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Scalability **I**nvestigation of hybrid **E**lectric concepts for **N**ext-generation **A**ircraft

Clean Sky 2 – Thematic Topic

SIENA: Overview and preliminary results

CHYLA Project Workshop – February 15, 2023

Collins Aerospace

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PROJECT OVERVIEW

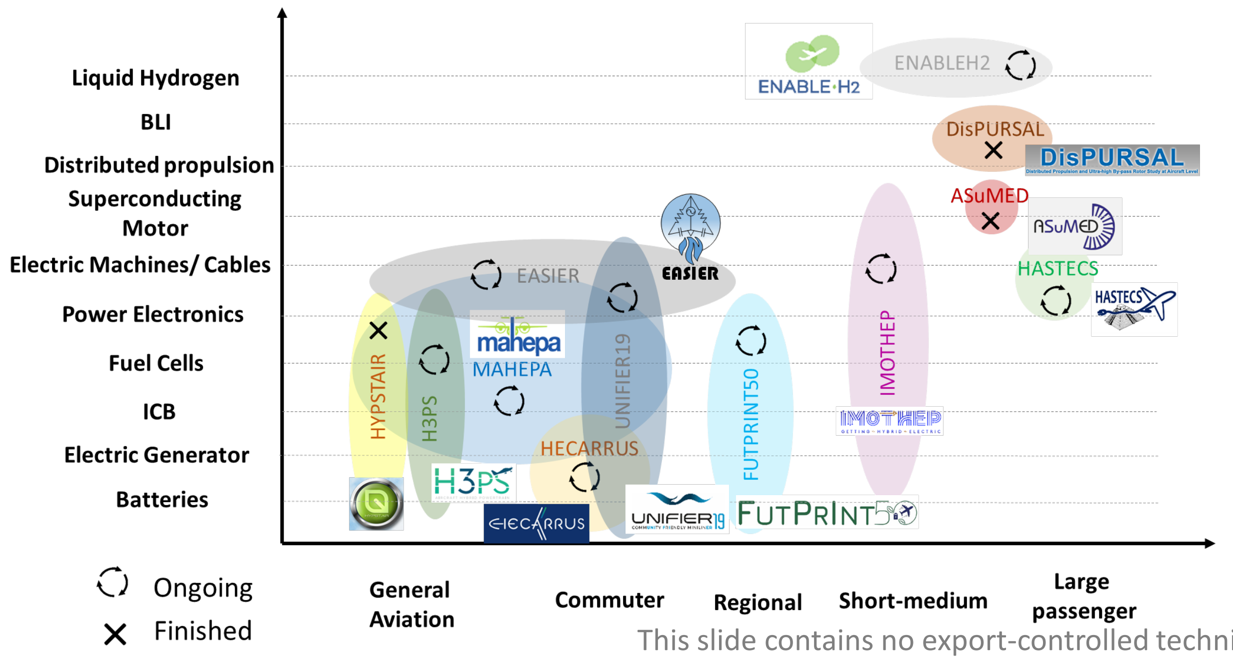
Project Overview: Motivation

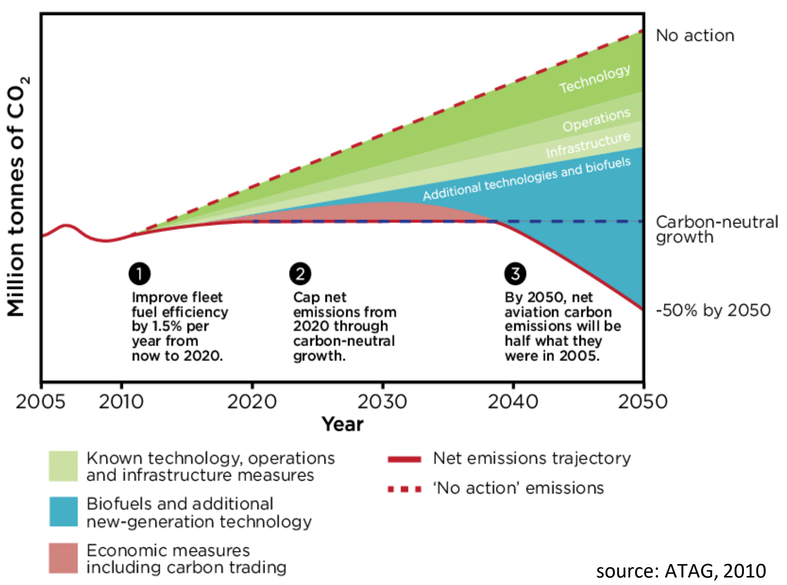
Aviation need: ***Accelerate the development*** *of non-polluting propulsion technologies*

What: **Transfer and build upon experience** from small aircraft towards large aircraft

"Given a vehicle class, can a less optimal architecture or technology trade-off enable scalability across multiple architectures?"

Why: the aviation sector is focusing on designing solutions to achieve emission goals for single A/C classes and operational concepts, resulting in multiple configurations developed in parallel.





source: ATAG, 2010

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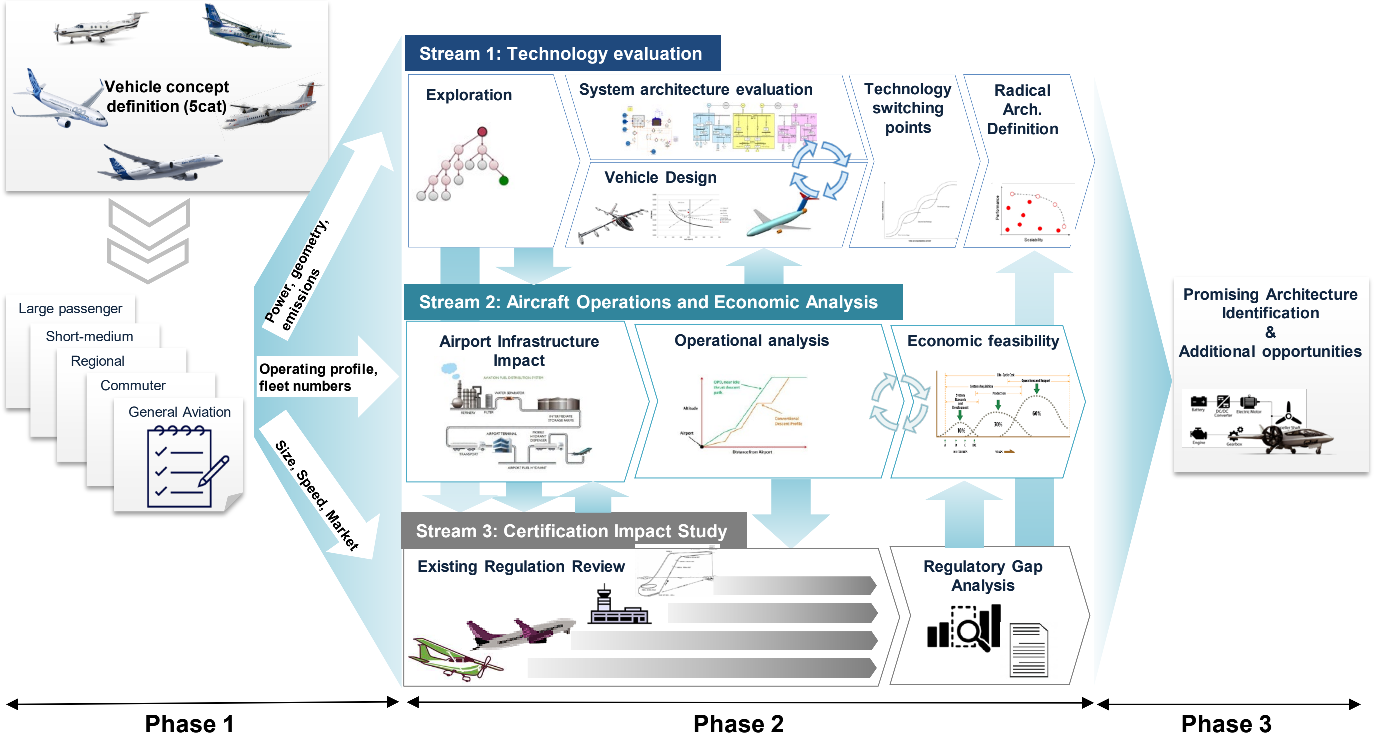
Project Overview: Ambition & Overall Concept

Ambition: accelerate the hybridization/electrification of the propulsion system through the identification of ***scalable-by-design*** architectures to support the achievements of all the CS2 high level goals.

