FT2025
SWEDISH AEROSPACE AT THE CROSSROADS
The 12th Swedish Aerospace Technology Congress
FT2025 in Stockholm
October 14-15, 2025

Instituto Tecnológico de Aeronáutica
Brazil

Technology Assessment of Sustainable Propulsion Systems in Aviation: Addressing Technical Challenges

Prof.Dr. Adson Agrico de Paula
Letícia Albergaria Oliveira

Stockholm, October 14

Summary

- Motivation
- Metodology
- Preliminary results
- Next steps
- Conclusion

Summary

- Motivation
- Metodology
- Preliminary results
- Next steps
- Conclusion

Motivation

- **Aviation faces a critical challenge**: balancing growth in air traffic with the urgent need to reduce carbon emissions.

- **Propulsion systems are central** to this transformation, they directly impact energy efficiency, fuel type compatibility, and environmental footprint.

- **Emerging technologies** such as hydrogen, hybrid-electric, and sustainable aviation fuels offer promising solutions, but each poses **technical integration challenges**.

- **A structured Technology Assessment (TA)** is essential to:
  - Evaluate technological readiness in realistic operational contexts
  - Guide investment and R&D priorities
  - Support policymaking and regulatory alignment

Objective of the Work

To develop a **Technology Assessment (TA) framework** capable of evaluating the **technical maturity**, **integration potential**, and **system-level performance** of emerging sustainable technology such as hydrogen, hybrid-electric, and sustainable aviation fuels within **realistic operational scenarios** for aviation.

The framework aims to:

- Support **evidence-based decision-making** in R&D and policy.
- Integrate **TRL, IRL, and SRL** metrics into a unified maturity evaluation.

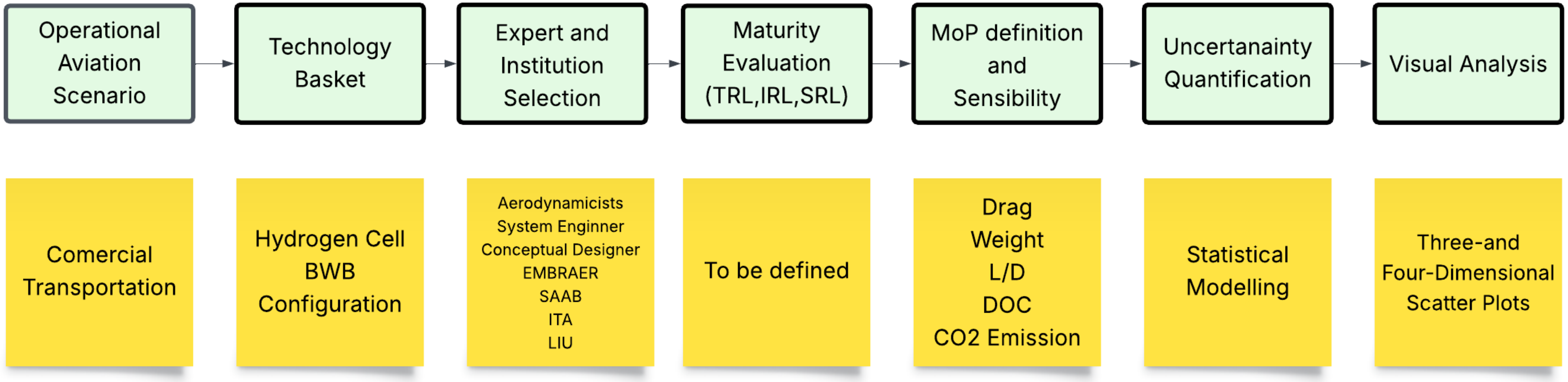
- Quantify **technical, economic, and environmental impacts** through **Measures of Performance (MoPs)**.

- Enable **visual analytics** for uncertainty and trade-off analysis among technologies.

