National Aeronautics and Space Administration

Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS)

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Outline

- Background
- Research Challenges
- Tool Development
- PEGASUS 2.0
- Conclusion

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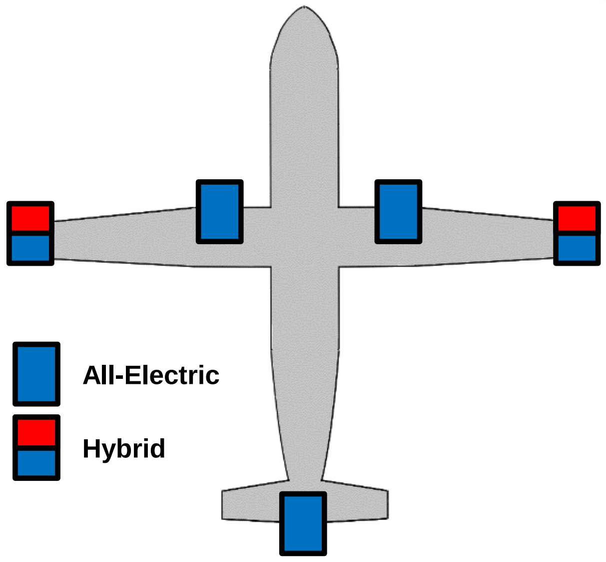
Background

- **Antcliff et al. (2016) were interested in revitalizing regional air transportation market.**
  - 400 nmi range sufficient for the vast majority of regional aircraft demand
  - Reduce emissions through electrification
  - Potential to reduce cost and enable new routes between underutilized airports
  - Focused on hybrid-electric propulsion due to the limitations of battery capacity to power practical mission ranges
- **Antcliff's first PEGASUS paper (2017)**
  - 48 passenger aircraft based on the ATR 42
  - Flies 400 nmi (plus reserves) as hybrid-electric; 200 nmi (plus reserves) all electric

Artist rendering of PEGASUS

Background

- **PEGASUS conceived as a technology collector, incorporating various research efforts at NASA**
  - Distributed electric propulsion (DEP)
  - Propulsion-airframe-integration (PAI)
  - Boundary layer ingestion (BLI)
- **Configuration**
  - Three propulsor classes:
    - Hybrid-electric wingtip propulsors
    - Electric inboard motors
    - Electric, aft BLI motor
- **Concept of Operations (ConOps)**
  - Hybrid-electric wingtip propulsors for thrust at cruise
  - Electric inboard propulsors for takeoff/climb assist
    - Featuring folding propellers
  - BLI propulsor primarily for drag reduction



	Takeoff & climb	Cruise & descent
Hybrid-electric wingtip	Partial	Full
Electric inboard	Full	None, folded
Electric BLI	Full	Full

Power available to each propulsor class through each phase of flight

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Research Challenges

- **Unique features of PEGASUS strained legacy tools.**

What metric is used for sizing decisions?

Ratio of wingtip to inboard thrust

How to account for propulsion-airframe integration?

What percent hybridization is best?

Critical loss of thrust concerns for wingtip propulsors

What is the structural impact of wingtip propulsors?

Stability and control implications

- **The team had performed research into these individual areas but had not produced a comprehensive aircraft design in several years.**

The goal was to develop a new baseline, called PEGASUS 2.0, based on the latest research and sizing approaches.

