine

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Improve propulsive efficiency – *Links with Fan Pressure Ratio, Bypass Ratio …*

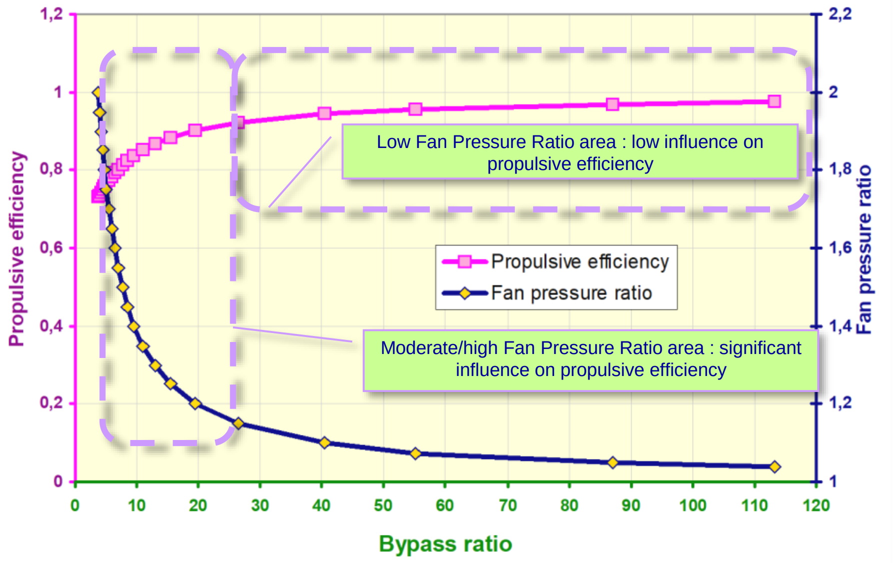
Simplified link between thrust and massflow :

$$FN = W \times \Delta V$$

constant

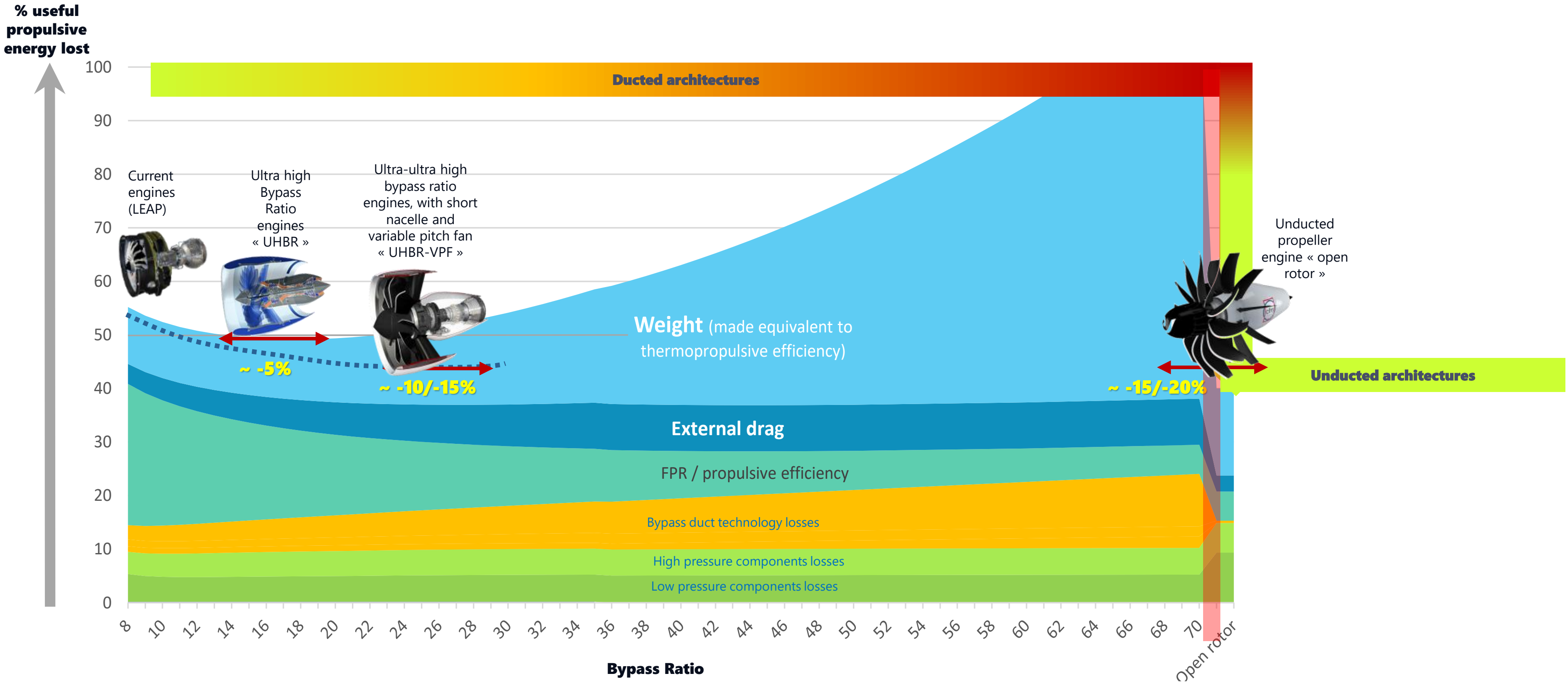
Increase massflow !

Decrease to improve propulsive efficiency



- Best propulsive efficiency can only be achieved with **very low fan pressure ratio** (1.05 to 1.2)
- Low fan pressure ratio means **significant BPR increase, thus increased external engine dimensions** to keep thrust capability
- BPR higher than 20 (i.e. FPR lower than 1,2) result in moderate influence on propulsive efficiency

Improving propulsive efficiency – Various architectural options and impacts



Improving ducted configurations - *« UHBR » engines (Ultra High Bypass Ratio)*

Improving ducted configurations - *« UHBR - VPF » engines (Variable pitch fan)*

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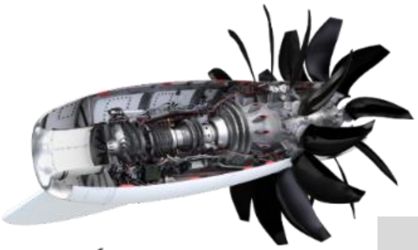
Unducted configuration « Open rotor » – Possible layouts

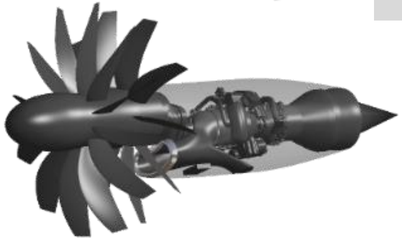
Counter-rotating propellers

(CROR, "UDF")

Pusher layout



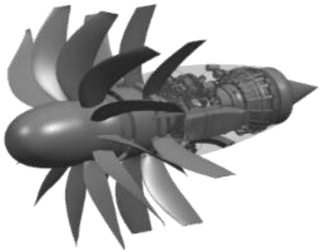
Puller layout

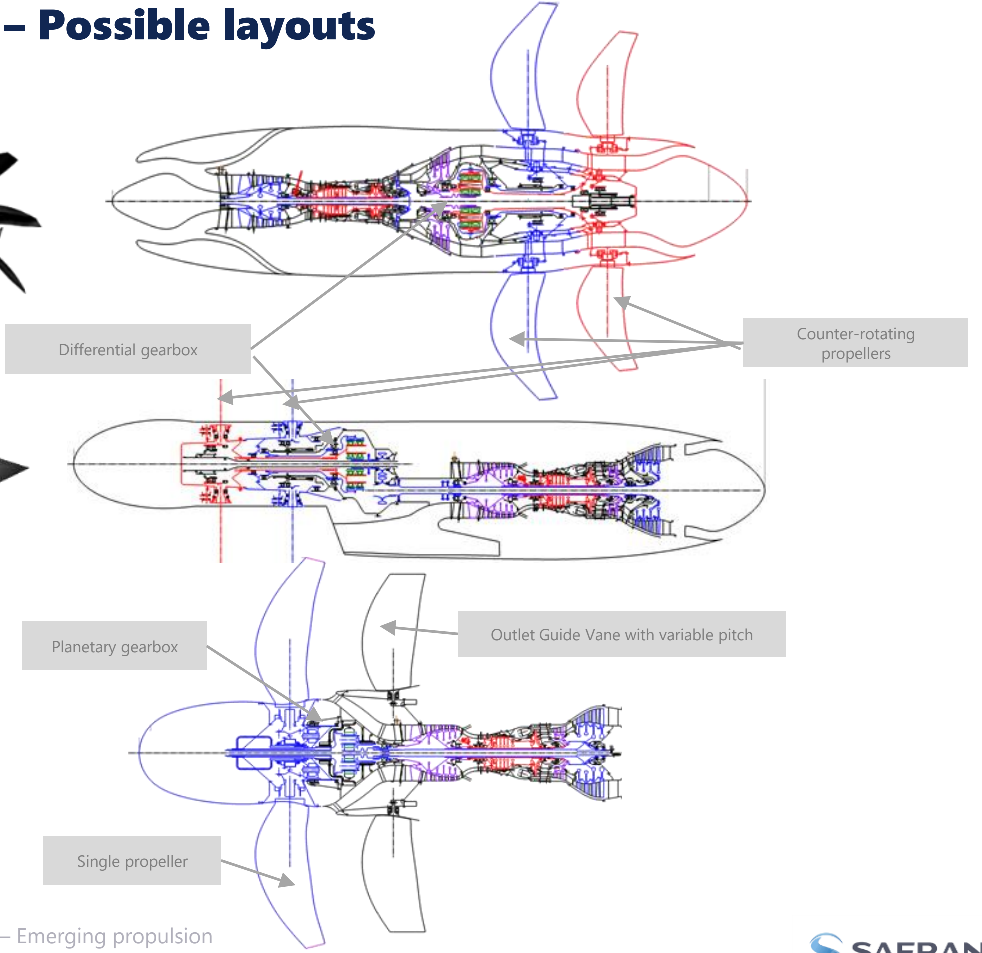


Single propeller with swirl recovery vane (active stator)