When: February 2021 – July 2023

How:

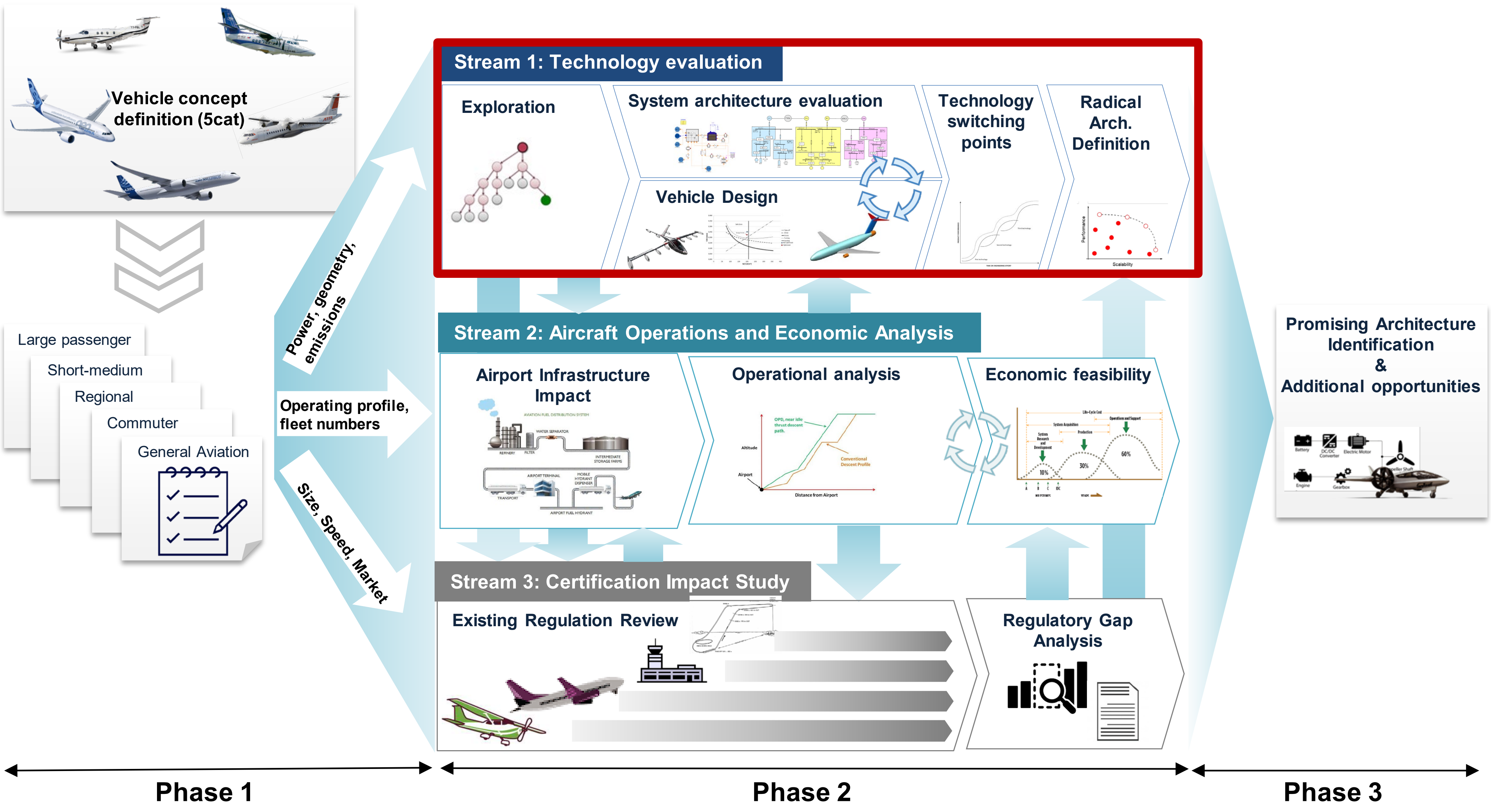


SIENA KPI	SIENA Target
Carbon-based fuel burned	-100% for General Aviation
Operational emissions	-80% for General Aviation
Life cycle cost	-5% for commuter
Entry into service	-20% reduction in time for passenger A/C
Design space size	+50% increase in technology options considered
Cross A/C categories technologies identified	Identification of 5 component technologies per category jump
Regulatory recommendations	3 or more recommendations extended per regulatory part

Consortium: Collins Aerospace Applied Research & Technology, Politecnico di Milano, EASA (3rd party)

External Advisory Board: Pratt & Whitney, Leonardo Aircraft, Piaggio Aerospace, Pipistrel Vertical Solutions, Air Dolomiti

Project Overview: Technical Approach



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TOOLS & METHODS

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HYPERION (**HY**brid **PER**formance Simulat**ION**) – Process

Inputs from system architecture evaluation

- On-board system weights
- Power penalties/benefits from detailed system modeling

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Sizing strategy

1. Design mass breakdown
2. Sizing mission simulation
3. Correction of initial guess
4. Sized aircraft

Modelling methods

- Design mass breakdown:
  - Airframe: historical regression corrected to account for innovation
  - Payload: user input
  - Propulsive components: physical modelling
- Sizing mission simulation: Flight mechanics equations

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HYPERION – Inputs

TLAR
- Payload
- Range
- TOFL
- Cruise speed
- Rate of climb
- Applicable CS

Adopted from baseline aircraft

Configuration
- Propulsion
  - Energy source
  - Series
  - Jet/TP
- Number of engines
- Pressurized cabin (Y/N)

Most suitable technology

Aerodynamics
- Aspect ratio
- C_L (clean, TO, max.)
- C_{D0} (clean, TO, LND)

Adopted from baseline aircraft

Propulsive components
- Batteries (spec. power & energy)
- Fuel cell/ICE (spec. power, efficiency modelling)
- Electric motor (spec. power, efficiency)
- Jet/TP (thermodynamic cycle)

Values from literature
- State-of-the-art values
- Expectation for the future (conservative & optimistic)

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System Architecture Evaluation– Process

Inputs from vehicle design

- Aircraft geometry
- Aircraft weights
- Mission profile
- Fuel burn

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Sizing strategy

1. Set systems architecture
2. Set model fidelity
3. Set technology choice
4. Get a/c-level inputs
5. Calculate power system
6. Analyze results

Power system model

- Power sinks
- Fuel pump
- Hydraulic power sys
- Pneumatic power sys
- Mechanical power sys
- Electric power sys
- Primary power sources

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Tools & Methods: System Architecture Evaluation

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System Architecture Evaluation– Subsystem Models

Fidelity ↑

	Hotel loads	Wing IPS	Cowl IPS	ECS	FC Act	LG Act	Fuel pump	Hydraulic	Pneumatic	Electric	Mechanical	Thermal	Engine	APU
Detailed				Thermal platform	Actuator platform	LGS platform publ. domain				Electrical architecture		Thermal platform	Engine model	
Parametric	Internal model	Public domain	Public domain	Public domain	Case study		Internal model	Internal model	Internal model	Internal model	Internal model			
Data load	Internal data	Internal data	Internal data	Internal data	Internal data Case study	Internal data						Internal data	Internal data	Internal data

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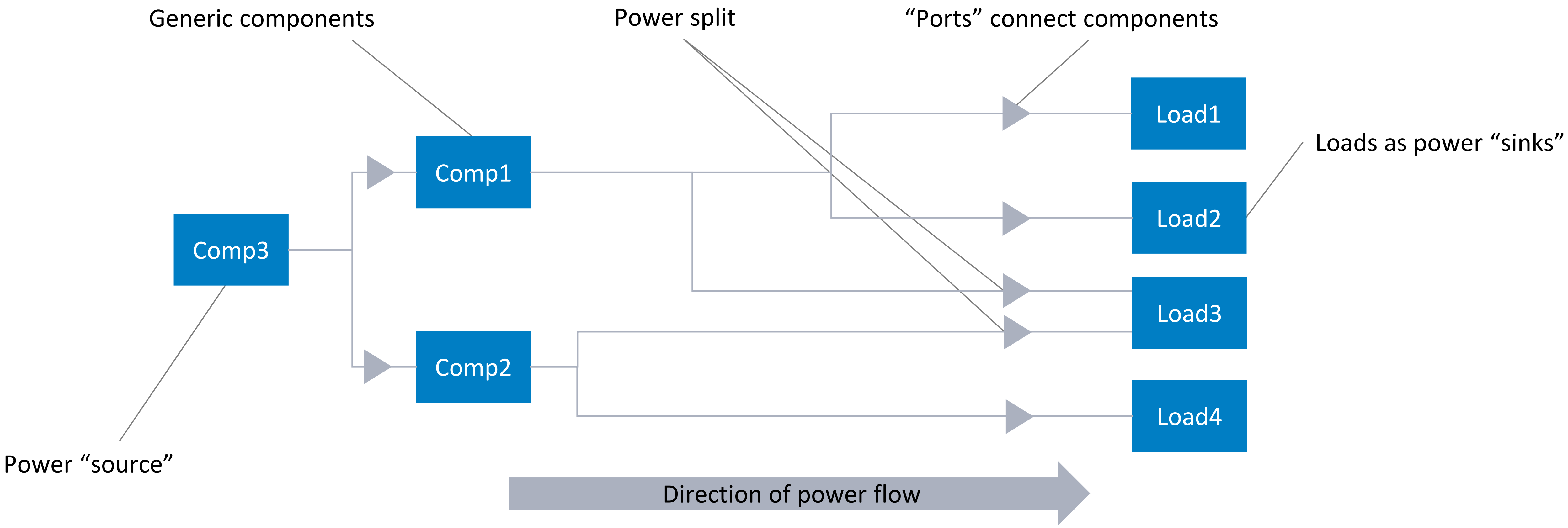
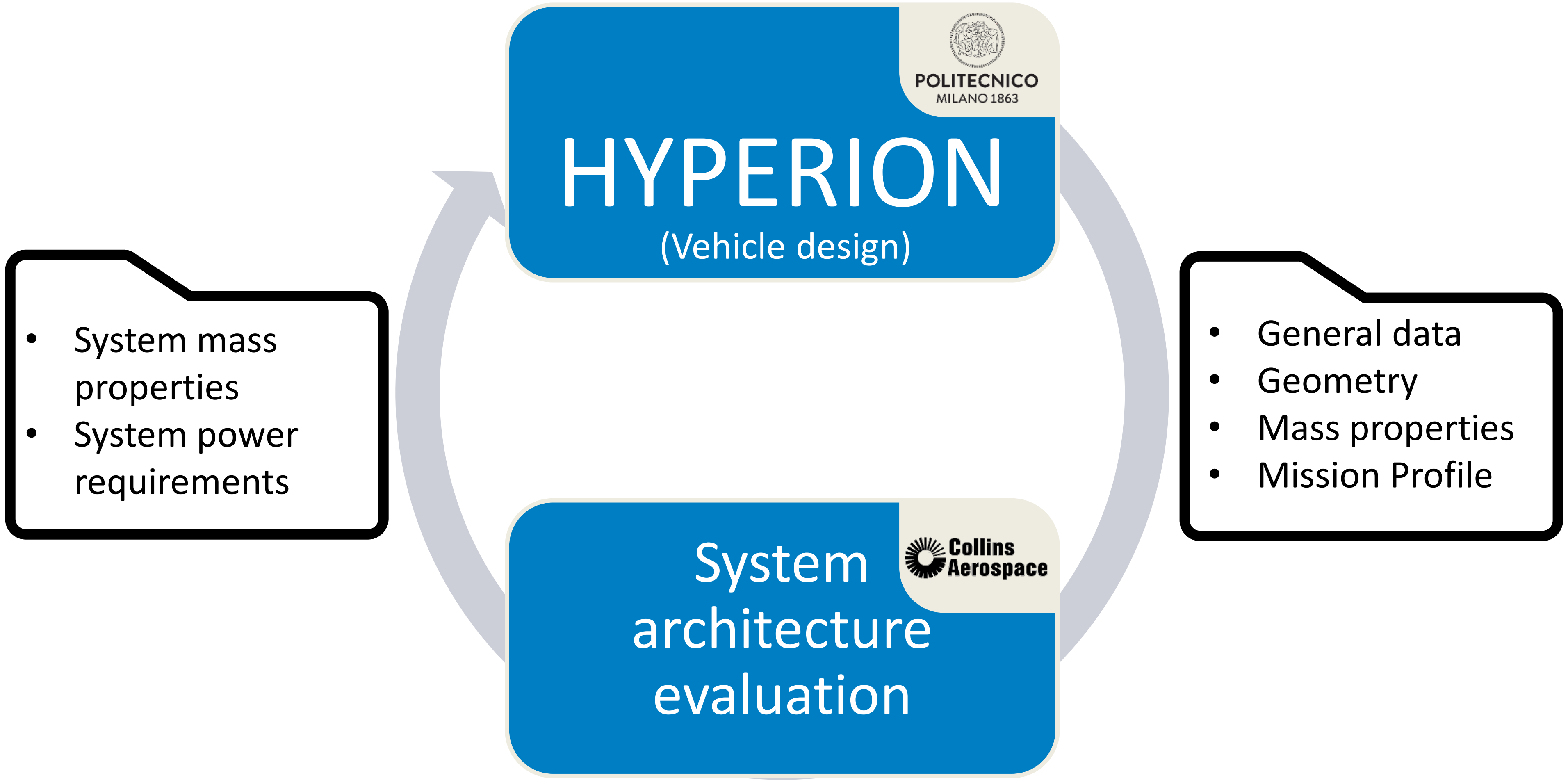
System Architecture Evaluation– Electric Power System