Summary

- Motivation
- Metodology
- Preliminary results
- Next steps
- Conclusion

Technology Assessment Framework



Operational Aviation Scenario	Comercial Transportation
Technology Basket	Hydrogen Cell BWB Configuration
Expert and Institution Selection	Aerodynamicists System Enginner Conceptual Designer EMBRAER SAAB ITA LIU
Maturity Evaluation (TRL,IRL,SRL)	To be defined
MoP definition and Sensibility	Drag Weight L/D DOC CO2 Emission
Uncertanainty Quantification	Statistical Modelling
Visual Analysis	Three-and Four-Dimensional Scatter Plots

Technology Assessment Framework

- Operational Aviation scenario
- Technology portfolio definiton
- Selection of institutions and experts
- Maturity Evaluation: TRL, IRL, and SRL
- MoP definition and Sensibility
- Uncertainty Quantification
- Visual Analytics

Role of the Operational Scenario

Operational
Aviation
Scenario

Why defining the operational scenario matters

- The *Technology Assessment* begins by establishing a **clearly defined operational scenario**, which serves as the **context for all subsequent evaluations**.
- This step does **not yet define future technologies**, but **sets the operational boundaries** within which those technologies will later be compared.
- A well-characterized scenario allows the TA process to:
  - Identify realistic mission constraints (range, payload, energy demand).
  - Represent actual market and infrastructure conditions.
  - Ensure that technology comparisons are **consistent and meaningful**.

Key idea:

The scenario acts as a foundation that enables a more precise and credible selection of the technology basket in the next phase

Characterizing the Operational Scenario

Operational Aviation Scenario

Elements to be defined before technology selection

- **Mission profile:** range, flight phases, duration, frequency of operations.
- **Aircraft characteristics:** capacity, weight, cruise speed, and altitude.
- **Operational context:** type of mission (passenger, cargo), regional airports, environmental conditions.
- **Energy and logistics environment:** available fuel types, refueling infrastructure, supply chain maturity.
- **Economic and regulatory framework:** operating costs, taxes, incentives, carbon pricing.

Key idea:
Establish a **realistic reference environment** that constrains and guides the future *Technology Assessment*.

This ensures that, in the **next phase**, the **technology basket** is chosen within **credible operational limits**, maximizing relevance for design, policy, and sustainability analysis.

Purpose of the Technology Portfolio

Technology Basket

Why defining a technology portfolio matters

- The **technology portfolio** represents the **core of the conceptual phase** in sustainable aircraft design.
- It anticipates **which technological solutions** are most likely to create impact in the next decades.
- The process draws on **technology forecasting and foresight**, which systematically explore the long-term future of science, technology, and society to identify **emerging strategic domains.**
- Global agencies and programs (ICAO LTTG, NASA SFNP & N+3, FAA initiatives, EU Clean Aviation, IATA roadmaps) collectively shape this landscape by setting emission-reduction targets and technological priorities.

Key idea:

The portfolio defines the technological "universe" from which viable sustainable-aviation pathways will be filtered and prioritized.

Initial Selection of Sustainable Technologies

Technology Basket

Broad Scouting Phase

- Identify **all candidate technologies** across propulsion, fuels, materials, aerodynamics, and systems.
- Use **international roadmaps and scientific reviews** (ICAO, Clean Aviation, NASA, FAA, IATA) and **expert consultations** from academia and industry.
- Establish **minimum inclusion criteria**:
  - Direct link to sustainability (emission reduction, efficiency, noise, environmental impact)
  - Systemic relevance (impact on weight, drag, fuel burn, cost)
  - International recognition (appearing in official or peer-reviewed roadmaps)
  - Integration potential (across multiple aircraft types)
  - Evidence of ongoing R&D or demonstration activity

Key idea:

Build a comprehensive map of emerging technologies before filtering.

Filtering and Prioritization

Technology Basket

Narrowing the portfolio to the most viable technologies

- Apply refined criteria to ensure **scalability and realistic adoption** within a 40-year horizon:
  - **Minimum maturity:** TRL ≥ 3 today, plausible path to application by 2050
  - **Technological consolidation:** avoid immature or divergent variants
  - **Industrial scalability** and standardization potential
  - **Infrastructure feasibility:** renewable-based supply and logistics
  - **Regulatory alignment:** compatibility with ICAO-CORSIA, EU-ETS, Net Zero policies
  - **Economic + social co-benefits:** reduced noise, local air quality, green jobs

- This ensures that the resulting set represents **credible, system-ready technologies** for the next stages of TA: TRL/IRL/SRL evaluation and sensitivity analysis.