(ORAS, « USF », « Open fan »)

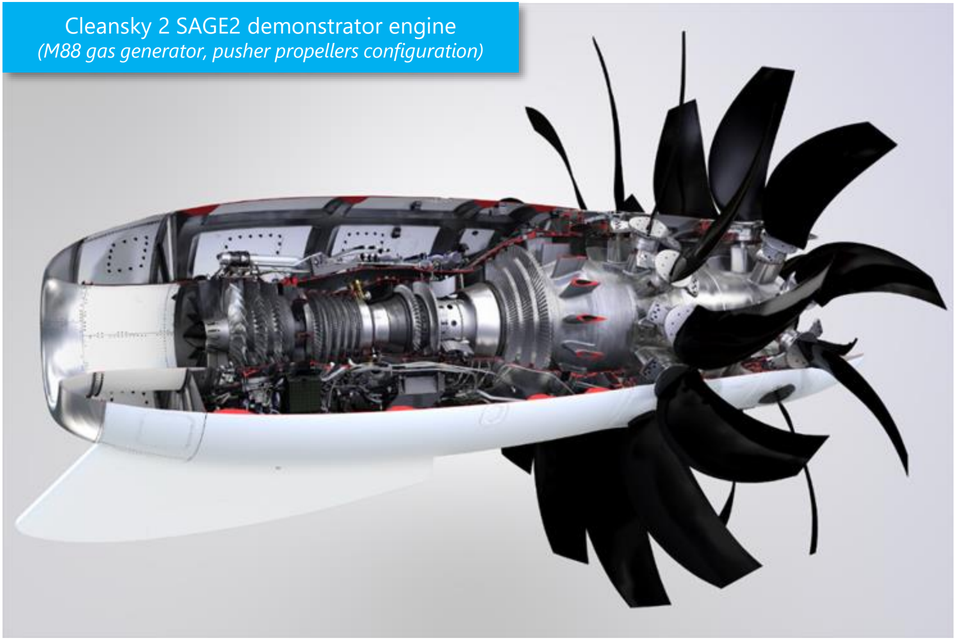
Puller layout





Open rotor in recent demonstration

Cleansky 2 SAGE2 demonstrator engine
(M88 gas generator, pusher propellers configuration)



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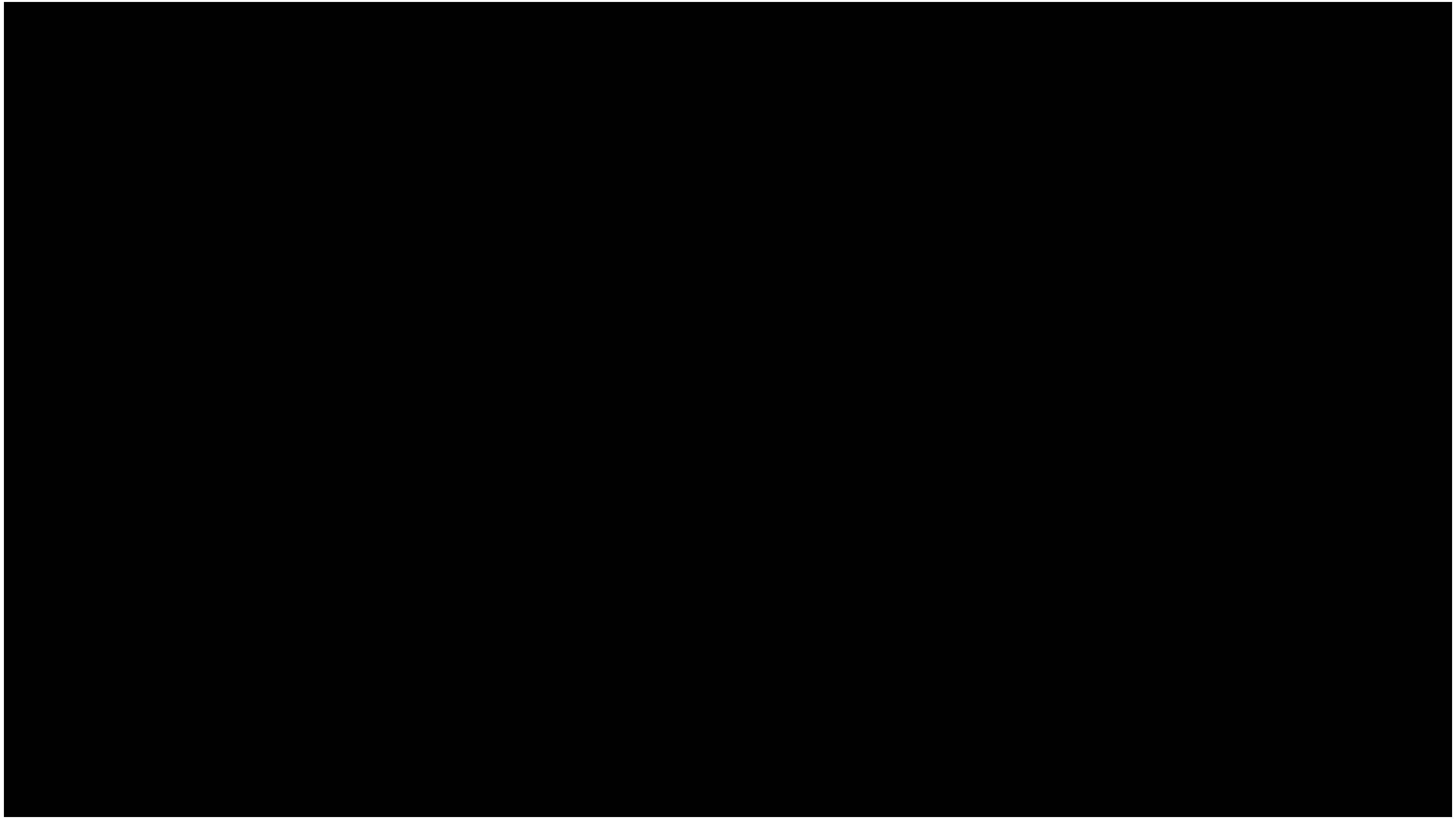
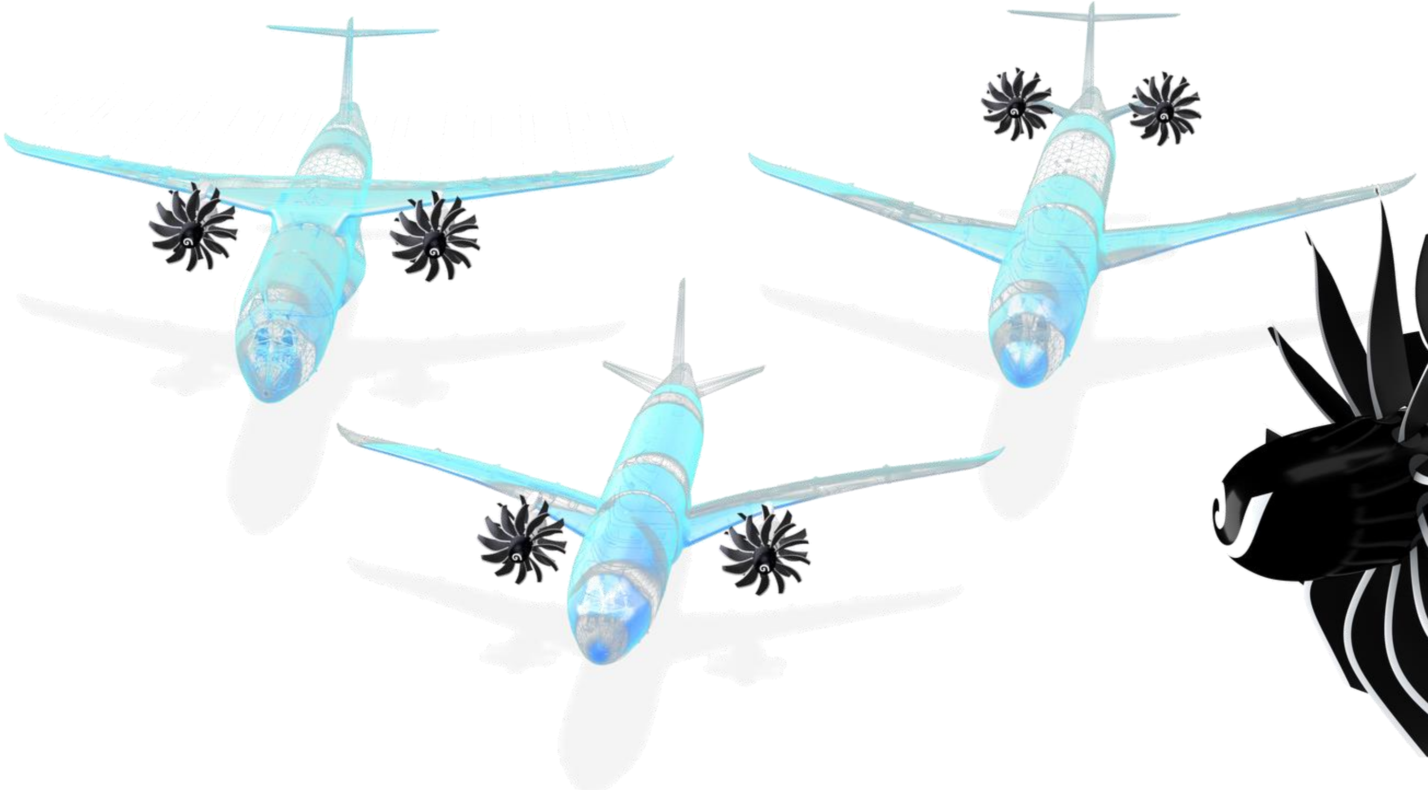
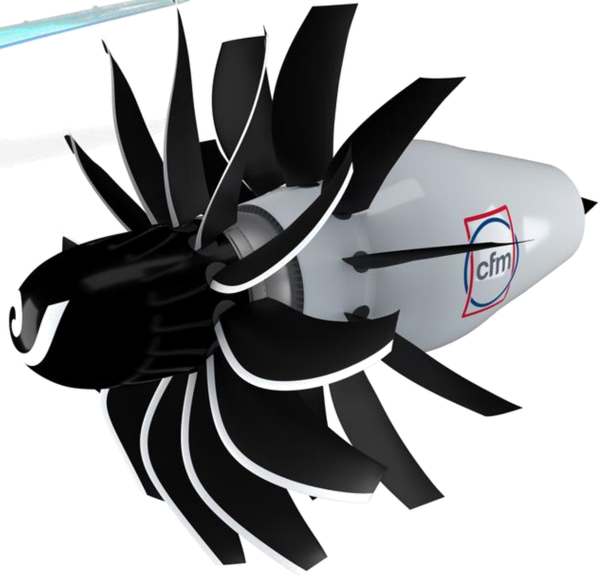
Open rotor in recent demonstration