Tools & Methods: Data Exchange



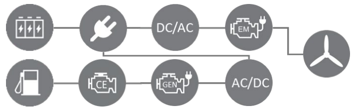
ARCHITECTURES & TECHNOLOGIES

Architectures & Technologies: Selected Preliminary Architectures

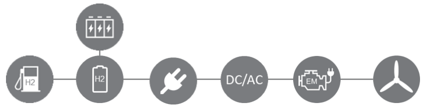
Category 1
Pilatus PC 12
CS-23 6-9 PAX

source: www.fly7.ch

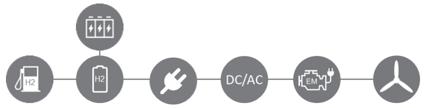
1) Series Hybrid (SH)



2) GH_2 Fuel-Cell-Electric (FCE)



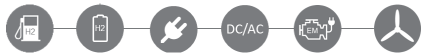
3) LH_2 Fuel-Cell-Electric (FCE)



Category 2
L 410 NG
CS-23 19 PAX

source: www.flightglobal.com

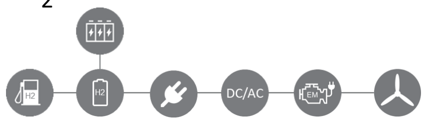
LH_2 Fuel-Cell-Electric



Category 3
ATR 72
CS-25 Turboprop < 70 PAX

source: www.atr-aircraft.com

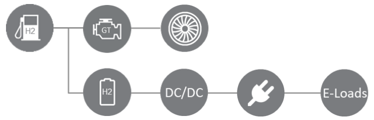
LH_2 Fuel-Cell-Electric



Category 4
Airbus A320neo
CS-25 Turbofan < 200 PAX

aircraft.airbus.com

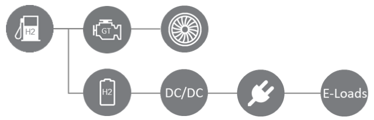
LH_2 Fuel-Cell-Powered Systems



Category 5
Airbus A350-900
CS-25 Turbofan > 200 PAX

aircraft.airbus.com

LH_2 Fuel-Cell-Powered Systems



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Architectures & Technologies: Investigation of 3 Technology Scenarios

Scenario 1: State Of The Art			
Component	**Parameter**	**Unit**	**Value**
E-Motor	Efficiency	%	95
	Specific weight	kW/kg	5.75
Battery	Efficiency	%	95
	Specific weight (power)	kW/kg	1.365
	Specific weight (energy)	kWh/kg	0.21
Fuel Cell	Specific weight	kW/kg	0.8

Scenario 2: Conservative Future (2035)			
Component	**Parameter**	**Unit**	**Value**
E-Motor	Efficiency	%	95
	Specific weight	kW/kg	11.1
Battery	Efficiency	%	95
	Specific weight (power)	kW/kg	2.275
	Specific weight (energy)	kWh/kg	0.35
Fuel Cell	Specific weight	kW/kg	4.8

Scenario 3: Optimistic Future (2050)			
Component	**Parameter**	**Unit**	**Value**
E-Motor	Efficiency	%	97
	Specific weight	kW/kg	16.45
Battery	Efficiency	%	95
	Specific weight (power)	kW/kg	4.2
	Specific weight (energy)	kWh/kg	1.15
Fuel Cell	Specific weight	kW/kg	8.8

PRELIMINARY RESULTS

Preliminary Results: Fuel-Cell-Electric ATR 72

Category 1
Pilatus PC 12
CS-23 6-9 PAX

source: www.fly7.ch

1) Series Hybrid (SH)
2) GH_2 Fuel-Cell-Electric (FCE)
3) LH_2 Fuel-Cell-Electric (FCE)

Category 2
L 410 NG
CS-23 19 PAX

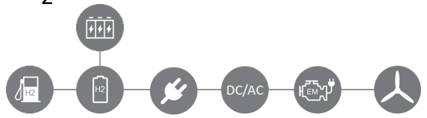
source: www.flightglobal.com

LH_2 Fuel-Cell-Electric

Category 3
ATR 72
CS-25 Turboprop < 70 PAX

source: www.atr-aircraft.com

LH_2 Fuel-Cell-Electric



Category 4
Airbus A320neo
CS-25 Turbofan < 200 PAX

aircraft.airbus.com

LH_2 Fuel-Cell-Powered Systems

Category 5
Airbus A350-900
CS-25 Turbofan > 200 PAX

aircraft.airbus.com

LH_2 Fuel-Cell-Powered Systems

Preliminary Results: Fuel-Cell-Electric ATR 72

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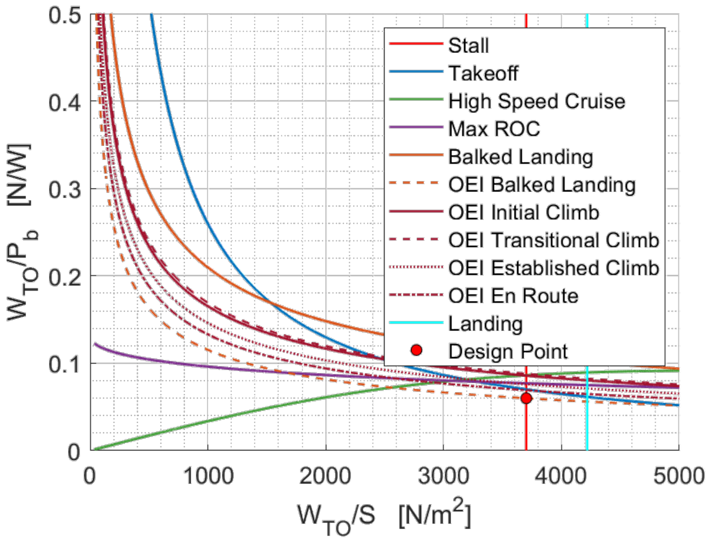
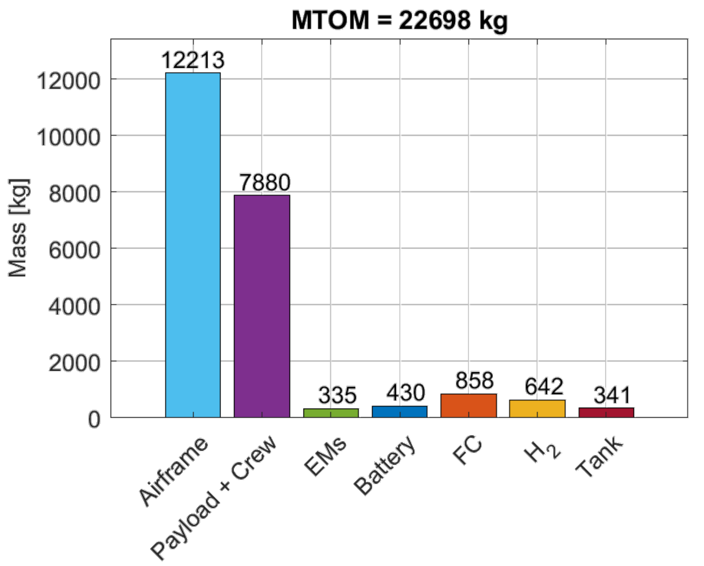
Aircraft-Level Results (HYPERION)*