Key idea:
A structured two-step process, scouting and filtering, enables a focused, evidence-based technology basket for sustainable aviation.

Framework

- Operational Aviation scenario
- Technology portfolio definiton
- Selection of institutions and experts
- Maturity Evaluation: TRL, IRL, and SRL
- MoP definition
- Technology Performance and Sensibility
- Uncertainty Quantification
- Visual Analytics

Expert Selection Principles

Expert and Institution Selection

Why expert selection is critical

- The reliability of TRL–IRL–SRL evaluations fundamentally depends on the **quality, diversity, and governance** of the expert panel.
- Experts combine **technical specialization** and **systemic understanding**, ensuring balanced, realistic maturity assessments.
- The selection process is **structured to minimize bias** and ensure coverage across institutional and disciplinary domains.

- **Institutional domains represented:**
  - **Aerospace industry** – design, integration, operation, and maintenance.
  - **Academia and research centers** – technical depth and modeling expertise.
  - **Regulatory agencies** – certification, policy, and airworthiness oversight.
  - **Start-ups and innovation hubs** – early-stage R&D and experimental validation.

Key idea:
Diversity in institutional origin and expertise ensures convergence between technical feasibility and real-world applicability.

Structure and Governance of the Expert Process

Expert and Institution Selection

Expert classification and participation

- Two complementary roles:
  - **Specialists (E):** deep expertise in propulsion, aerodynamics, materials, energy storage, or systems.
  - **Generalists (G):** broad experience in system integration and conceptual design.
- Minimum coverage criteria per technology:
  - ≥ 16 active evaluators
  - ≥ 4 institutional domains
  - ≥ 2 specialists directly related to the topic
  - ≥ 1 regulatory representative (for safety-related techs)

- **Governance framework:**
  - ○ **Scientific coordination:** defines domains and supervises methodological integrity.
  - ○ **Process moderator:** manages anonymization and consensus iterations.
  - ○ **Data analyst:** performs statistical validation and cross-matrix verification.

Outcome:

A transparent, traceable, and consensus-driven maturity evaluation combining specialist accuracy with system-level coherence.

Maturity Evaluation: TRL, IRL and SRL

Maturity
Evaluation
(TRL,IRL,SRL)

Technology Inputs

- Each technology has an individual **TRL (Technology Readiness Level)** how mature it is.
- The **IRL (Integration Readiness Level)** measures how well two technologies are understood and tested **together**.

Inputs:

$$[TRL]\ n\times 1 \quad \text{and} \quad [IRL]\ n\times n$$

Compute the SRL for Each Technology in the System

- For every combination (*technology vector t*), the local SRL is computed by:

$$[SRL]_{n\times 1}=[norm]_{n\times n}\times[IRL]_{n\times n}\times[TRL]_{n\times 1}$$

This gives the **SRL_i** for each technology *within* that specific combination, reflecting its own maturity **plus** its integration with the others.

Compute the Composite SRL for the Technology Vector

$$SRL_{composite} = \frac{1}{n}\sum_{i=1}^{n}\frac{SRL_i}{m_i}$$

Weighted average considering how many interfaces (m_i) each technology has.
Produces **a single SRL value for the entire combination** (the "system maturity").

Purpose of Measures of Performance (MoPs)

Why MoPs are essential in Technology Assessment

- MoPs quantify **how each technology or cluster affects system-level performance** in the conceptual design phase.
- Extend beyond classical indicators such as aerodynamic to include **economic** and **environmental** dimensions.
- Enable a **multi-domain evaluation** of technology impact, supporting trade-offs between performance, cost, and emissions.
- Serve as the **link between TRL/IRL/SRL evaluation and system-level performance metrics**.

- **Key idea:**
  MoPs transform qualitative maturity assessment into quantitative, sustainability-oriented system evaluation.