Open rotor in future layouts (puller USF configuration)



CFM RISE ™

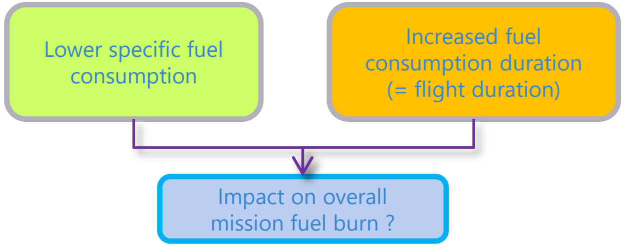


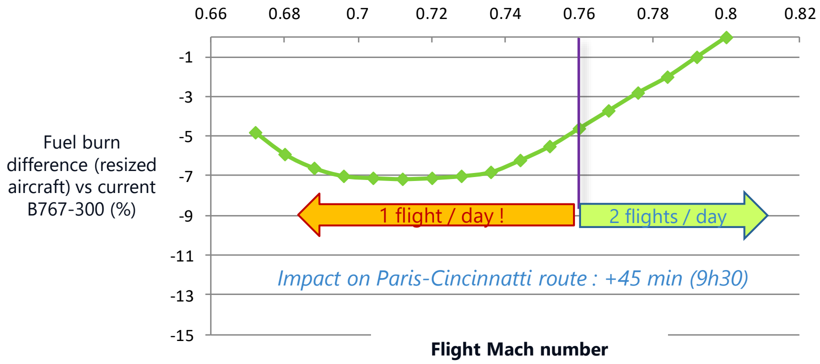
Improving propulsive efficiency : *modify inlet flow speed ?*

- **2 main ways to interact with propulsive efficiency** :
  - → Reduce exhaust speed
  - →Take advantage of specific fuel consumption dependency to flight speed :

$$SFC = \frac{Wf}{FN} = \underbrace{\frac{Wf.FHV}{FN.V_0}}_{\frac{1}{\eta_{thp}}} \frac{V_0}{FHV} = \frac{V_0}{\eta_{thp}.FHV}$$

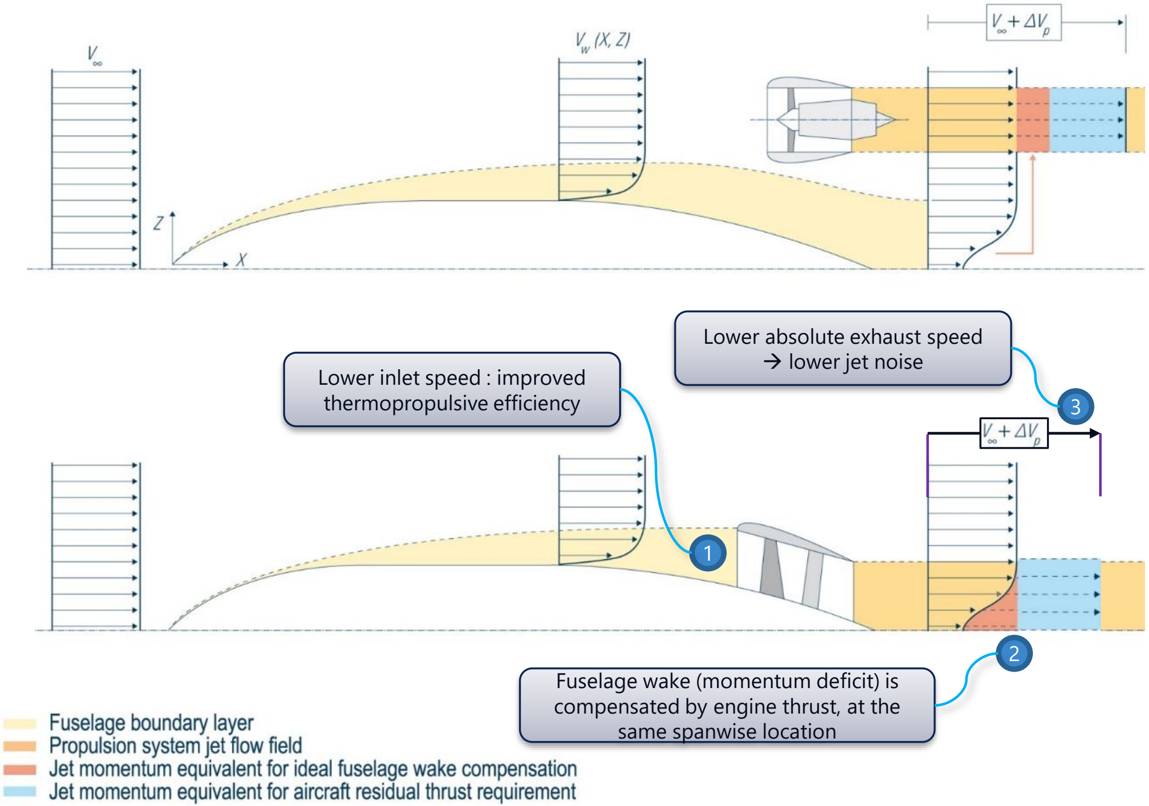
- → Fly slower?





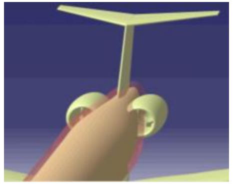
Example on Boeing 767-300ER
Stanford University study AIAA 2014-0181