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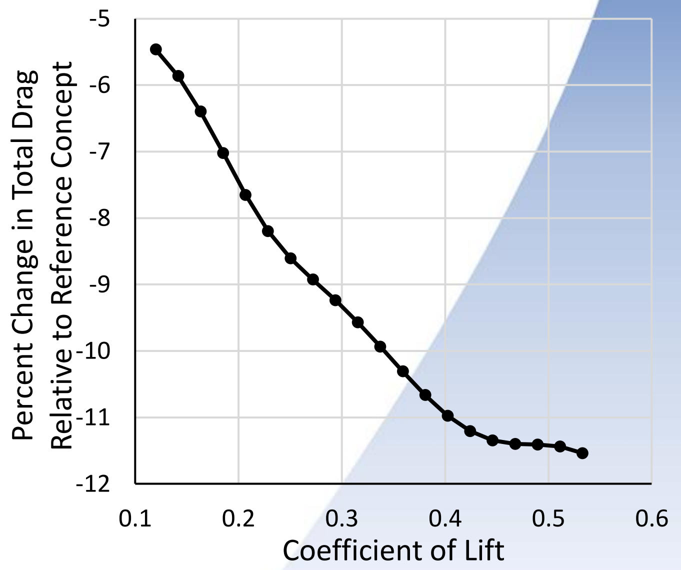
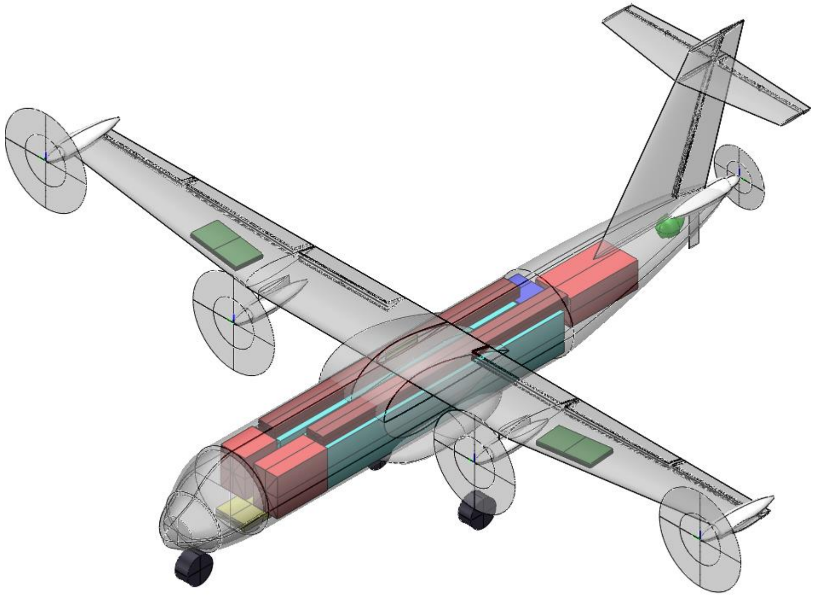
Tool Development

- **Answering these questions required new tools.**
- **To perform an integrated design, surrogate models were developed that could easily be incorporated into the sizing and mission analysis process.**
- **Aerodynamic Surrogate (Ordaz et al. 2020)**
  - Developed computational fluid dynamic (CFD) models in FUN3D
  - Modeled the impact of wingtip propulsors and aft BLI propulsor on aerodynamic performance compared to a baseline, conventional configuration
  - Produced surrogate models of PAI benefits that could more easily be integrated into the aircraft sizing codes, without having to execute CFD as part of the process
  - Learned the BLI propulsor was not showing appreciable benefits and decided to remove it from the vehicle

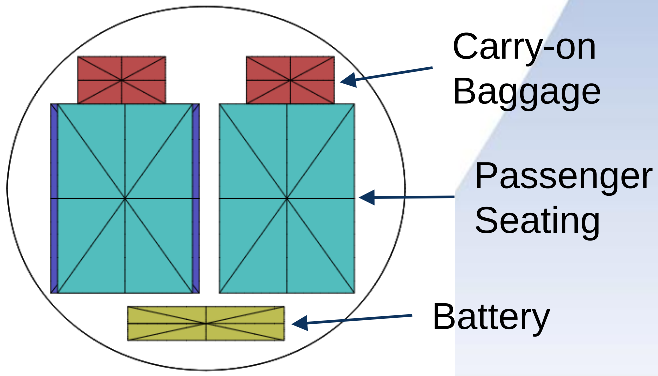


Tool Development

- **Wing Weight Surrogates from Georgia Tech (Solano et al. 2021)**
  - Developed surrogates for the weight of the wing as a function of propulsor placement and propulsor weight
  - Learned that dynamic analysis is necessary – using static loads shows weight at the wingtip to be a benefit whereas dynamic loads showed them to be a detriment
- **Dynamic Stability and Flying Qualities**
  - Built a database of aerodynamic and control derivatives, estimating control surface areas and deflections
  - Created a simplified mass properties model to compute moments of inertia and center of gravity
  - Used six-degree-of-freedom (6-DOF) model to calculate stability modes and flying qualities
  - 6-DOF analysis performed "outside the loop" on the final configurations to ensure acceptable stability and control