TASA
TECHNOLOGY ASSESSMENT
SUSTAINABLE AVIATION

Technical, Economic and Environmental MoPs

MoP definition
and
Sensibility

Technical MoPs

- Lift-to-drag ratio (L/D), Thrust-to-weight (T/W), Power-to-weight (P/W)
- Specific fuel or energy consumption (SFC / SEC)
- Empty weight ratio (W_e/MTOW)
- Energy Conversion Efficiency (ECE)

Economic MoPs

- Direct Operating Cost (DOC)
- Energy cost per passenger-km (CE)

Environmental MoPs

- CO_2, NO_x, and H_2O emissions (WTT + TTW)
- Lifecycle emission intensity (ELCA)
- Equivalent CO_2 per MJ of delivered energy
- Noise and air quality índices

Key message:

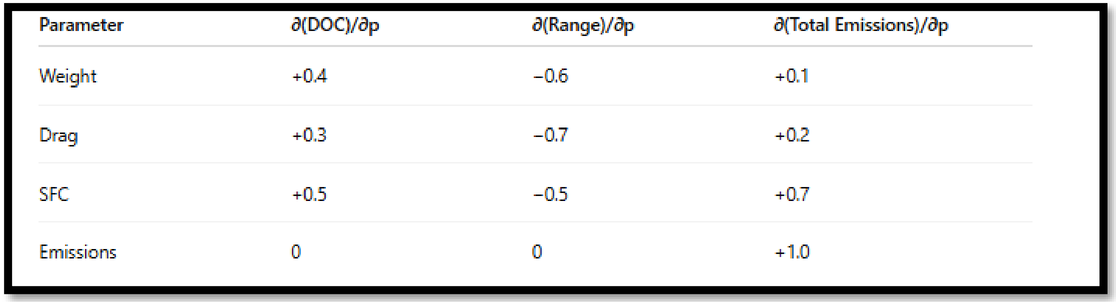
Together, these domains ensure a holistic view of sustainability in aircraft technology assessment.

Integration of MoPs within the Framework

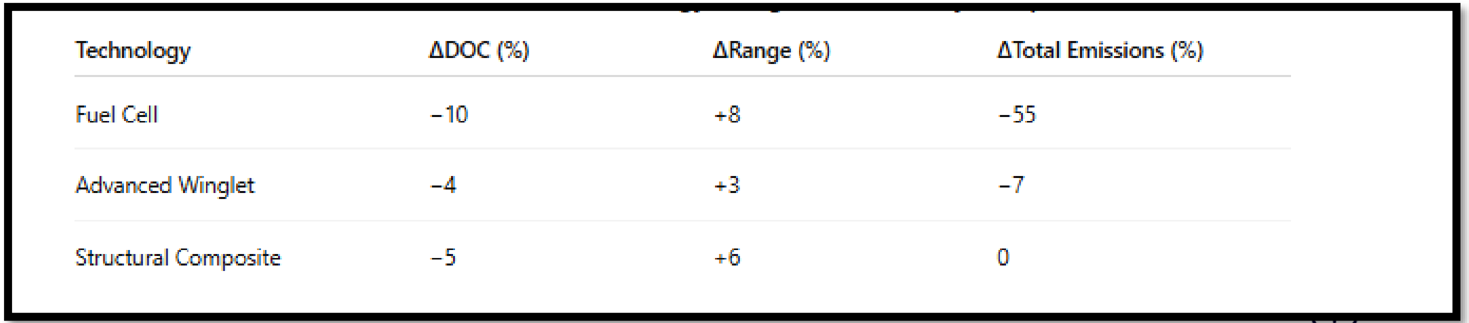
MoP definition and Sensibility

Computation and Use in the TA Framework

- Effects of each technology $[E]$propagated to system characteristics via sensitivity matrices:
- $[\Delta Eff] = [E] \times [S]$
- Produces a **quantitative link** between technological inputs and system-level responses.
- MoP:
  - Range
  - Cost
  - Emission



Parameter	∂(DOC)/∂p	∂(Range)/∂p	∂(Total Emissions)/∂p
Weight	+0.4	−0.6	+0.1
Drag	+0.3	−0.7	+0.2
SFC	+0.5	−0.5	+0.7
Emissions	0	0	+1.0



Technology	ΔDOC (%)	ΔRange (%)	ΔTotal Emissions (%)
Fuel Cell	−10	+8	−55
Advanced Winglet	−4	+3	−7
Structural Composite	−5	+6	0

Key idea:

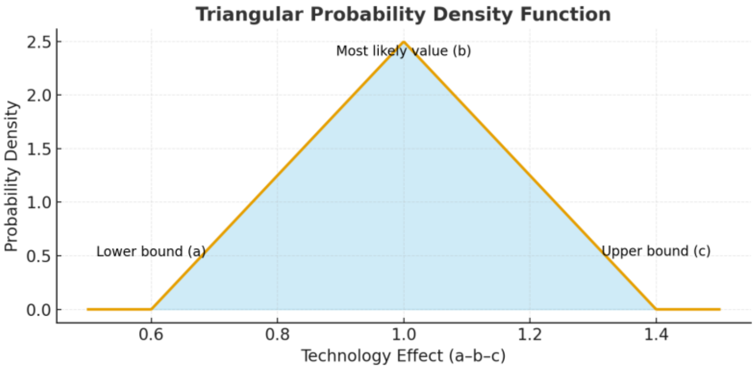
MoPs enable objective ranking of technologies under sustainability-driven criteria.

Uncertainty Quantification

Uncertanainty Quantification

Identification & Classification

- **Aleatory uncertainty:** inherent variability
- **Epistemic uncertainty:** lack of knowledge, reducible via experiments or maturation.
- **Focus:** epistemic uncertainty in predicted technology effects.



Characterization

- Represented by **Probability Density Functions (PDFs)** → usually **triangular** *(a: lower, b: most likely, c: upper)*.
- Each technology effect modeled as:
- $[E_\sigma]_{n\times p\times 3} = (a, b, c)$

Reduction

- Reducing **epistemic uncertainty** → via **technology maturation** (increasing TRL).
- Higher TRL → narrower PDF → smaller performance variability.

- **Key idea***:*
  To account for variability and lack of knowledge in estimating technology impacts, ensuring **uncertainty-informed decision-making** in technology portfolio selection.

Visual Analytics

Visual Analysis

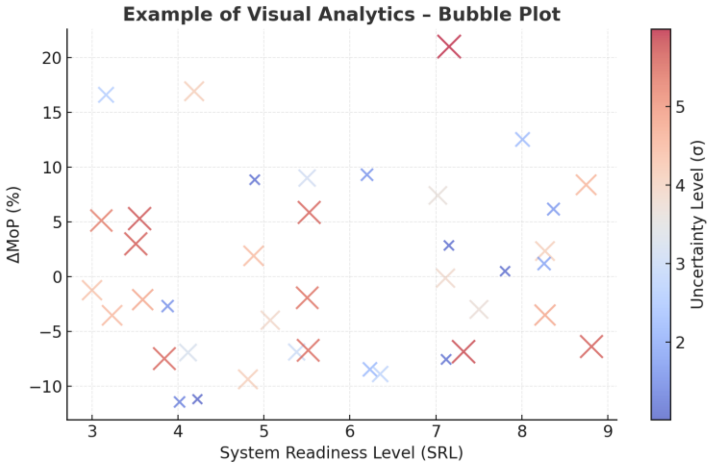
Role in the Framework

- Bridges the gap between **quantitative data** (UQ results, SRL, MoPs) and **qualitative decision-making**.
- Enables understanding of **trade-offs, robustness, and interdependencies** among technologies.
- Supports **interactive exploration** of technology combinations and performance metrics.

Main Techniques

- Bubble Plots

- 3D or 4D scatter plots where:
  - **X-axis:** SRL
  - **Y-axis:** ΔMoP (%)
  - **Color (Hue):** percentile (e.g., 80th)
  - **Bubble size:** standard deviation → *robustness measure*
- Show uncertainty effects and highlight **Robust Pareto** solutions.



- Parallel Coordinates Plots (PCP)

- Visualize **multi-objective relationships** among SRL, technology IDs, and MoPs.
- Each **polyline = one technology vector** (combination).
- **Dynamic filtering** enables selection by thresholds (e.g., SRL ≥ 0.5 or $\Delta \text{MoP}_3 \leq -15\%$).
- Identifies **patterns, trade-offs, and correlations**.

Impact

- Provides **intuitive visualization** of large, multidimensional datasets.
- Enables **robust decision-making under uncertainty**.
- Facilitates **communication** between analysts, engineers, and decision-makers.

Key idea*:*
To support **human reasoning and decision-making** through visual representations that make high-dimensional data interpretable in the technology portfolio selection process.