A way to decrease inlet speed : fuselage boundary layer ingestion

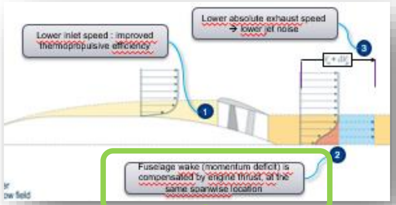


Legacy configuration

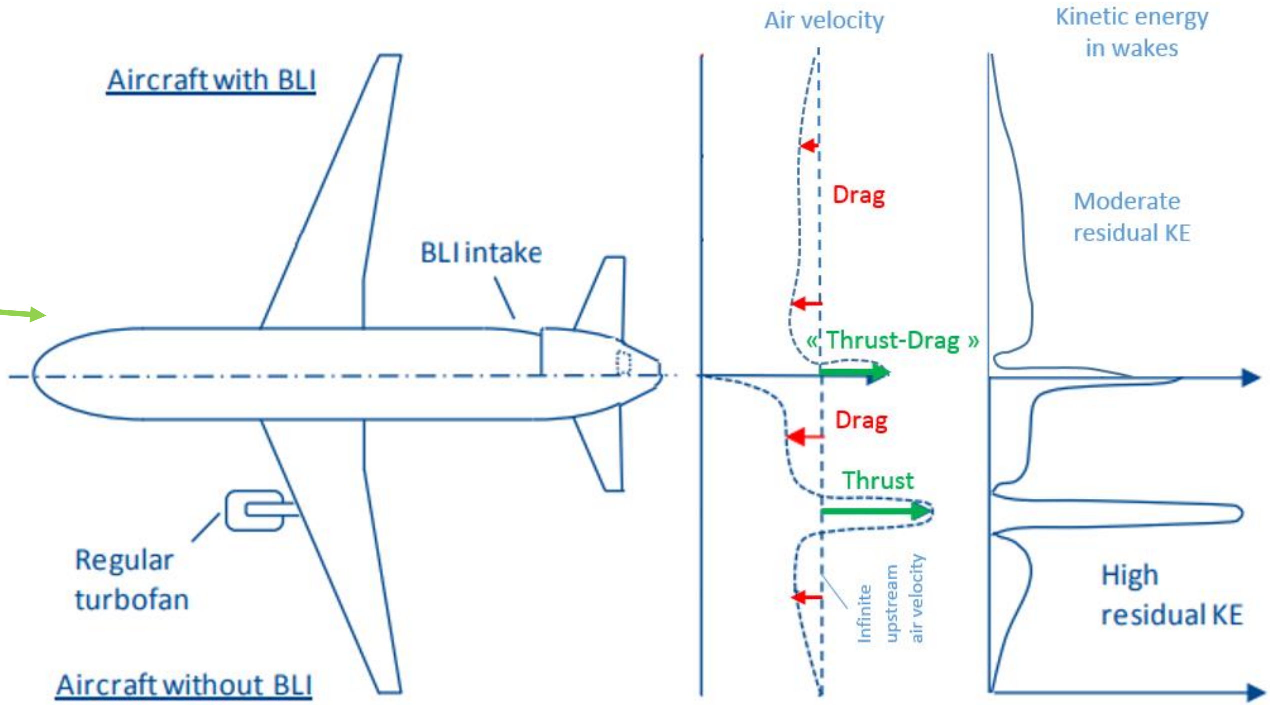
Boundary **L**ayer **I**ngestion configuration



Boundary Layer Ingestion – Overall efficiency impact

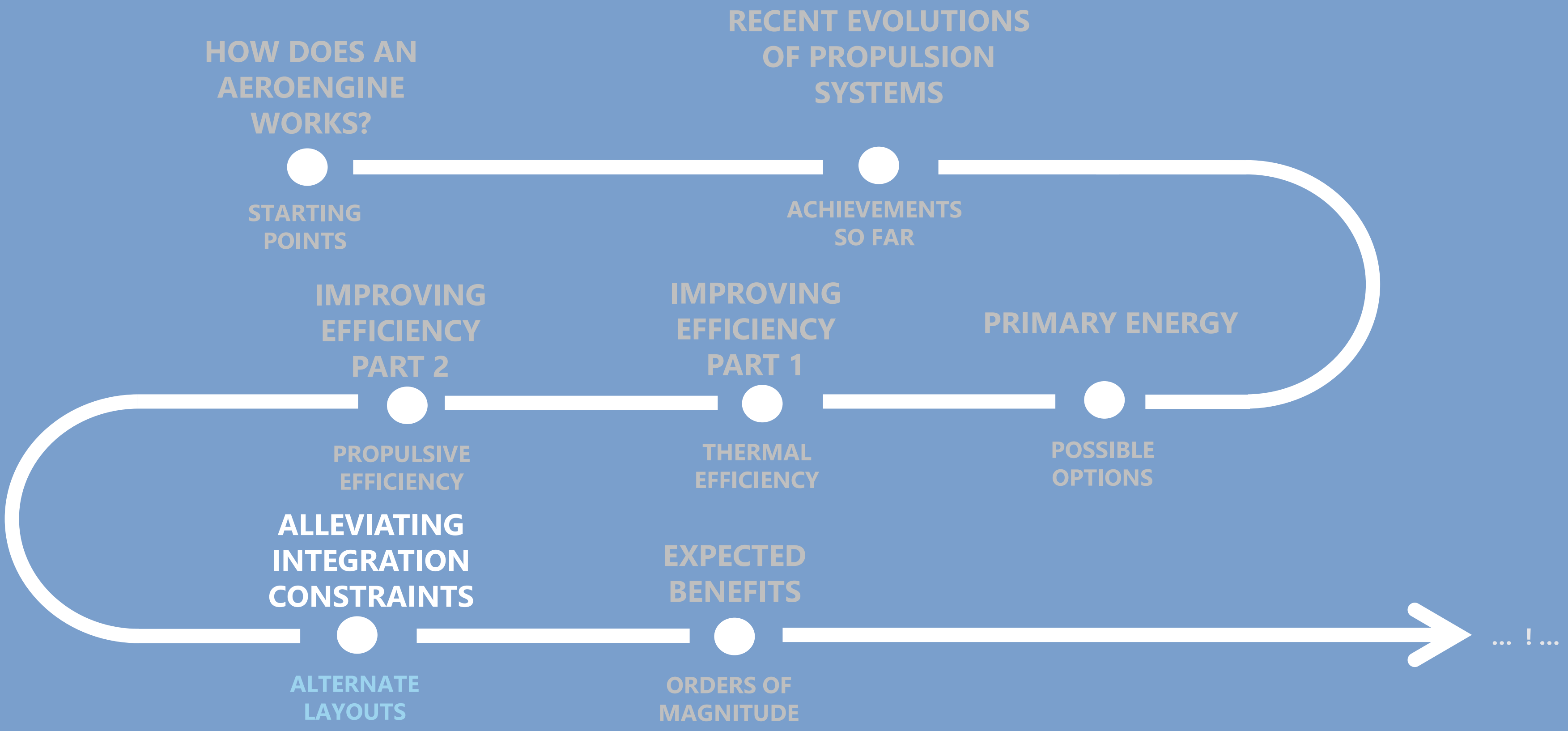


« Better propulsive efficiency = minimized exhaust kinetic energy (V^2) »



Still a number of challenges :

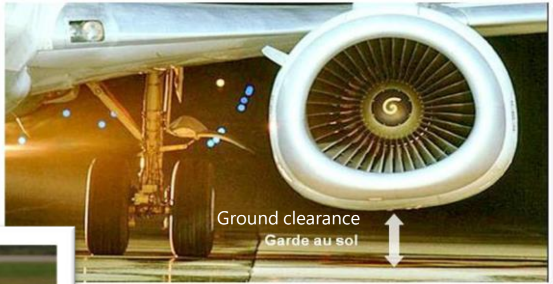
- Fan design tolerant to distorsion
- Rear end engine integration
- Unclear split between « thrust » and « drag » (airframer / engine manufacturer boundary)


HOW DOES AN AEROENGINE WORKS?
STARTING POINTS
RECENT EVOLUTIONS OF PROPULSION SYSTEMS
ACHIEVEMENTS SO FAR
PRIMARY ENERGY
POSSIBLE OPTIONS
IMPROVING EFFICIENCY PART 1
THERMAL EFFICIENCY
IMPROVING EFFICIENCY PART 2
PROPULSIVE EFFICIENCY
ALLEVIATING INTEGRATION CONSTRAINTS
ALTERNATE LAYOUTS
EXPECTED BENEFITS
ORDERS OF MAGNITUDE
… ! …

BPR and installation challenges

Re-engining with constant airframe

Boeing 737 MAX
LEAP-1B, BPR 8.5



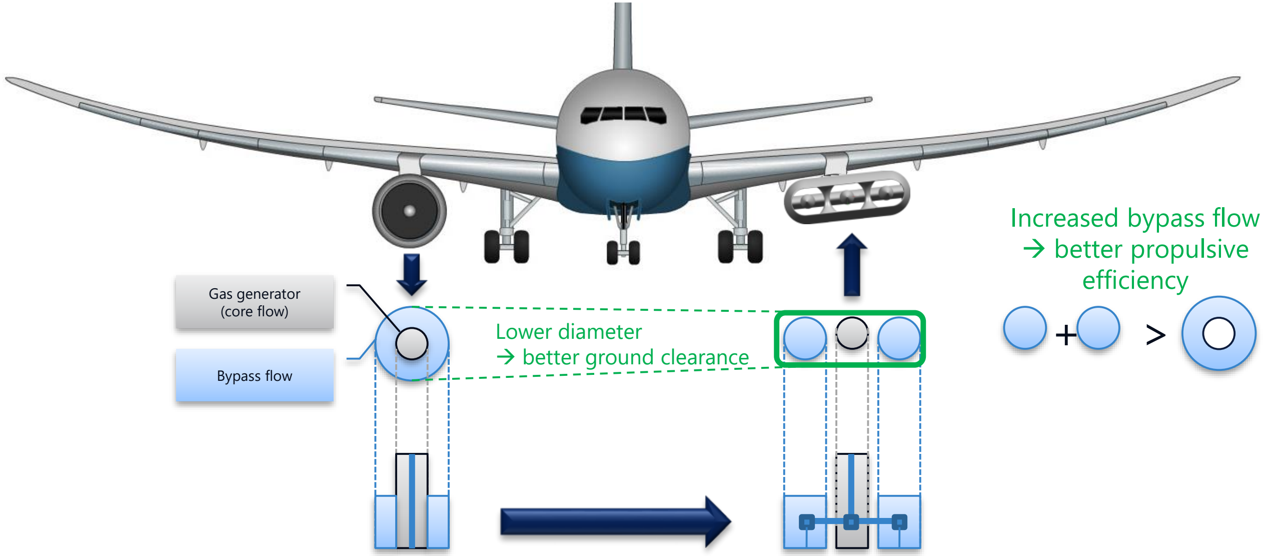
Boeing 737 NG
(-700/800/900)
CFM56-7B, BPR 5

Boeing 737 Classic
(-400/500/600)
CFM56-3, BPR 5

Boeing 737 original
(-100/200)
JT8D, BPR 1.7

Minimizing installation constraints : distributed propulsion

- Distributed propulsion enables higher BPR (hence better propulsive efficiency), while minimizing installation constraints (ground clearance)