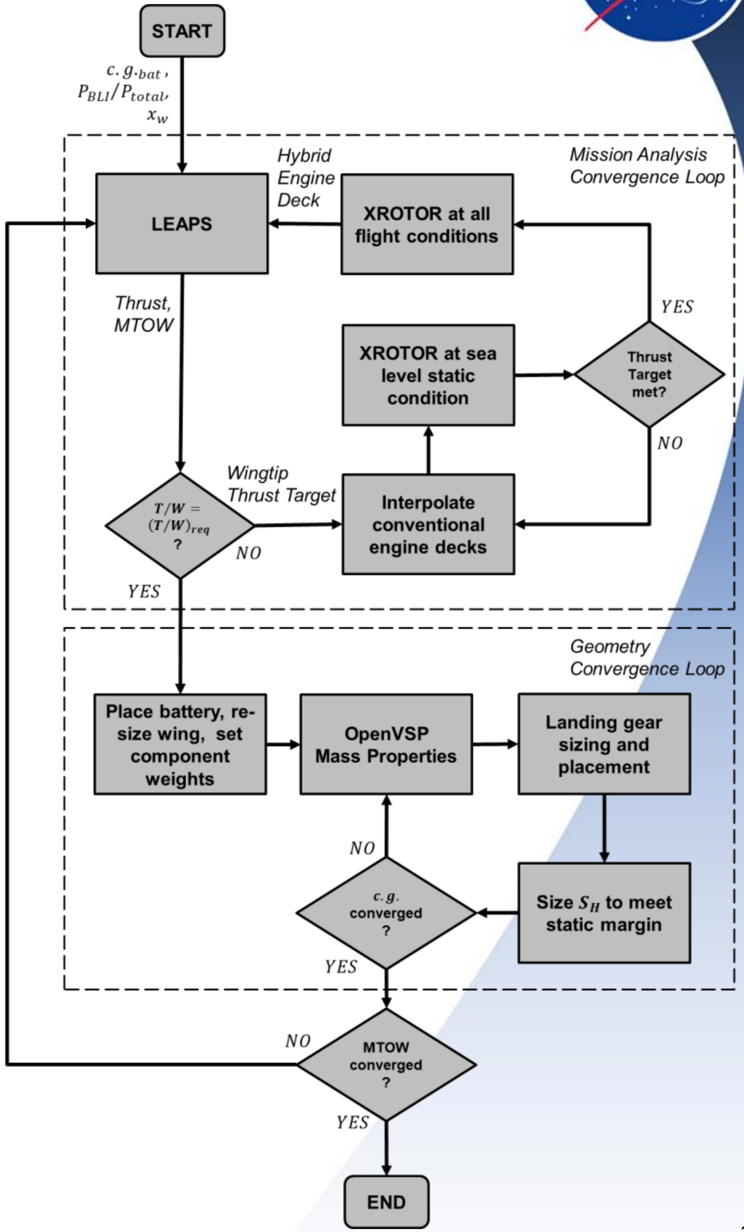
Mass properties model



Fuselage cross section

Tool Development

- **Code Integration**
  - Data passed between geometry model (OpenVSP) and aircraft sizing and mission analysis code (LEAPS)
  - Added aerodynamic and wing weight surrogate models
- **Updated ConOps**
  - The 200 nm all-electric mission was removed based on concerns related to leaving the gas turbine off during the all-electric mission.
  - To limit the impact of Critical Loss of Thrust due to the wingtip propulsors, the gas turbine throttle at takeoff was constrained and parametrically varied.
- **Design Trades**
  - Chose equivalent CO_2 (CO_2e) as main figure of merit, since it considers fuel and electric energy consumption
  - Explored trades on electric motor size, thrust split between wingtip and inboard propulsors, and gas turbine throttle at takeoff