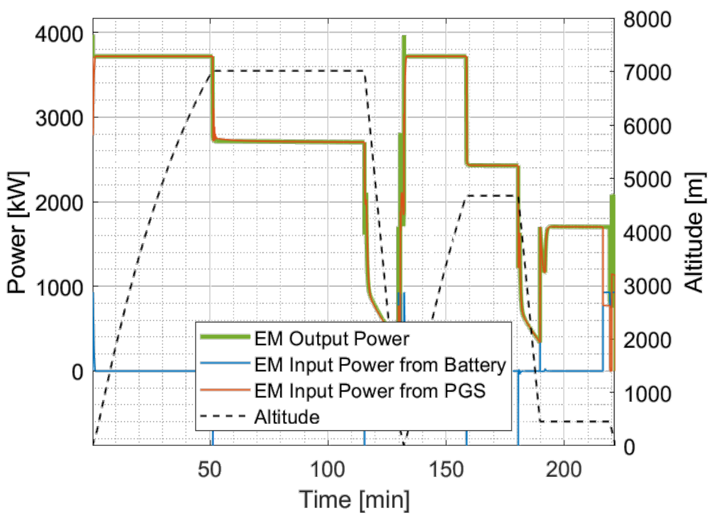
Sizing matrix plot



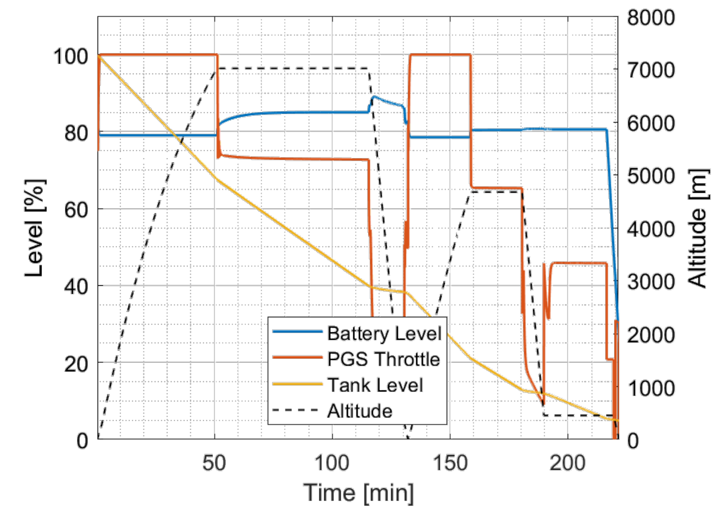
Mass distribution



Mission power rating



Mission power management



*Results based on the conservative technology scenario

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Preliminary Results: Fuel-Cell-Electric ATR 72

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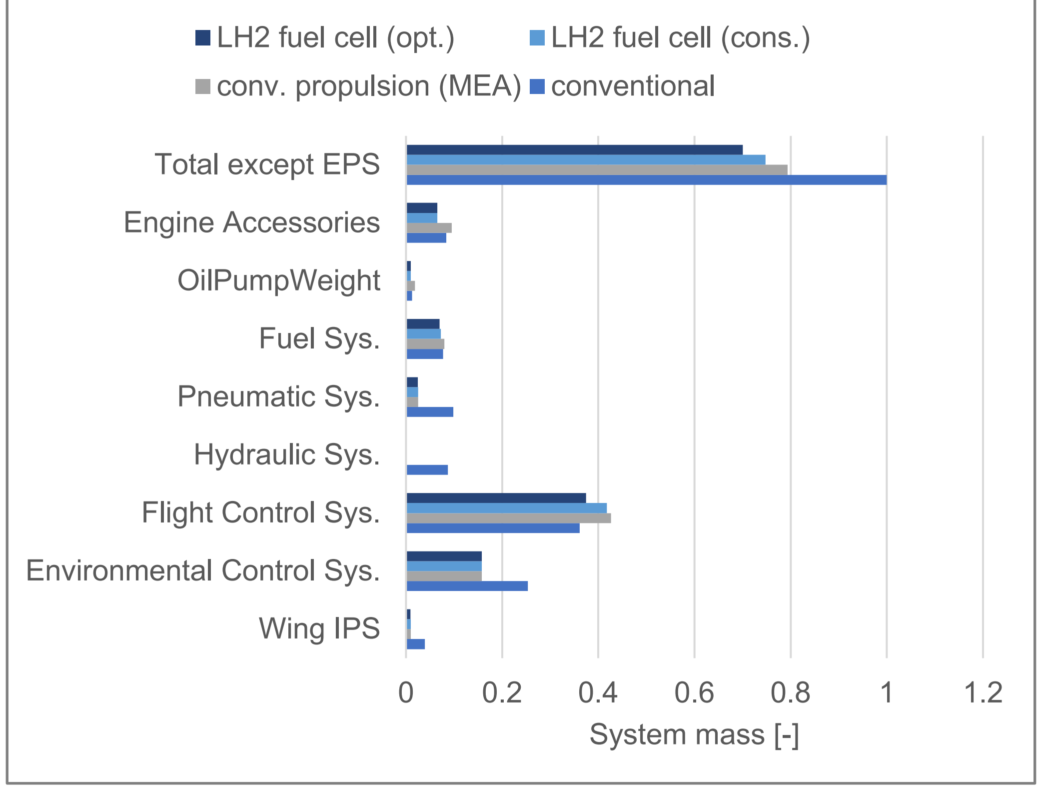
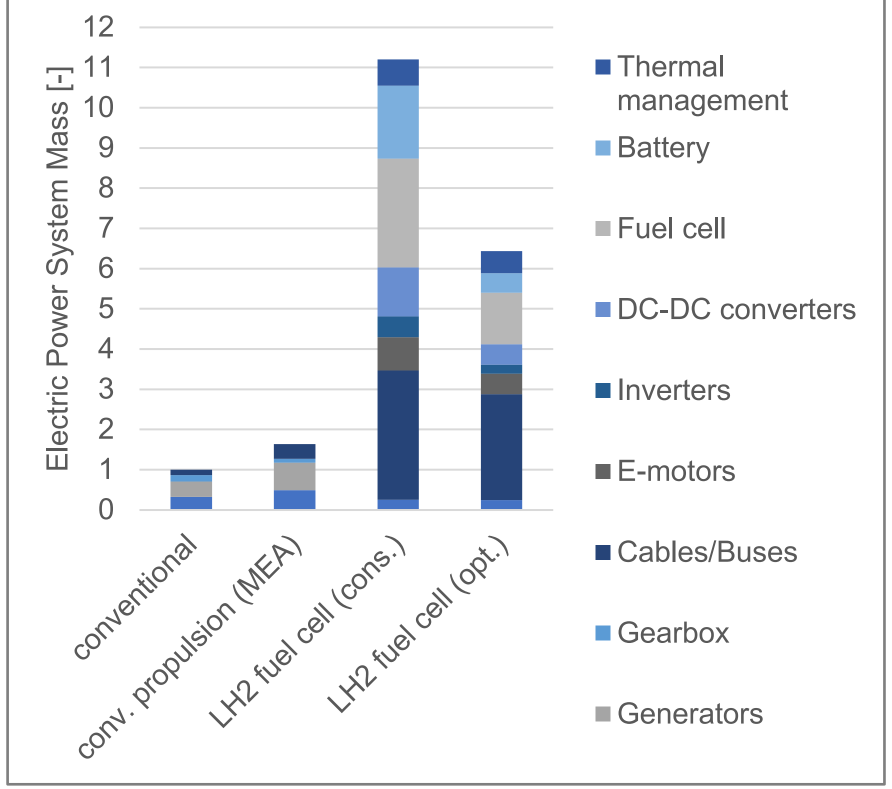
System-Level Results