- Challenges : increased installation drag, auxiliary fans drive system, additional weight and complexity

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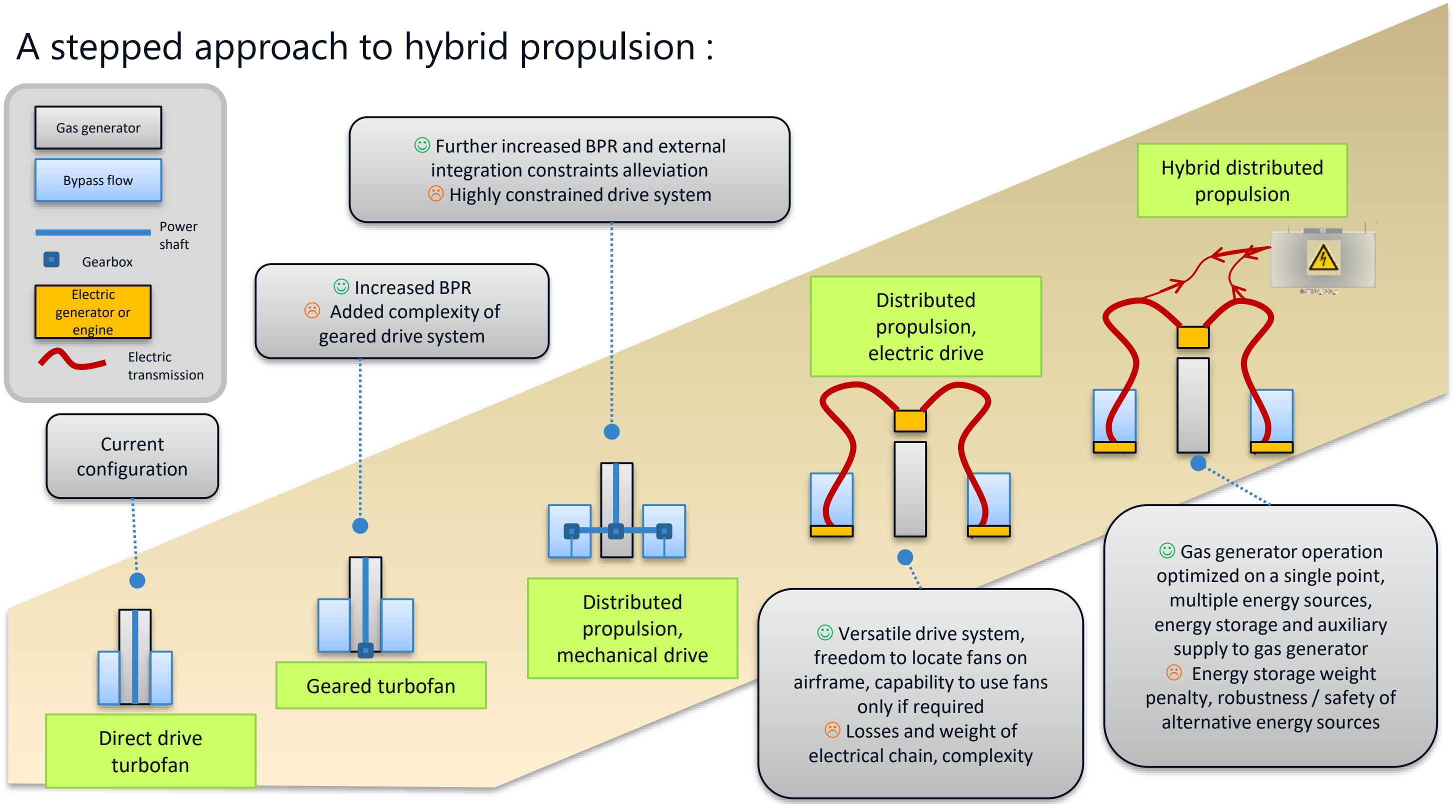
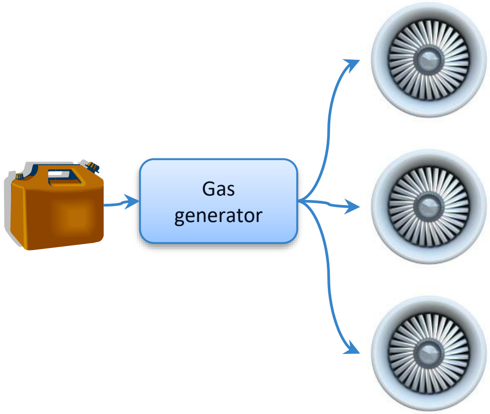
Optimizing onboard energy sources : hybrid propulsion

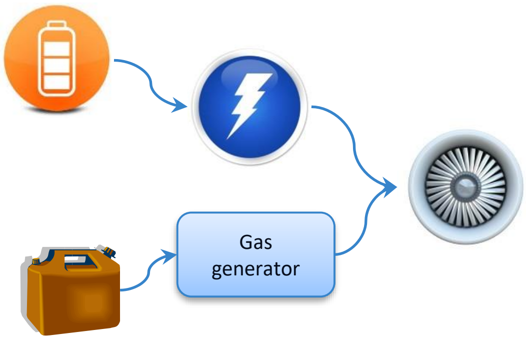
- A stepped approach to hybrid propulsion :



Hybridization, distribution, same logic



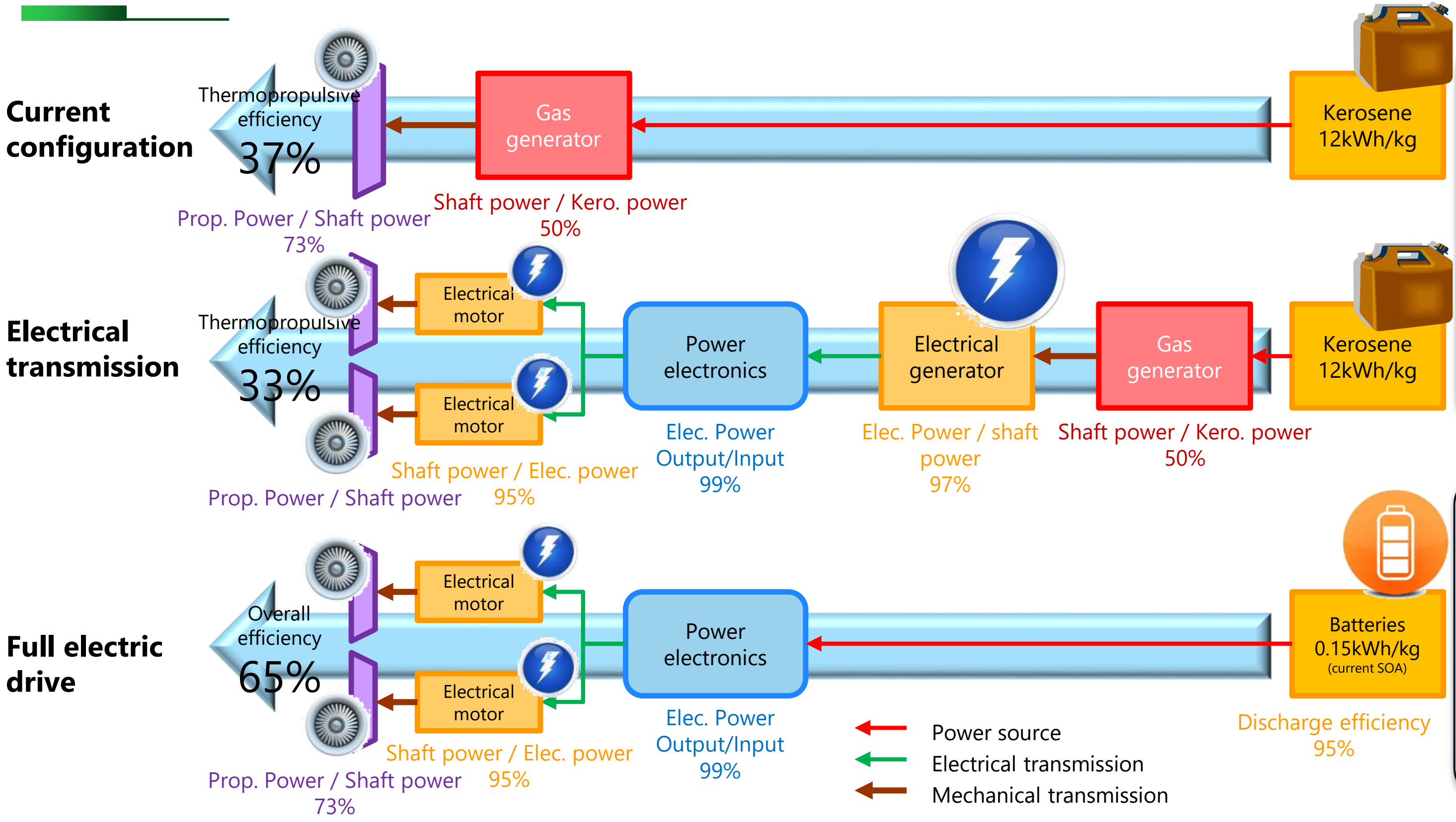
Distributed propulsion



Hybrid propulsion

- And any kind of combination of these 2 logics…
  - ➔ A joint investigation of these 2 concepts

Hybridization vs fully electric transmission ?