Tool Development

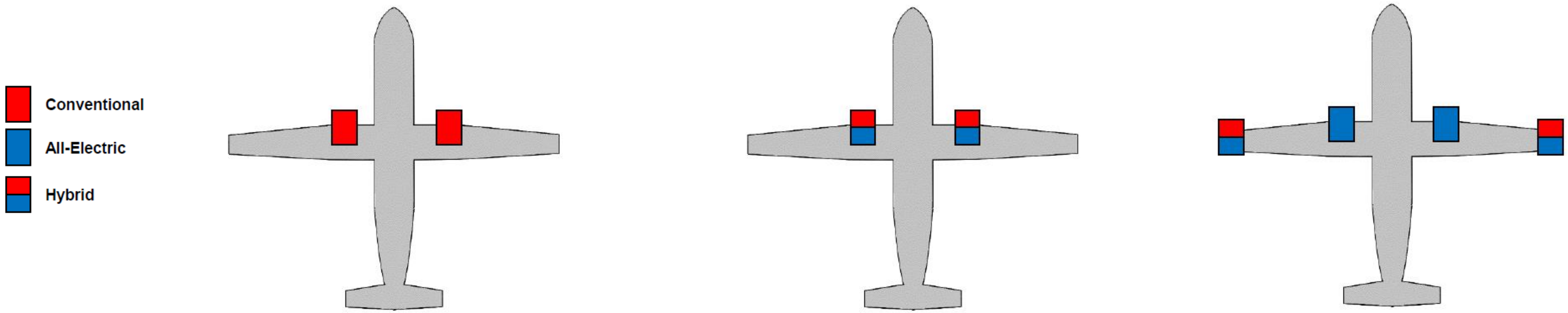
Development of Comparator Aircraft

- Quantifying the benefits of PEGASUS required appropriate baseline vehicles.
- What benefits are unique to the PEGASUS configuration, beyond those attributed to the transition to hybrid-electric propulsion?

Advanced Conventional Baseline (ACB)
- Modeled after the ATR-42
- Features technology improvements to bring it to a “modern” aircraft

Hybrid-Electric Baseline (HEB)
- Same thrust-to-weight and wing loading as the ACB and PEGASUS
- Hybrid-electric propulsion

PEGASUS 2.0
- Parallel hybrid-electric wingtip propulsors for cruise
- Fully electric inboard propulsors for takeoff assist