Sumário

- Motivation
- Metodology
- Preliminary results
- Next steps
- Conclusion

Aviation Operational Scenario

Establishing a realistic environment for technology assessment

Mission Profile

- Range: ~800nm –1,300 nm
- Duration: < 2 hours
- Frequency: high (multiple daily flights)
- Phases: taxi, climb, cruise, descent, landing (short sectors)

Reference Aircraft

Feature	ATR 72	Dash 8 Q400
Passenger Capacity	70–78	~74
Range	~800 nm	~1300 km
Cruise Speed	~510 km/h	~667 km/h
Use Case	Efficient regional routes	Higher-speed regional operations

Operational Context

- Type of mission: passenger transport
- Airports: regional, some with limited infrastructure
- Environmental conditions: variable (tropical to subtropical)
- Ground time: short turnaround (~30 min)

Energy & Logistics Environment

- Fuel: Jet-A1
- Refueling infrastructure: basic, with potential for adaptation
- Supply chain: mature for conventional fuels

Economic & Regulatory Framework

- Incentives for low-emission aviation
- National and regional carbon pricing mechanisms
- Infrastructure and operation cost sensitivity

💡 Key idea

A clearly defined regional operational scenario based on ATR 72 and Dash 8 Q400 provides a credible, constrained environment for assessing future propulsion and energy technologies, supporting decisions grounded in realistic technical, economic, and infrastructure conditions.

Technology Basket

Technology Selection Process

The definition of the technologies was carried out in **two complementary phases**, both conducted by **specialists and generalists from the Aeronautics Institute of Technology (ITA)**:

Phase 1 – Selection: identification of candidate technologies across different aviation domains, based on literature reviews and international research roadmaps.

Phase 2 – Filtering: analysis and consolidation of the selected of **45 technologies**, resulting in the final set presented in this study.

	Tecnology Readiness Level	
Architecture	Pure hydrogen engine	t1
	Ethanol engine	t2
	Kerosene Engine / Hydrogen Cell	t3
	Hydrogen Engine / Hydrogen Cell	t4
	Battery / Hydrogen Cell	t5
	Battery / Kerosene Engine	t6
Aerodynamics & Configurations	Configuration – BWB	t7
	Configuration – Box Wing	t8
	Configuration – High Aspect Ratio Wings	t9
	Active Flow Control	t10
	Boundary Layer Ingestion – BLI	t11
	Distributed Electric Propulsion	t12
Propulsion	Hydrogen Engine	t13
	Hydrogen Cell	t14
	Battery	t15
	Ethanol Engine	t16
	Electric Engine	t17
Storage	GH_2 Tank	t18
	Cryogenic LH_2 Tank	t19
	Structural LH_2 Tank	t20
	Non-structural LH_2 Tank	t21
	Solid Hydride Metal Storage	t22
	Liquid Ammonia + On-board Cracking	t23
	Liquid ethanol + onboard cracking	t24
	Solid-state Li-metal battery	t25
Structures & Materials	Auxetic Structures (CA – Auxetic)	t26
		t27
	Multiscale Structures (CA – Multiscale)	t28
	Graphene Structures (CA – Graphene)	t29
	Carbon Fiber Thermoplastic Composites (CA – Carbon Fiber Thermoplastic Composites)	t30
	Aluminum–Lithium Alloys (Al–Li)	t31
Thermal Management Systems	Liquid Cooling Systems	t32
	Air Cooling Systems	t33
	Skin Heat Exchangers	t34
	Passive systems	t35
	Pump two phase systems	t36
	Phase Change Material (PCM) for batteries	t37
	Absorption refrigerator	t38
	Thermoelectric effects	t39
	Vortex tube	t40
	Thermionic energy converter	t41
	Joule-Thomson effect	t42
	Caloric materials	t43
	Thermoacoustic heat engines	t44
	Cryo-cooling systems	t45

TRL evaluation

TRL Evaluation and Convergence Process

- The maturity evaluation was conducted through a **convergence cycle** involving **specialists and generalists from the Aeronautics Institute of Technology (ITA)**.
- All evaluators assigned maturity levels independently, and **collective rounds were repeated until at least 75% agreement was achieved** for each technology.
- This **75% consensus threshold** ensured convergence between domain expertise and system-level perspectives, resulting in a **robust and representative final evaluation**.