Interest for an indirect electrical transmission is low … unless « positive snowball effects » are found (opening of new turbomachinery sizing capabilities, alleviation of constraints, distributed propulsion …)

Full electric propulsion is unrealistic for « big » aircraft (> regional), because of **extemely low energy density** of electricity storage and conversion devices

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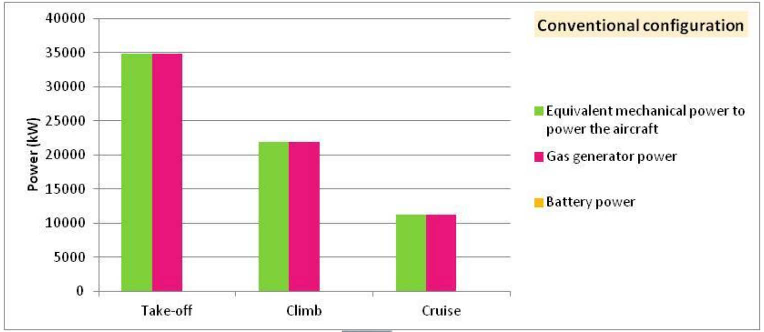
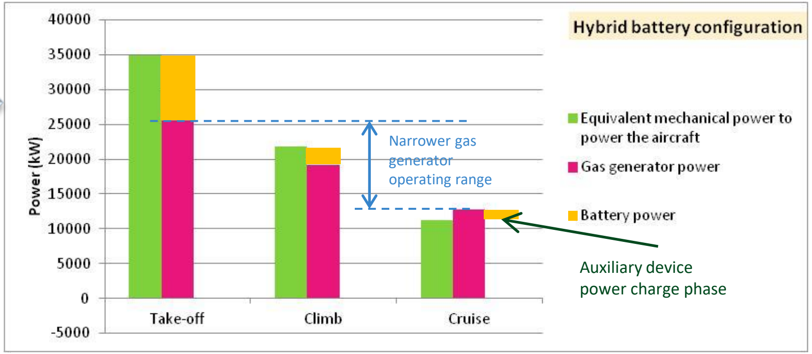
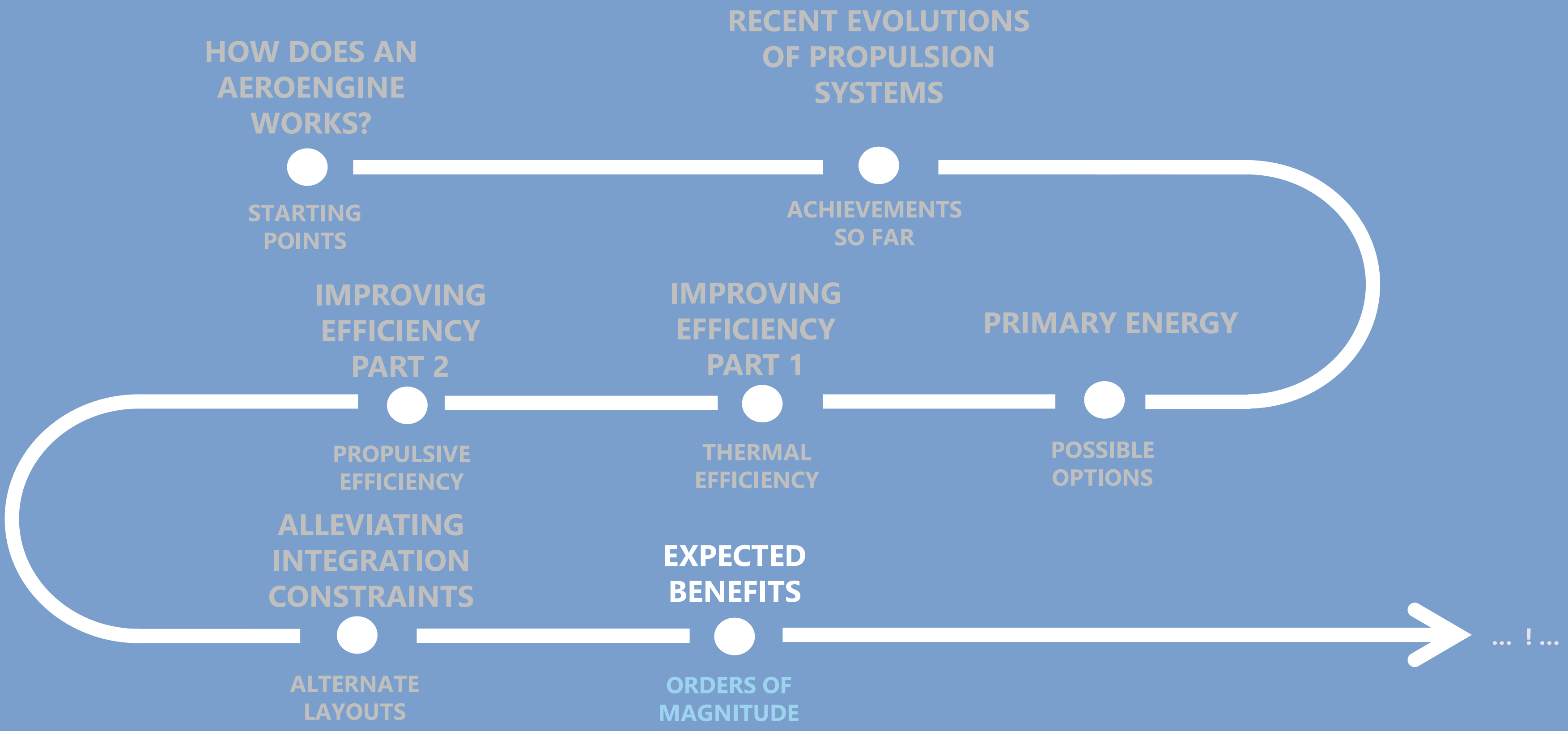
A global system approach to consider:
example of a constant operating point gas generator



- High energy expectation discrepancy between flight phases (range by 3.5)
- T/O is a sizing case, even if representing the shortest phase of the mission

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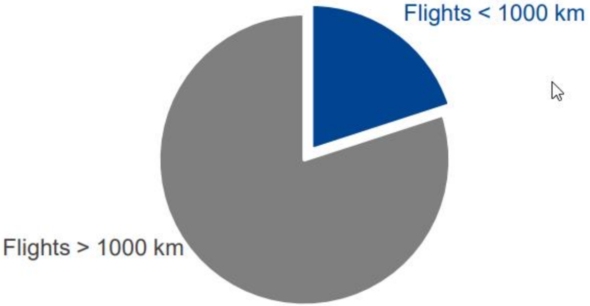
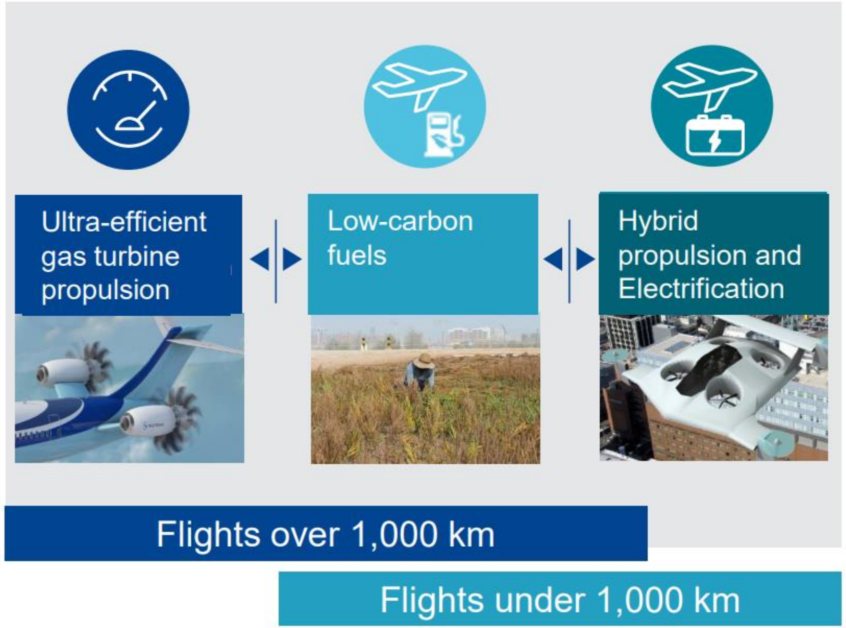
ORDERS OF MAGNITUDE
… ! …

Differenciated applicability of options

CO_2 emissions



Source : DLR/ Sabre 2014



Flights accounting for 80% of CO_2 emissions will largely continue to use combustion propulsion systems until at least 2040.