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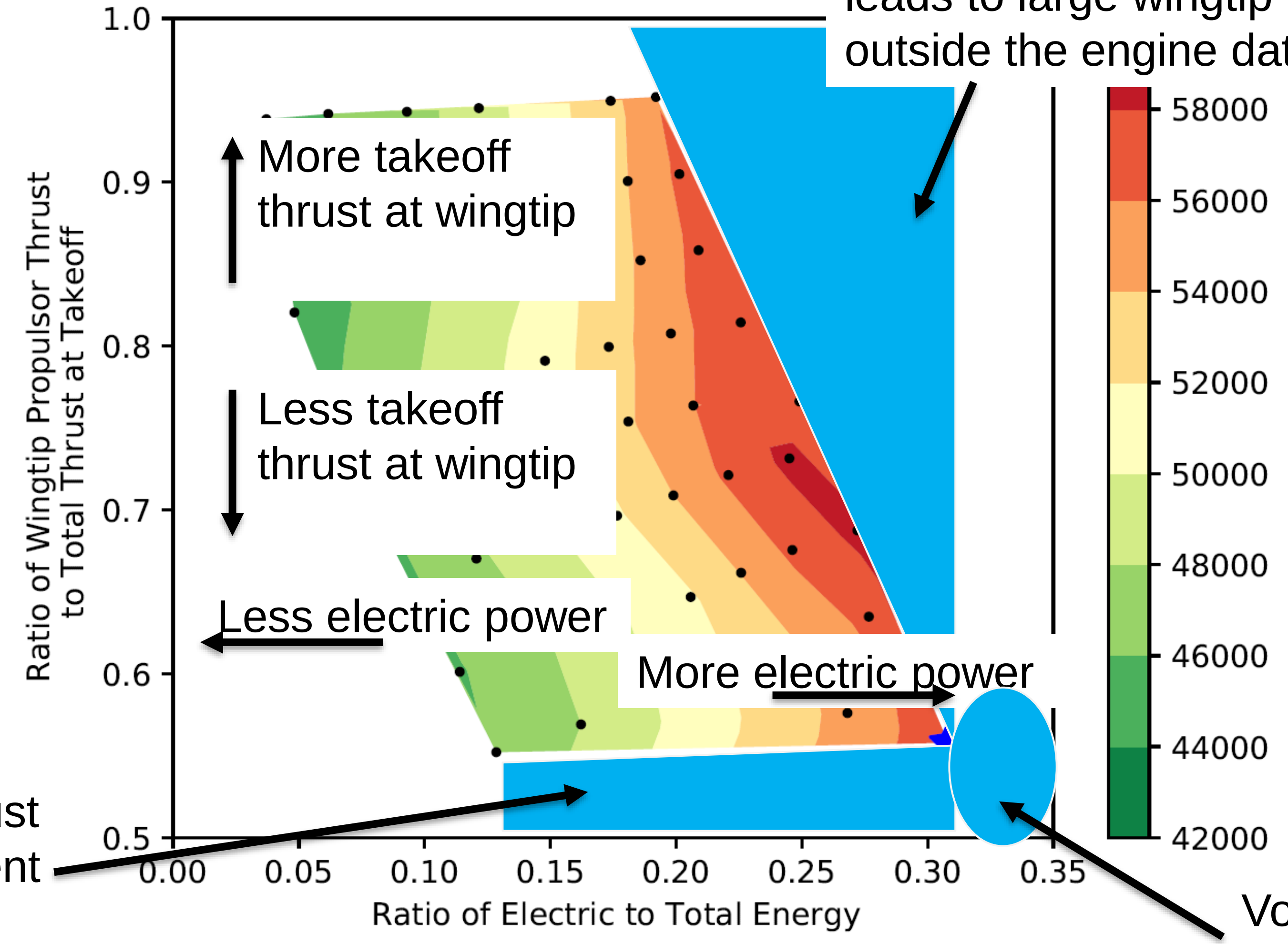
PEGASUS 2.0

- **Results from design exploration**

Low inboard thrust with high hybridization (and MTOW) leads to large wingtip engines outside the engine database.



High inboard thrust leads to insufficient wingtip thrust for cruise.