	Tecnology Readiness Level		TRL
Architecture	Pure hydrogen engine	t1	4
	Ethanol engine	t2	4
	Kerosene Engine / Hydrogen Cell	t3	4
	Hydrogen Engine / Hydrogen Cell	t4	4
	Battery / Hydrogen Cell	t5	5
	Battery / Kerosene Engine	t6	4
Aerodynamics & Configurations	Configuration – BWB	t7	4
	Configuration – Box Wing	t8	4
	Configuration – High Aspect Ratio Wings	t9	4
	Active Flow Control	t10	3
	Boundary Layer Ingestion – BLI	t11	6
	Distributed Electric Propulsion	t12	4
Propulsion	Hydrogen Engine	t13	4
	Hydrogen Cell	t14	6
	Battery	t15	4
	Ethanol Engine	t16	4
	Electric Engine	t17	4
Storage	GH_2 Tank	t18	4
	Cryogenic LH_2 Tank	t19	6
	Structural LH_2 Tank	t20	5
	Non-structural LH_2 Tank	t21	4
	Solid Hydride Metal Storage	t22	5
	Liquid Ammonia + On-board Cracking	t23	4
	Liquid ethanol + onboard cracking	t24	4
	Solid-state Li-metal battery	t25	4
Structures & Materials	Auxetic Structures (CA – Auxetic)	t26	4
		t27	5
	Multiscale Structures (CA – Multiscale)	t28	6
	Graphene Structures (CA – Graphene)	t29	5
	Carbon Fiber Thermoplastic Composites (CA – Carbon Fiber Thermoplastic Composites)	t30	7
	Aluminum–Lithium Alloys (Al–Li)	t31	7
Thermal Management Systems	Liquid Cooling Systems	t32	7
	Air Cooling Systems	t33	7
	Skin Heat Exchangers	t34	7
	Passive systems	t35	7
	Pump two phase systems	t36	7
	Phase Change Material (PCM) for batteries	t37	5
	Absorption refrigerator	t38	3
	Thermoelectric effects	t39	3
	Vortex tube	t40	2
	Thermionic energy converter	t41	2
	Joule-Thomson effect	t42	2
	Caloric materials	t43	2
	Thermoacoustic heat engines	t44	2
	Cryo-cooling systems	t45	3

MoP

Technical MoPs

- Lift-to-drag ratio (L/D), Power-to-weight (P/W)
- Specific fuel (SFC)
- Empty weight ratio (W_e/MTOW)
- Energy Conversion Efficiency (ECE)

Economic MoPs

- Direct Operating Cost (DOC)
- Energy cost per passenger-km (CE)

Environmental MoPs

- CO_2, NO_x, and H_2O emissions (WTT + TTW)
- Equivalent CO_2 per MJ of delivered energy
- Noise (dB)

Sumário

- Motivation
- Metodology
- Preliminary results
- **Next steps**
- Conclusion

Next steps

- **Finalize and validate with experts**
  Complete the internal evaluation and convergence process with **specialists and generalists from ITA** to ensure methodological robustness.

- **Engage key stakeholders**
  Invite **universities, regulatory agencies, industry partners, and startups** to participate in a **joint validation cycle**, expanding the assessment collaboratively.

- **Collaborative alignment**
  Partners will review and refine the integration process collectively, incorporating cross-institutional perspectives.

- **Prepare results for dissemination**
  Consolidate findings for **presentation at the 2026 AIAA Aviation Forum**.

Sumário

- Motivation
- Metodology
- Preliminary results
- Next steps
- Conclusion

Conclusion

- The **Technology Assessment framework** enables a structured evaluation of **sustainable technologies for aviation**.

- The process integrates **technical, economic, and environmental dimensions**, ensuring realistic assessment within operational scenarios.

- The **convergence cycle** with specialists and generalists guarantees methodological consistency and credible maturity evaluation.

- The **preliminary validation at ITA** builds **awareness and readiness** for the next collaborative phase with universities, industry, and agencies.

- The process provides an **opportunity for rational convergence between research and industry**, fostering a **holistic vision of sustainable technologies** and supporting **strategic decisions for society**.