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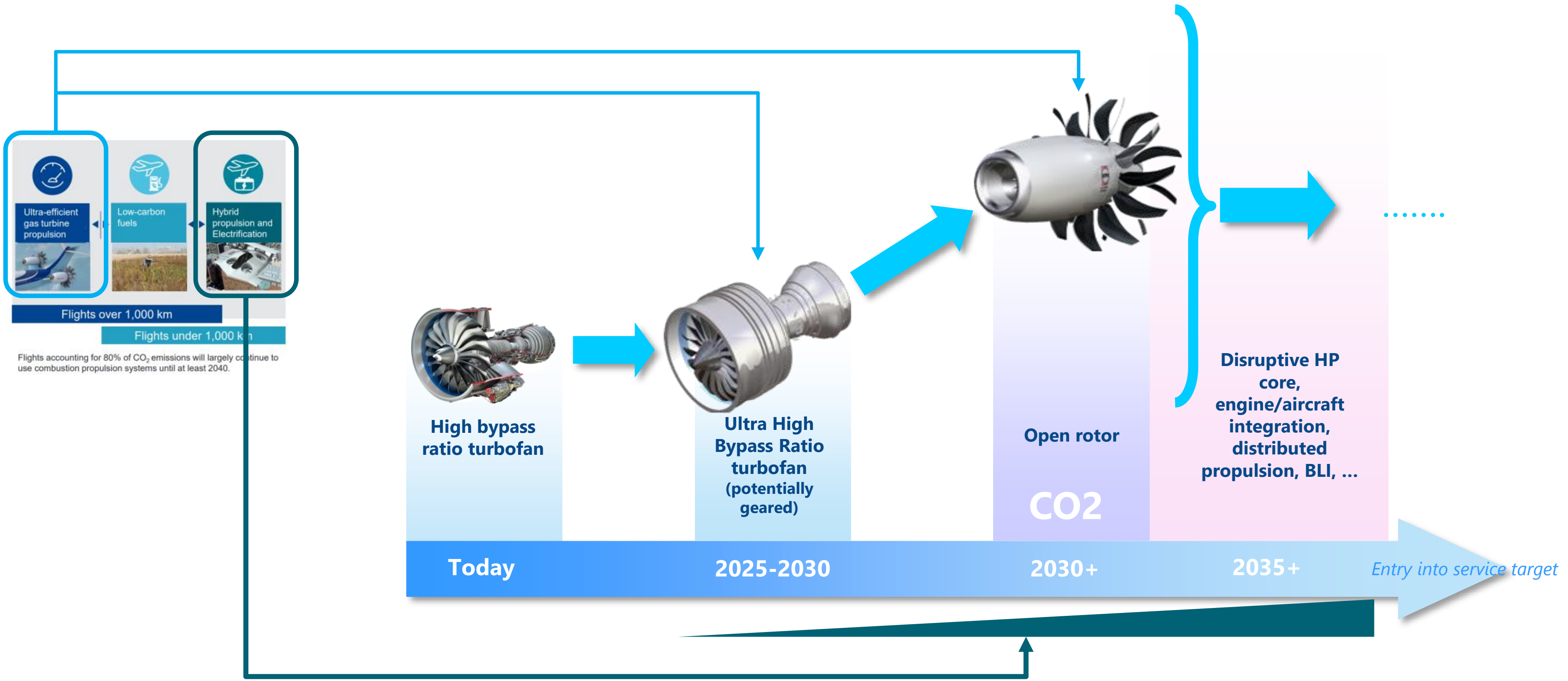
Future perspectives for Ultra efficient gas turbine propulsion



Alternate energies : hydrogen as a long term option,with synthetic and biofuels rise in the mid-term

Biofuels
Using conventional resources (biomass, waste, algae, etc.)

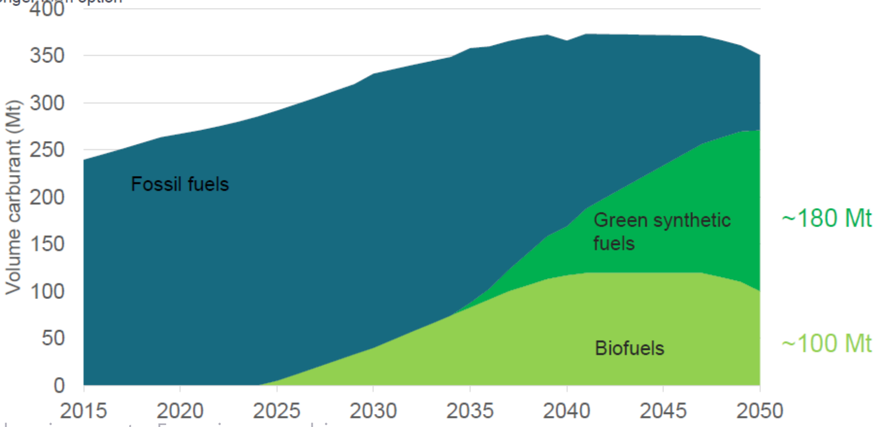
Green synthetic fuels
from decarbonated hydrogen

Existing aircraft and infrastructures

Liquid hydrogen

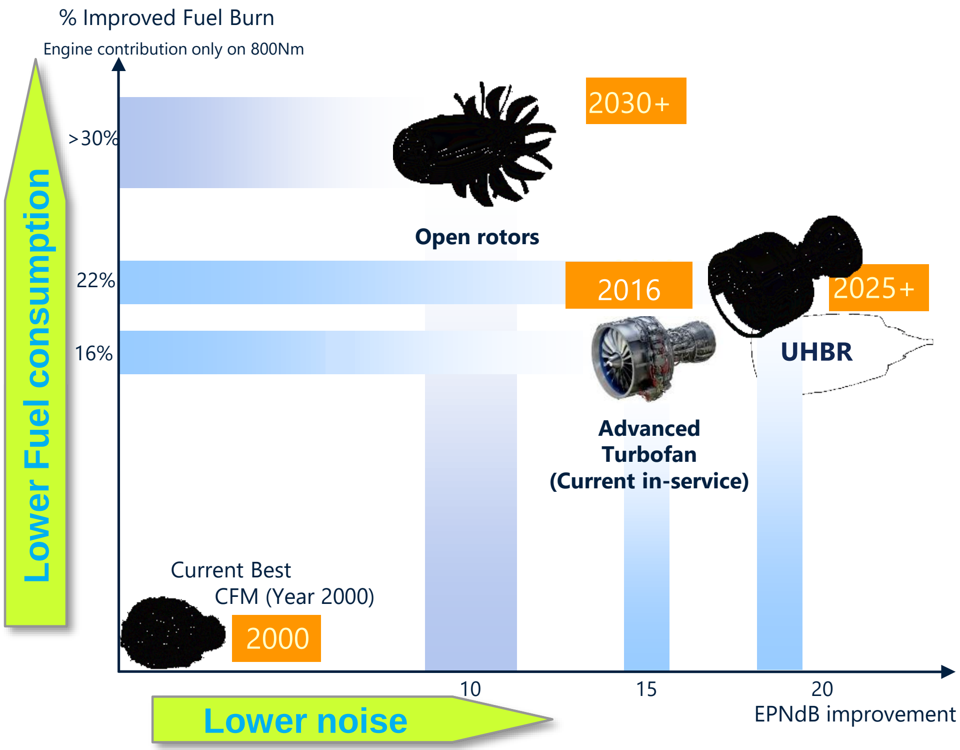
Disruptive aircraft, new infrastructures
→ Higher risk and longer term option

Flights accounting for 80% of CO_2 emissions will largely continue to use combustion propulsion systems until at least 2040.