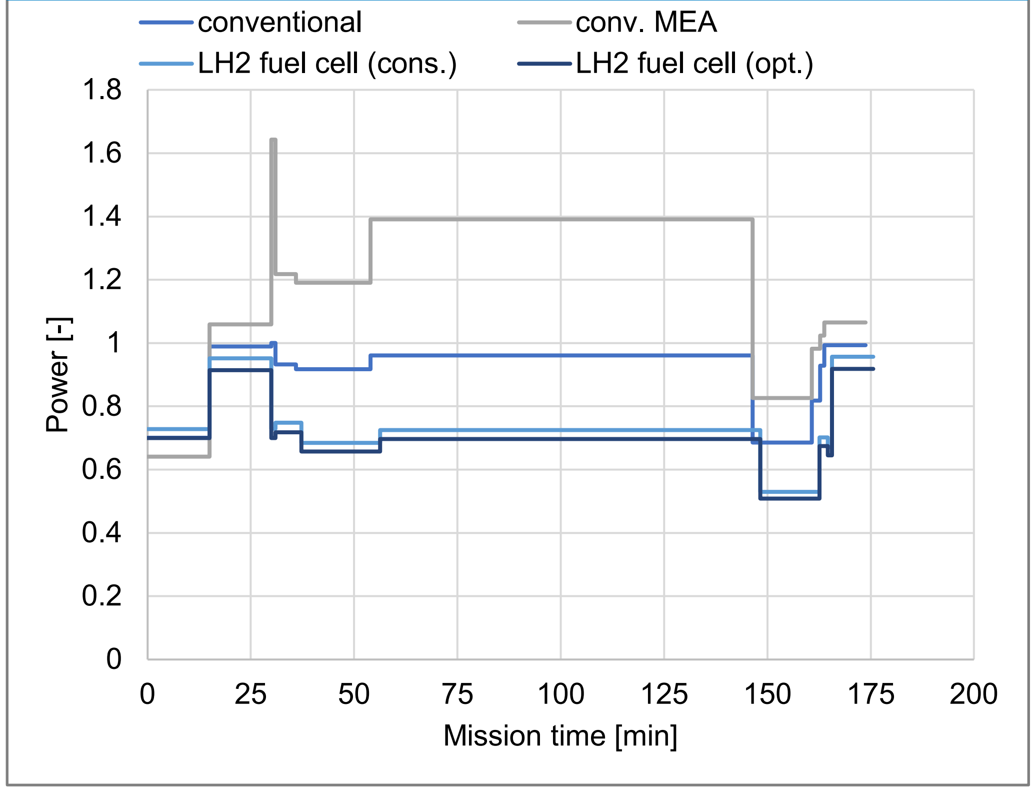
Total system mass breakdown



Electric system mass breakdown



Electric system power demand*



*Only secondary systems, no propulsion

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Preliminary Results:
Fuel-Cell-Electric ATR 72

Category 1
Pilatus PC 12
CS-23 6-9 PAX

source: www.fly7.ch

1) Series Hybrid (SH)

2) GH_2 Fuel-Cell-Electric (FCE)

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source: www.flightglobal.com

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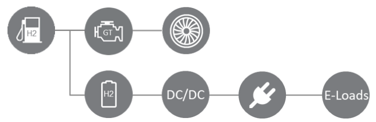
aircraft.airbus.com

LH_2 Fuel-Cell-Powered Systems



Category 5
Airbus A350-900
CS-25 Turbofan > 200 PAX

aircraft.airbus.com

LH_2 Fuel-Cell-Powered Systems

Preliminary Results: A320 – Jet fuel vs. Liquid Hydrogen

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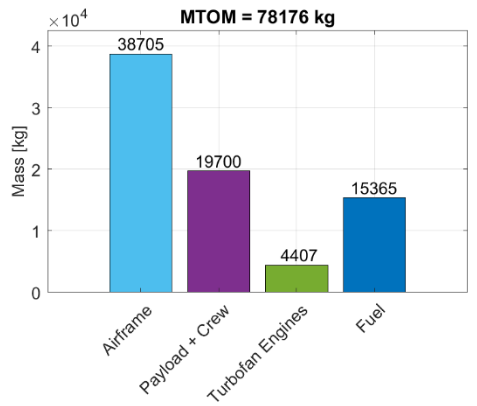
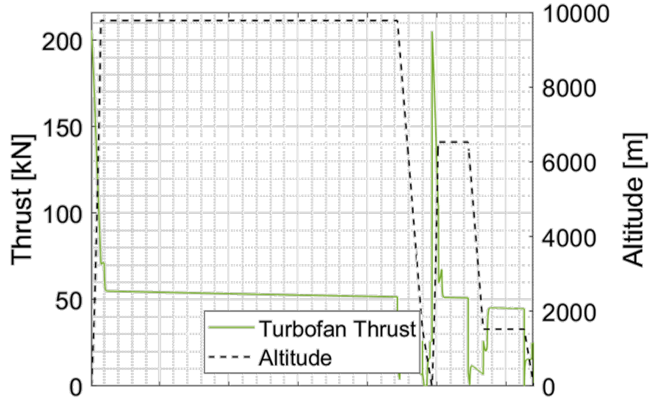
Aircraft-Level Results (HYPERION)

Jet-Fuel-Burning A320

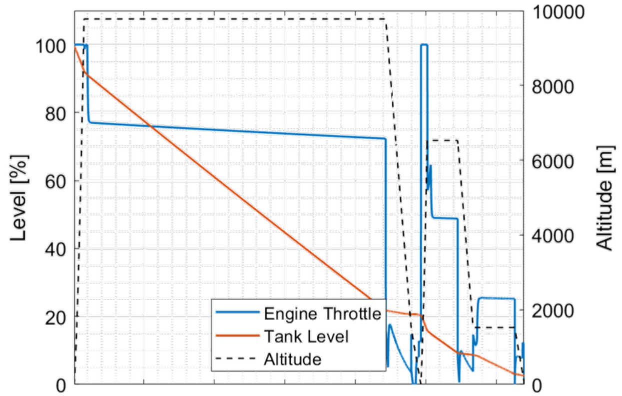
Mass distribution



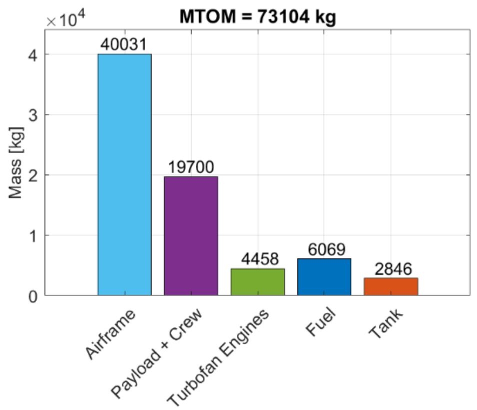
Mission thrust rating

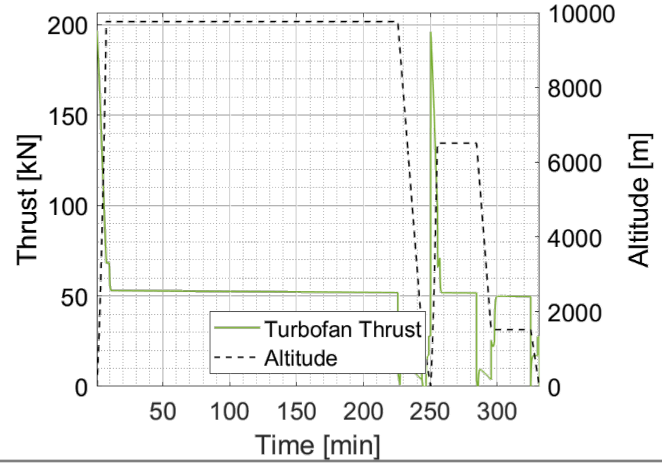


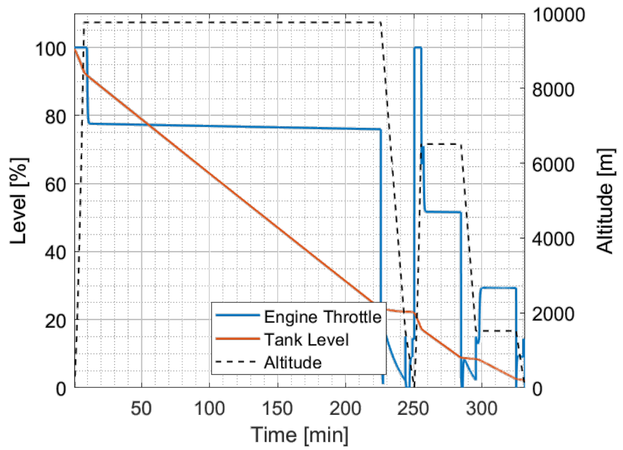
Mission power management



H_2-Burning A320







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Preliminary Results: A320 – Jet fuel vs. Liquid Hydrogen