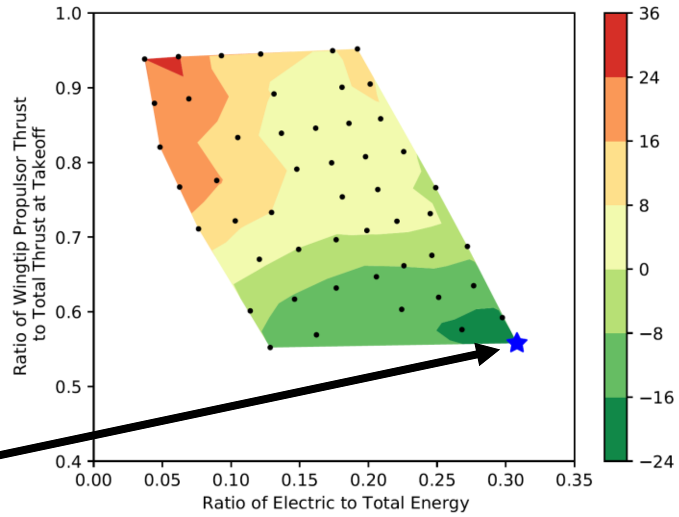
Contours of MTOW at 50% GT Throttle

Volumetric limit on battery capacity

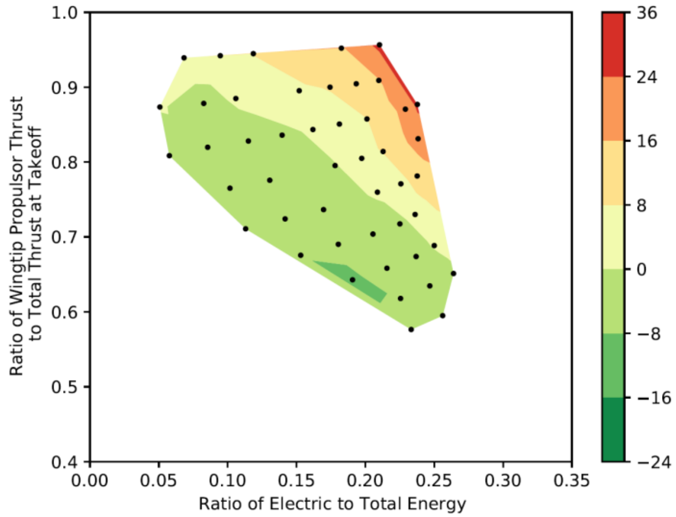
PEGASUS 2.0

- **CO_2e contours with respect to conventional baseline**

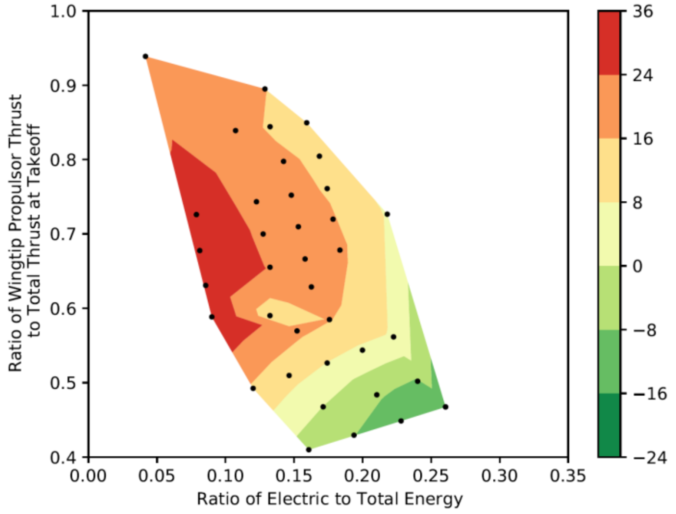
Lowest CO_2e case.