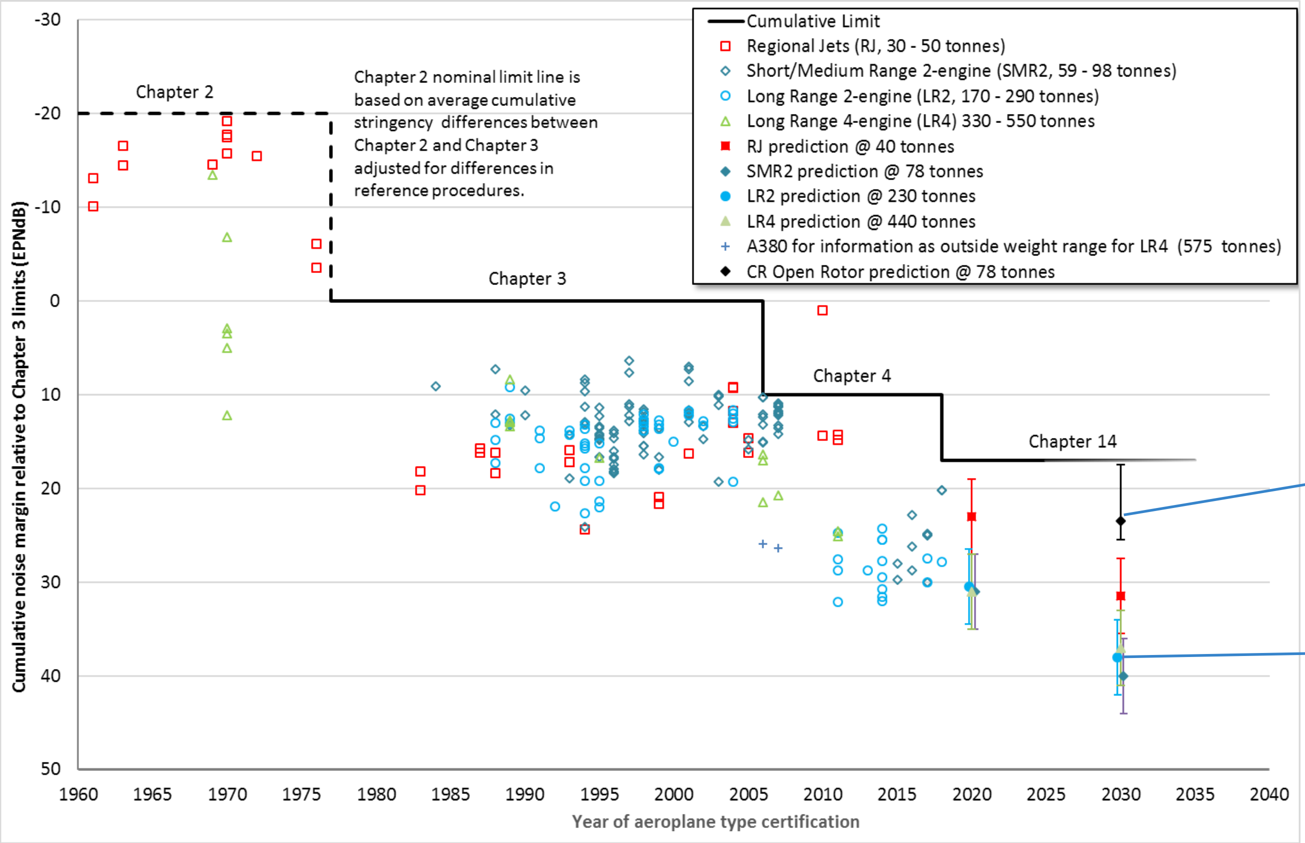


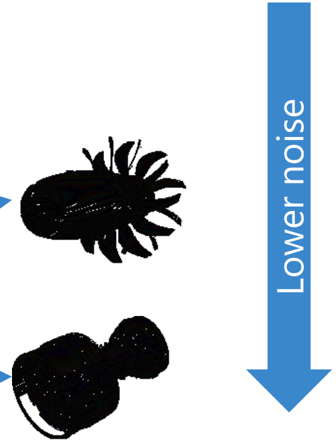
Current production of biofuels (mainly for cars): ~ 90 Mt

A few figures – Fuel burn vs noise

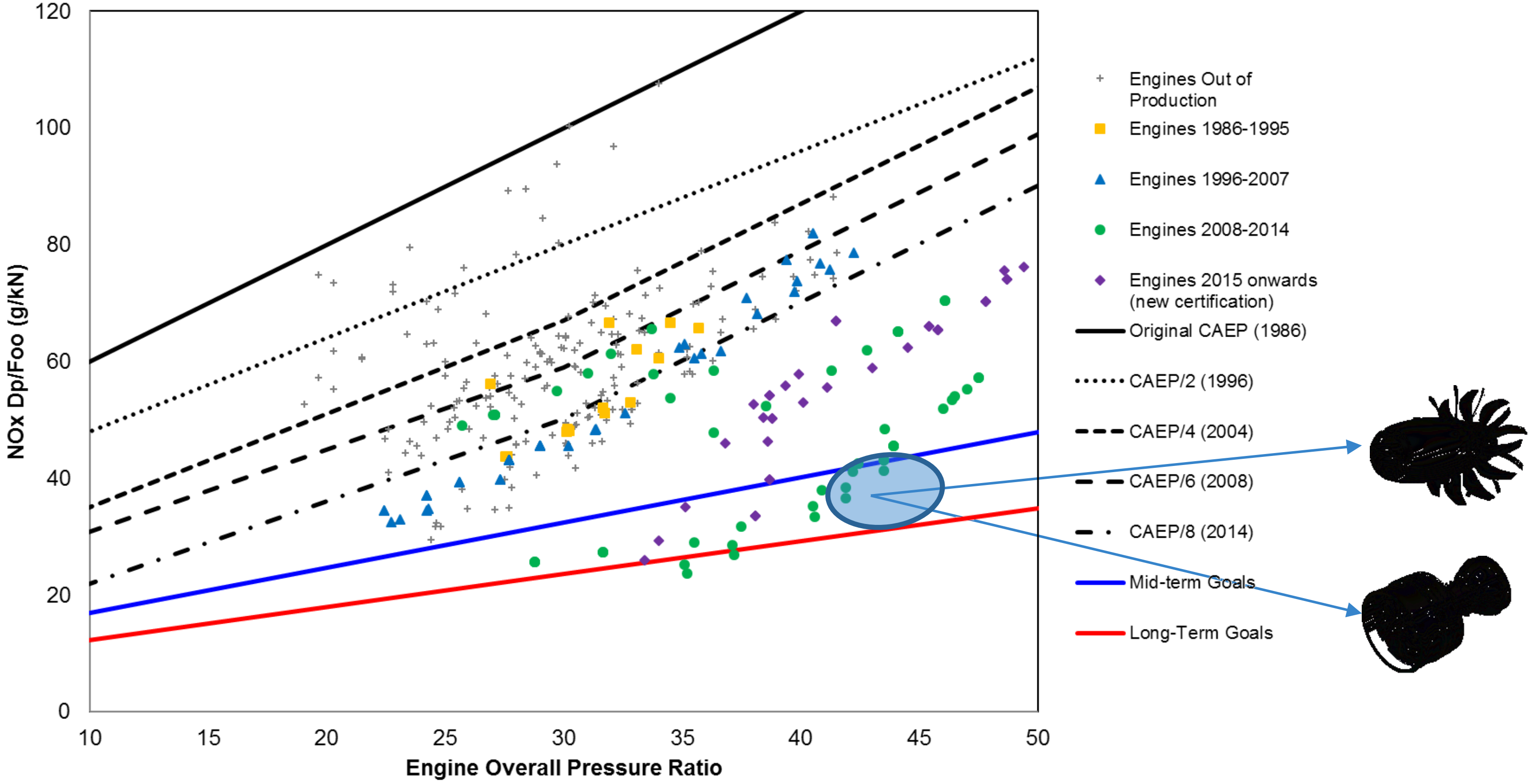


A few figures – Noise (vs certification limits)

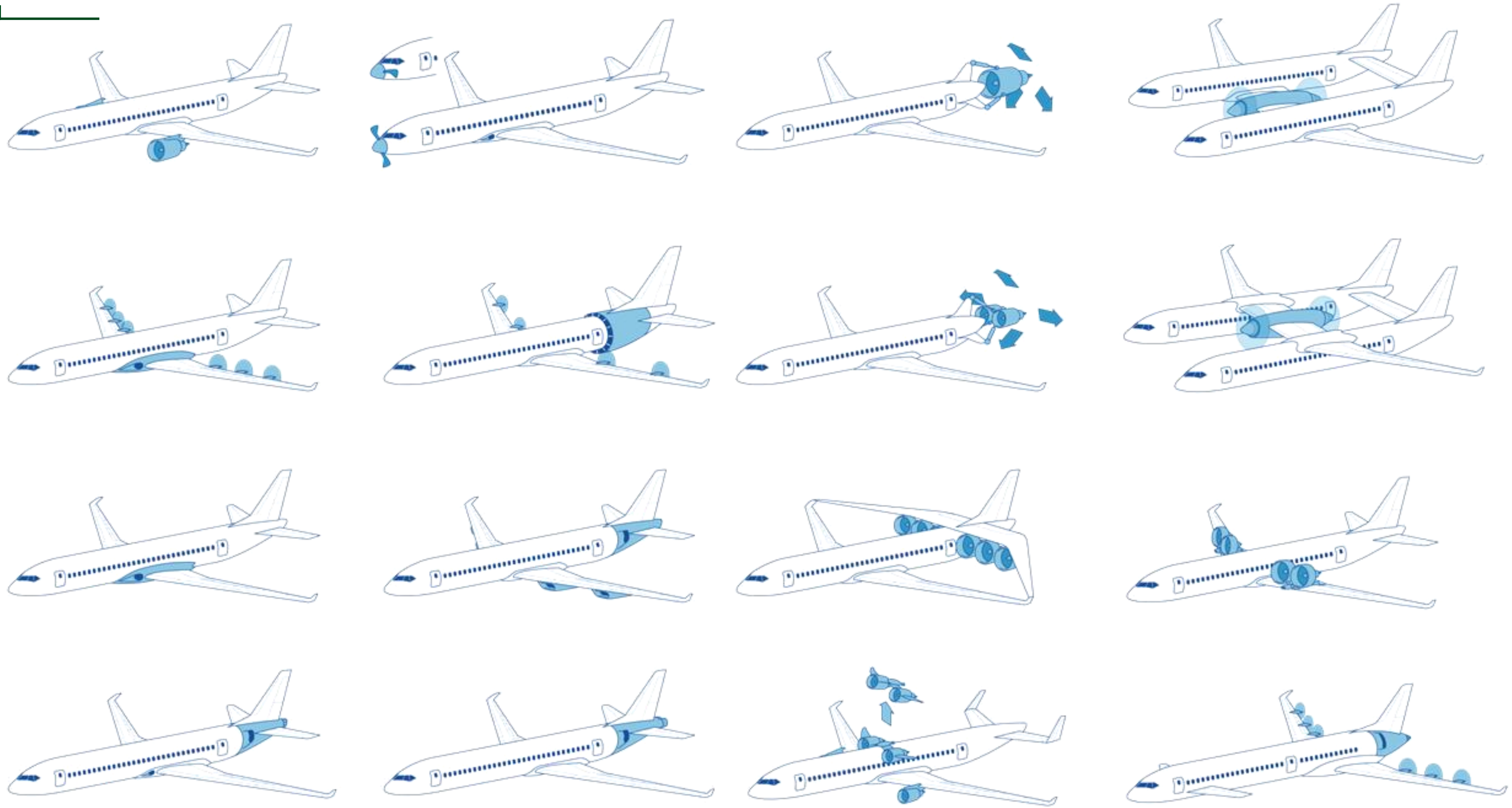




A few figures – NOx emissions (vs certification limits)



Which configuration for future aircraft platform ?



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