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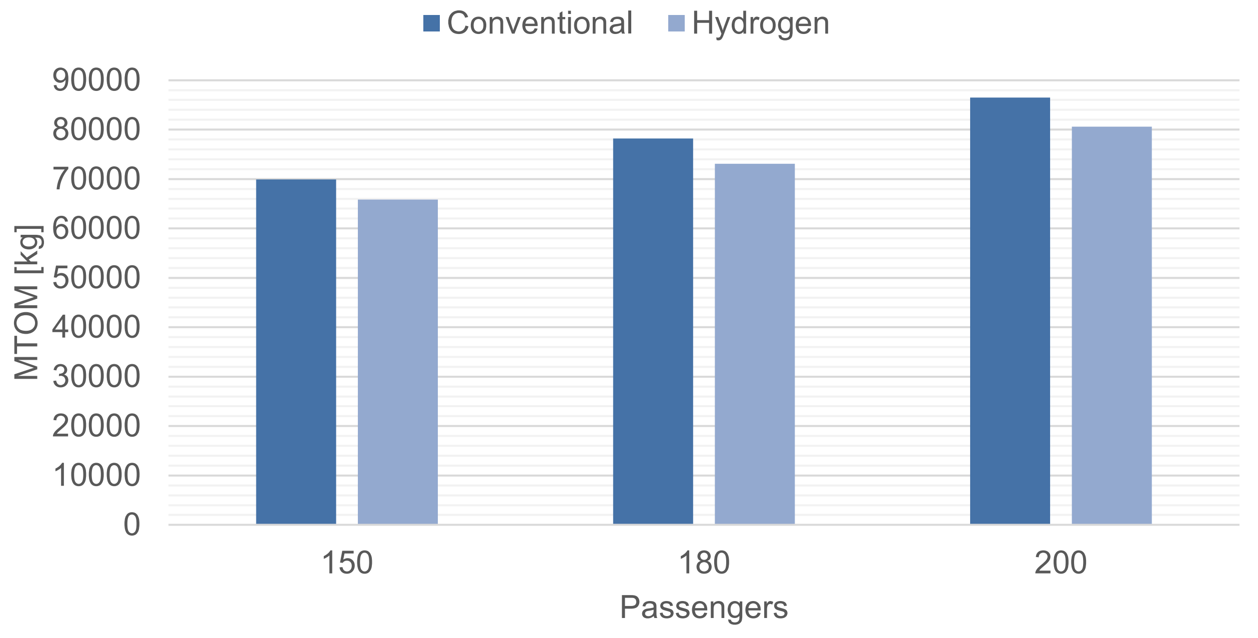
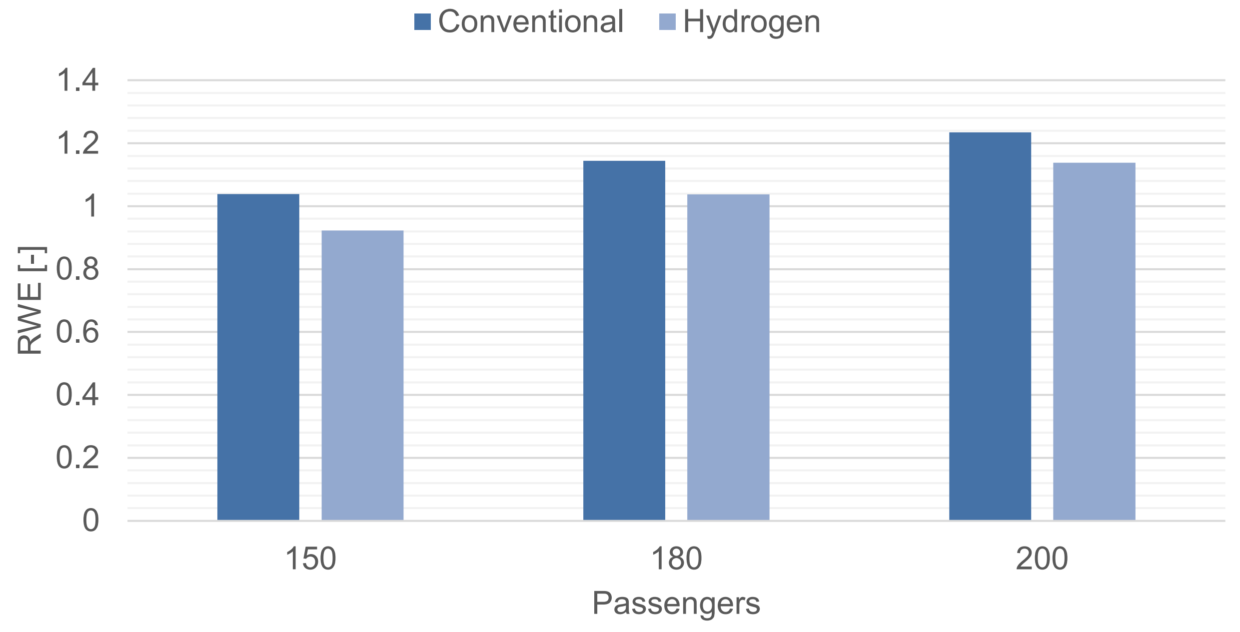
Aircraft-Level Results (HYPERION)

Maximum Takeoff Mass



Revenue Work to Energy (RWE)*



- Comparable sensitivity to payload variation for both hydrogen and jet-fuel-based designs
- Larger aircraft have a better RWE

$$*RWE = \frac{R \cdot m_{PL} \cdot g}{m_{fuel} \cdot LHV + E_{bat}}$$

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Preliminary Results:
A320 – Jet fuel vs. Liquid Hydrogen

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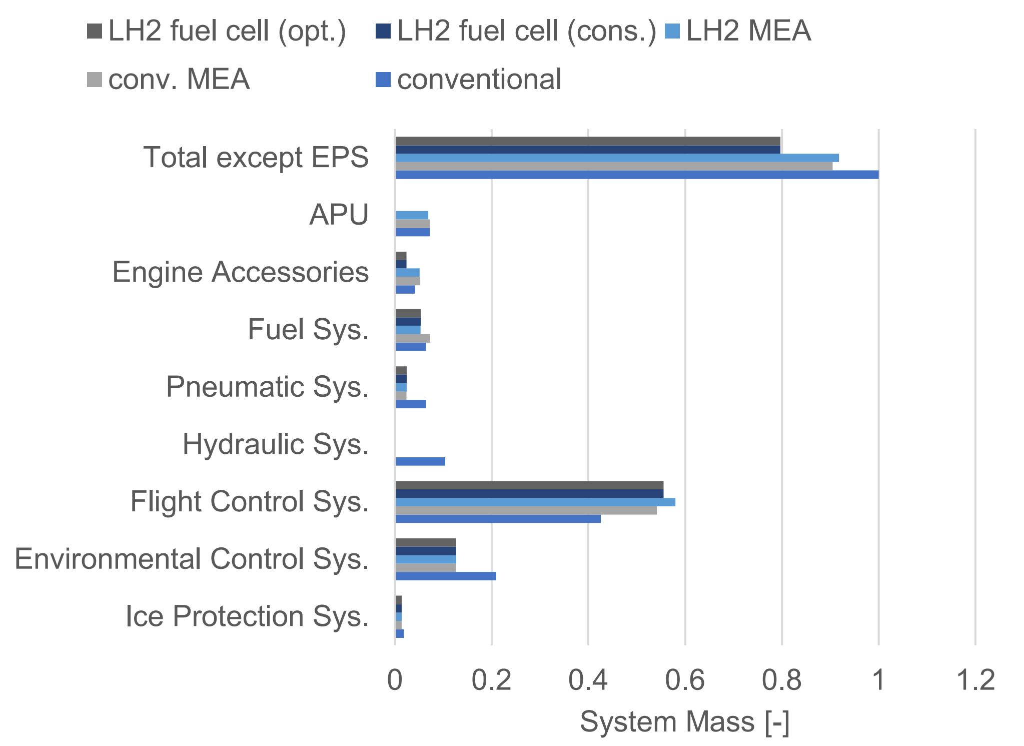
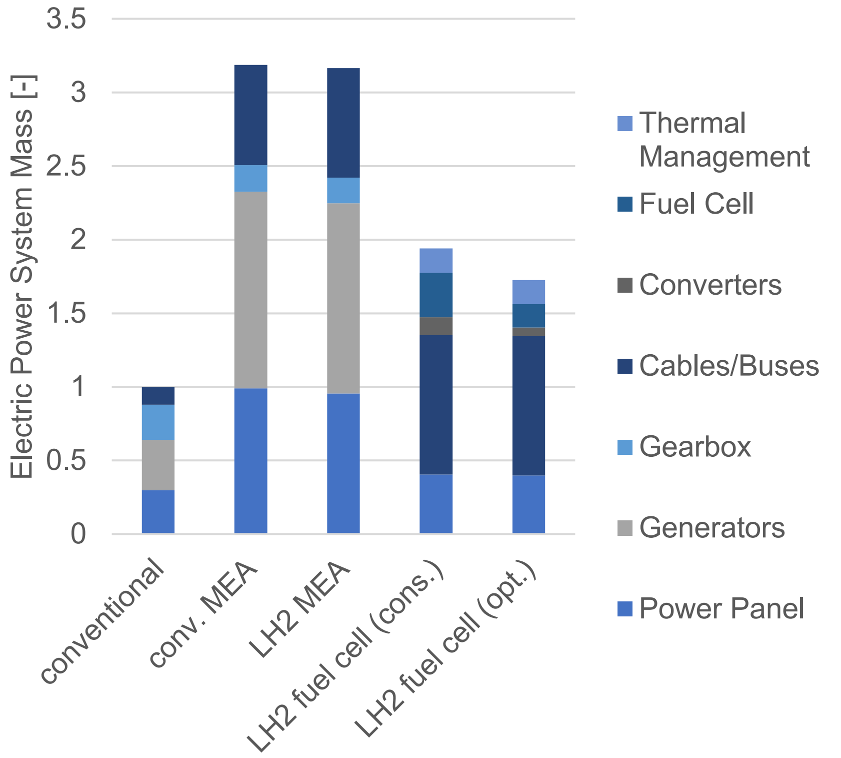
System-Level Results