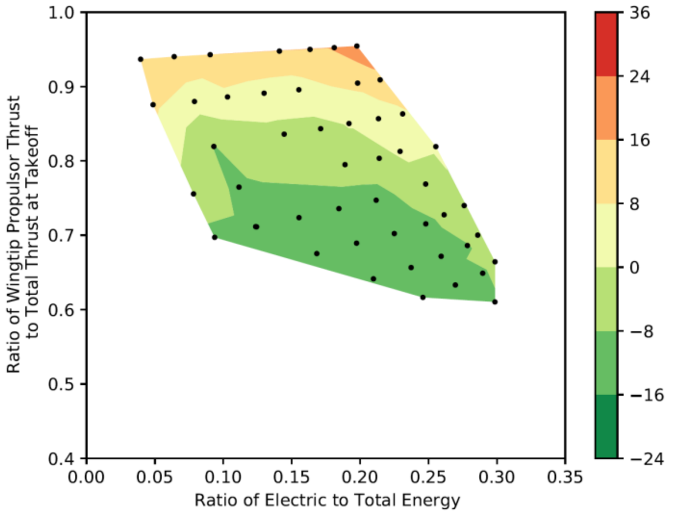
50% GT throttle



100% GT throttle



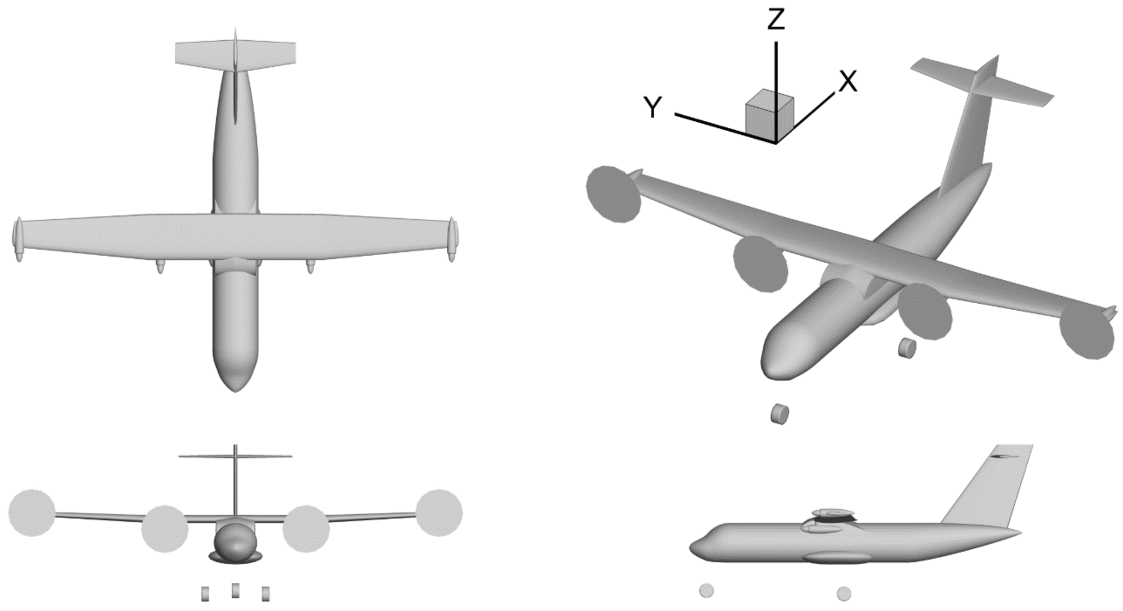
30% GT throttle

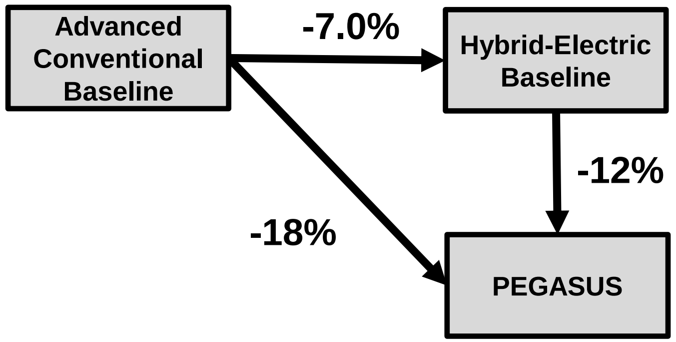


70% GT throttle

PEGASUS 2.0

	MTOW, lb	Battery Weight, lb	Wing Area, ft^2	Tail Volume Coefficient	Block Fuel, lb	Total Electric Energy, MJ	Total Energy, MJ	CO_2e, lb
ACB	36,850	0	527	0.089	1,446	0	28,300	5,440
HEB	38,860	1,460	555	0.090	1,316	863	26,630	5,060
PEGASUS	57,270	13,600	818	0.107	925	8060	26,170	4,468





Reduction in CO_2e across concepts

PEGASUS shows greatest reduction in CO_2e, albeit with increases in maximum takeoff weight (MTOW).

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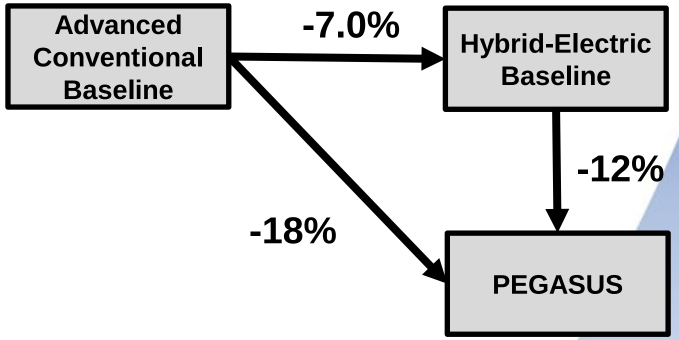
Conclusion

- **Goal was to establish an updated PEGASUS configuration, taking into account previous research**
- **Updated ConOps, removing 200 nmi all-electric mission and removing BLI propulsor**
- **The team developed new capabilities and tools:**
  - PAI surrogate models
  - Wing weight surrogates
  - Dynamics and stability simulation
- **PEGASUS reduced CO_2e over the conventional baseline and hybrid-electric baseline vehicle, with increased MTOW.**



Reduction in CO_2e across concepts

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