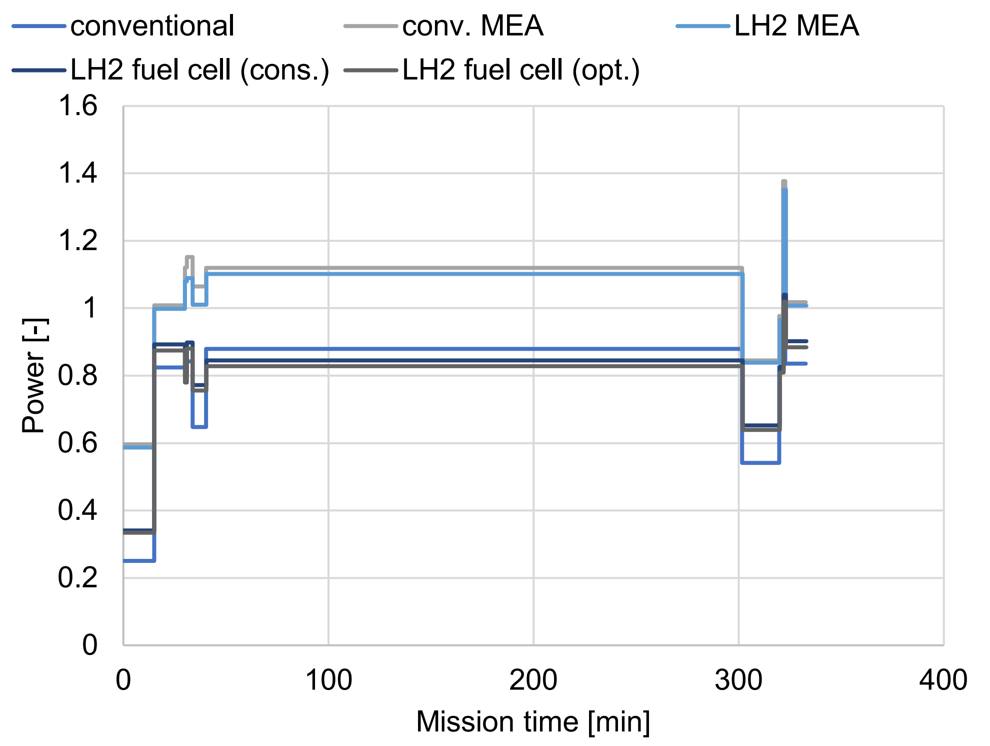
Total system mass breakdown



Electric system mass breakdown



Electric system power demand



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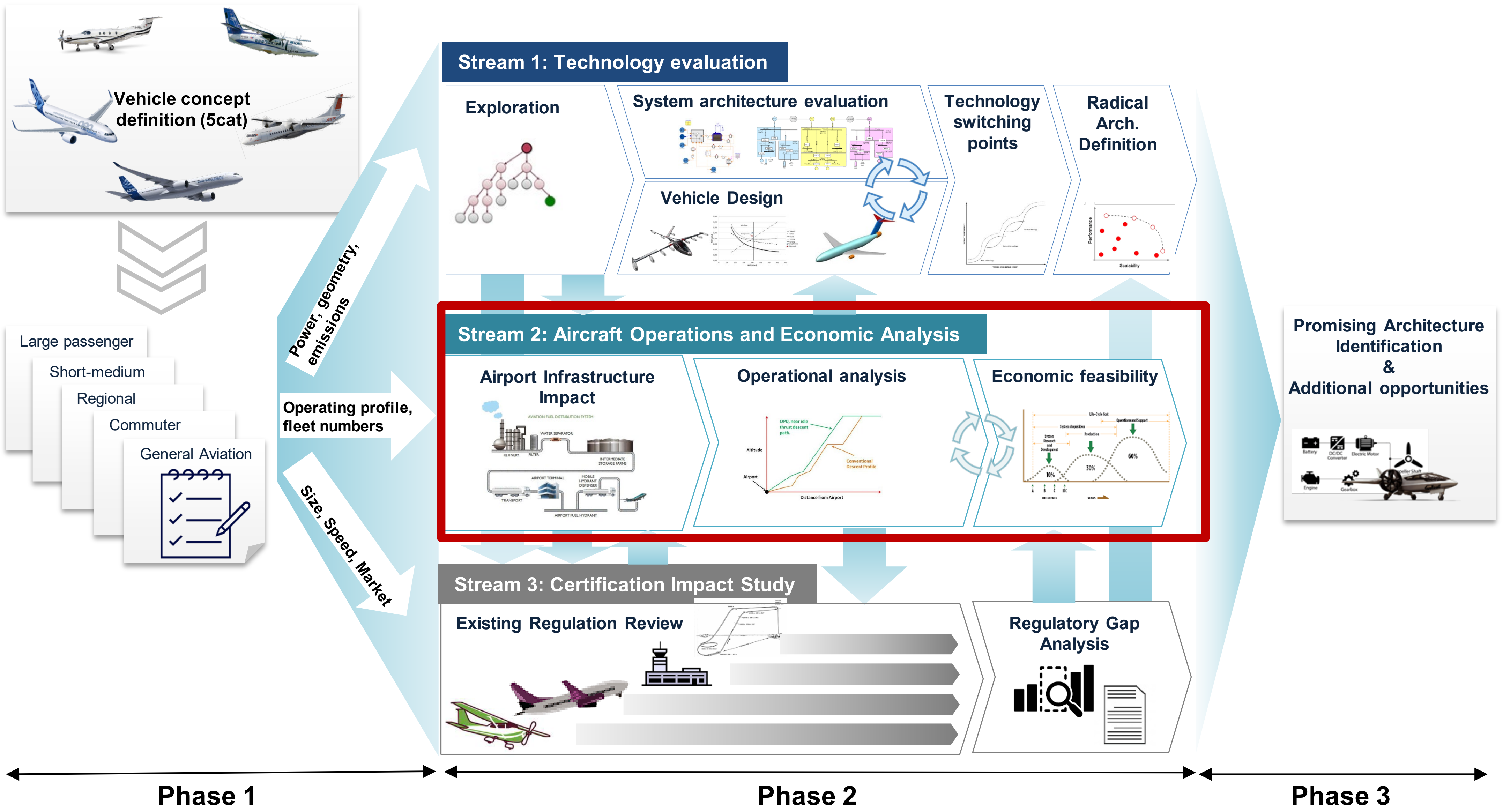
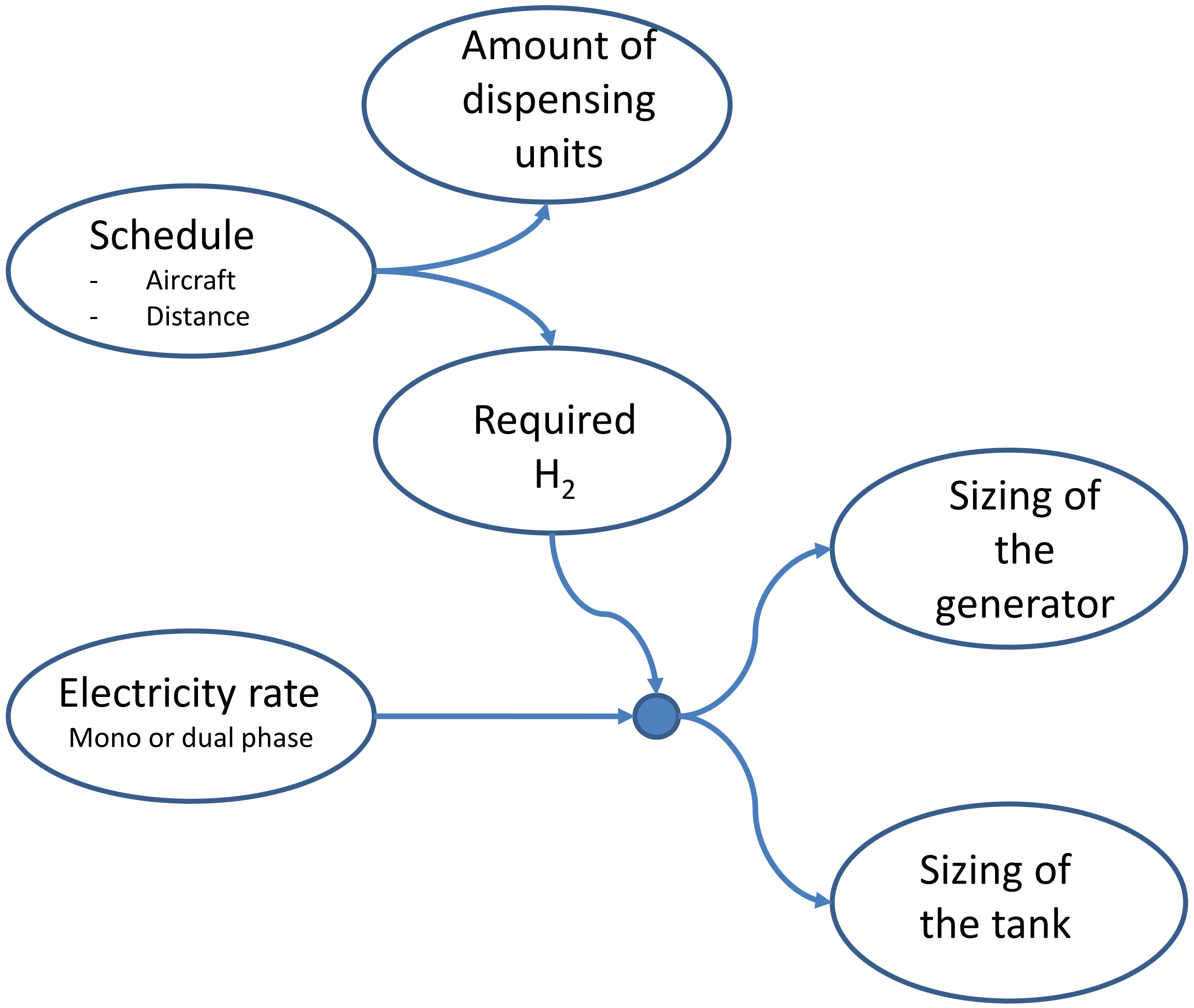
Project Overview: Technical Approach



Airport infrastructure sizing strategy



Dedicated Tool: AHRES

Integration over 10 min timesteps to optimize the cost function which includes:

- Energy cost;
- Generator cost;
- Tank cost
- Dispensing units cost.

The main constraint comes from the airport schedule.

Airport infrastructures

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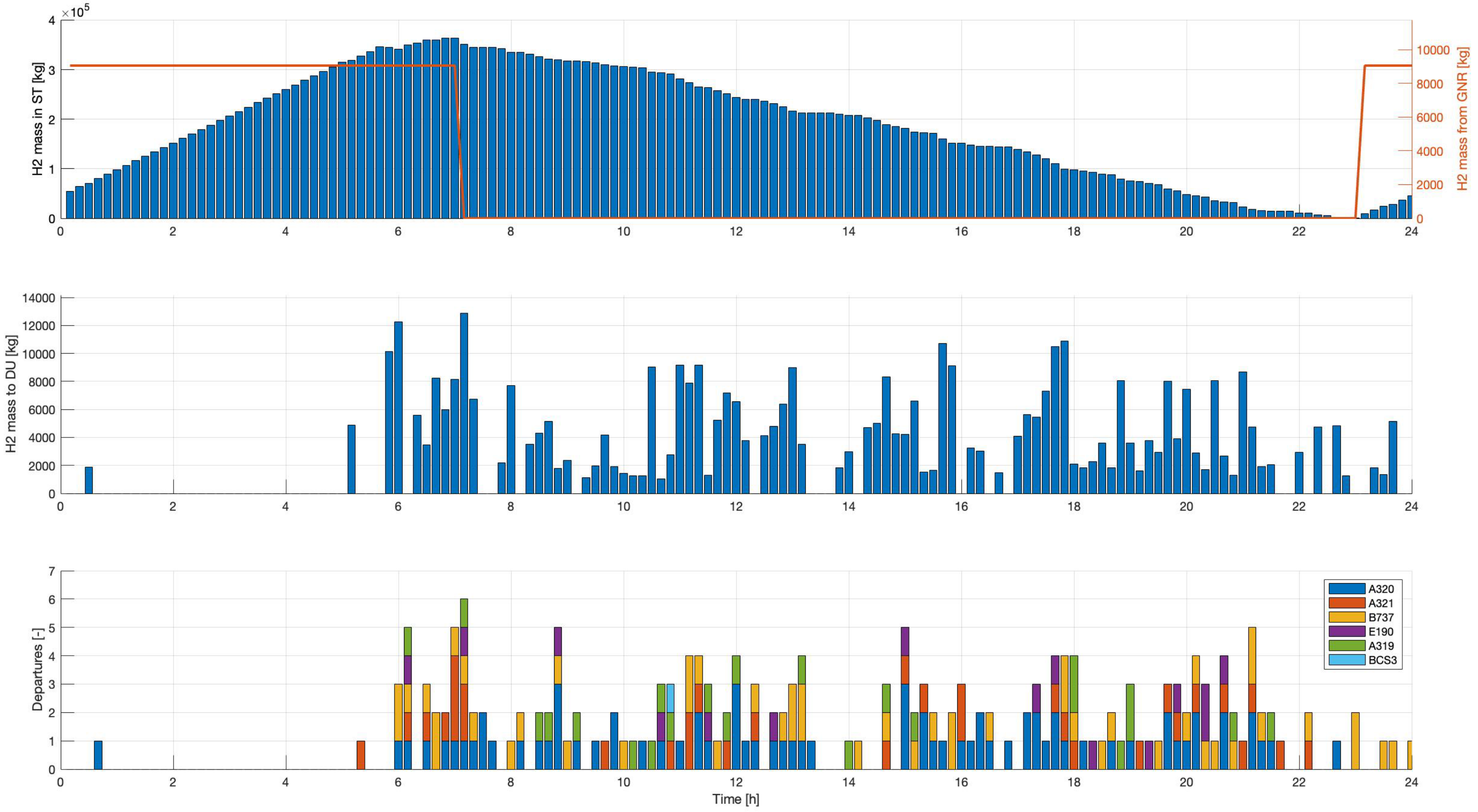
- MXP Short haul schedule 19/07/22 results (AHRES)

Dual-rate electricity price

Daily H_2 production:
376 840 kg/d

Maximum H_2 mass in tank:
362 990 kg

H_2 cost:
5,08 €/kg



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Summary & Conclusion

- Connection of overall vehicle design (PoliMi) and systems architecture evaluation (Collins) provides valuable insights on electric propulsion concepts
- Studies show impact of system architectures and technology scenarios on vehicle performance
- Fuel-cell-electric systems appear scalable for a wide range of applications
- Hydrogen-powered aircraft tend to have lower energy-efficiency, but also lower emissions

Ongoing Work & Outlook

- WP2: Design space exploration & scalability investigation
  1. Architecture exploration: identification of feasible candidate architectures
  2. Architecture investigation: design & optimization of candidate architectures
  3. Identification of technology switching/crossover points
  4. Definition of “radical” system architectures
- WP3: Aircraft Operations and Economic Analysis
  1. Key mission per aircraft category
  2. Airport infrastructure assessment
  3. Enabling factors & barriers for novel aircraft architectures
  4. Overall business case
- WP4: Certification analysis (with EASA)

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BACKUP

References

[1] Air Transport Action Group, “The right flightpath to reduce aviation emissions”, 2010

[2] A. García Garriga, P. Govindaraju, S. S. Ponnusamy, N. Cimmino and L. Mainini, “A modelling framework to support power architecture trade-off studies for More Electric Aircraft”, in *6th CEAS Air & Space Conference Aerospace Europe*, Bucharest, 2017.

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[6] A. Rolando, L. Trainelli, C. Riboldi and F. Salucci, “D9.2: Study on hybrid electric powertrain technology and component scalability, MAHEPA” 2021.

[7] NAE and CPEE, “Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions”, National Academies Press, 2016.

[8] R. H. Jansen, C. Bowman, A. Jankovsky, R. Dyson and J. L. Felder, “Overview of NASA electrified aircraft propulsion (EAP) research for large subsonic transports”, in *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Atlanta, GA, 2017.

[9] A. H. Wienhausen, “High Integration of Power Electronic Converters enabled by 3D Printing”, PhD thesis, RWTH Aachen University, 2019.

Architectures & Technologies: Investigation of 3 Technology Scenarios

Scenario 1: State Of The Art			
Component	Parameter	Unit	Value
E-Motor/Generator	Efficiency		0.950
	Specific weight	kW/kg	5.750
	Voltage	V	230.000
	Phases		3
DC/AC Converter	Efficiency		0.950
	Specific weight	kW/kg	9.000
DCBUS	Efficiency		0.990
	Voltage	V	540.000
DC2DC Converter	Efficiency		0.970
	Specific weight	kW/kg	9.000
Battery	Efficiency		0.950
	Specific weight (power)	kW/kg	1.365
	Specific weight (energy)	kWh/kg	0.210
Fuel Cell	Output Voltage	V	540.000
	Operating Temperature	C	180.000
	Operating pressure	kPa	30.000
	Area-specific resistance	kOhm/cm^2	0.00003
	H2 fuel efficiency		0.950
	Specific weight	kW/kg	0.800
Thermal Management	Pump Efficiency		0.850
	Motor Controller Efficiency		0.950
	Coolant heat capacity	J/kgK	2770
	Coolant density	kg/m^3	659
	Specific pump weight	kg/kW	3.000
	Specific fluid weight	kg/m	0.750
	Specific ducting weight	kg/m	2.500

Scenario 2: Conservative Future			
Component	Parameter	Unit	Value
E-Motor/Generator	Efficiency		0.950
	Specific weight	kW/kg	11.100
	Voltage	V	230.000
	Phases		3
DC/AC Converter	Efficiency		0.970
	Specific weight	kW/kg	9.000
DCBUS	Efficiency		0.990
	Voltage	V	540.000
DC2DC Converter	Efficiency		0.970
	Specific weight	kW/kg	9.000
Battery	Efficiency		0.950
	Specific weight (power)	kW/kg	2.275
	Specific weight (energy)	kWh/kg	0.350
Fuel Cell	Output Voltage	V	540.000
	Operating Temperature	C	180.000
	Operating pressure	kPa	30.000
	Area-specific resistance	kOhm/cm^2	0.00003
	H2 fuel efficiency		0.950
	Specific weight	kW/kg	4.800
Thermal Management	Pump Efficiency		0.850
	Motor Controller Efficiency		0.950
	Coolant heat capacity	J/kgK	2770
	Coolant density	kg/m^3	659
	Specific pump weight	kg/kW	3.000
	Specific fluid weight	kg/m	0.750
	Specific ducting weight	kg/m	2.500

Scenario 3: Optimistic Future			
Component	Parameter	Unit	Value
E-Motor/Generator	Efficiency		0.970
	Specific weight	kW/kg	16.45
	Voltage	V	230.000
	Phases		3
DC/AC Converter	Efficiency		0.990
	Specific weight	kW/kg	19.000
DCBUS	Efficiency		0.990
	Voltage	V	540.000
DC2DC Converter	Efficiency		0.990
	Specific weight	kW/kg	56.300
Battery	Efficiency		0.950
	Specific weight (power)	kW/kg	4.2
	Specific weight (energy)	kWh/kg	1.15
Fuel Cell	Output Voltage	V	540.000
	Operating Temperature	C	180.000
	Operating pressure	kPa	30.000
	Area-specific resistance	kOhm/cm^2	0.00003
	H2 fuel efficiency		0.950
	Specific weight	kW/kg	8.8
Thermal Management	Pump Efficiency		0.850
	Motor Controller Efficiency		0.950
	Coolant heat capacity	J/kgK	2770
	Coolant density	kg/m^3	659
	Specific pump weight	kg/kW	3.000
	Specific fluid weight	kg/m	0.750
	Specific ducting weight	kg/m	2.500

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Clean Sky 2