Alternate Energy Based Sizing Method

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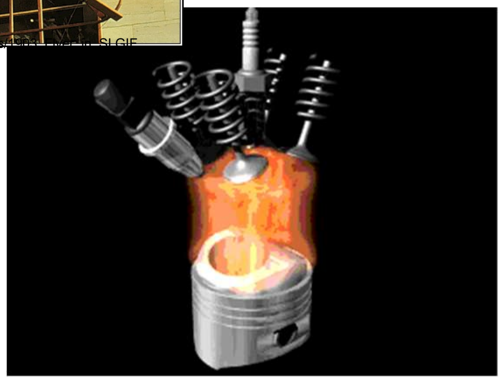
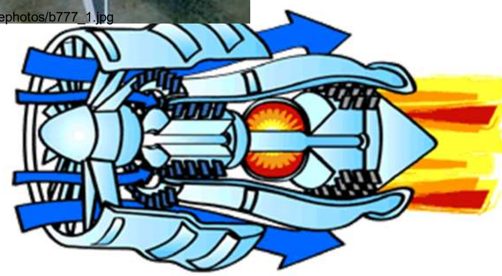
After a Century of Efforts

Flying still depends on internal combustion engines

http://www.first-to-fly.com/History%20Images/1903_Flyer_in_SI.GIF



http://www.globalaircraft.org/photos/planephotos/b777_1.jpg



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Aviation's Contribution to Climate Change

CO_2 | NO_x | H_2O | SO_x HC Soot

Ocean uptake | Chemical Reactions | Alter microphysical processes at 8-13 km

ΔCO_2 | ΔCH_4 | ΔO_3 | ΔH_2O | Aerosol, Contrails, Clouds

Climate Change:
Changes in temperatures, sea level, ice/snow cover, precipitation, etc.

Schematic adapted from Lee et al., "Aviation and Global Climate Change in the 21st Century," Atmospheric Environment, vol. 43, no. 22-23, 35203537, 2009.

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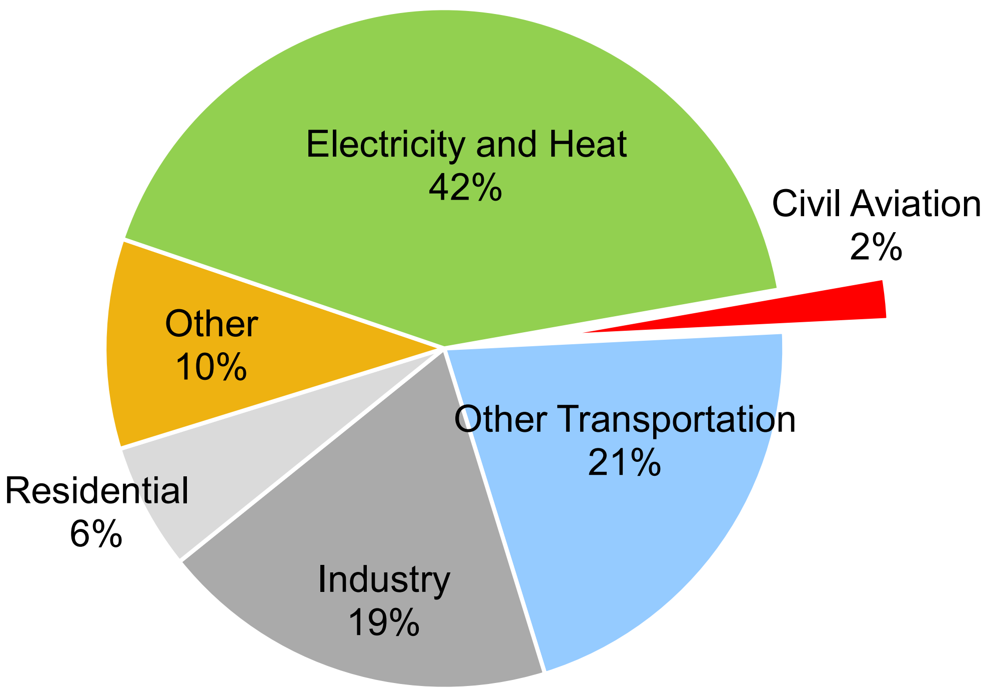
Aviation CO_2 Emissions and Future Goals

Global CO2 Emissions by Sector in 2013 [2]

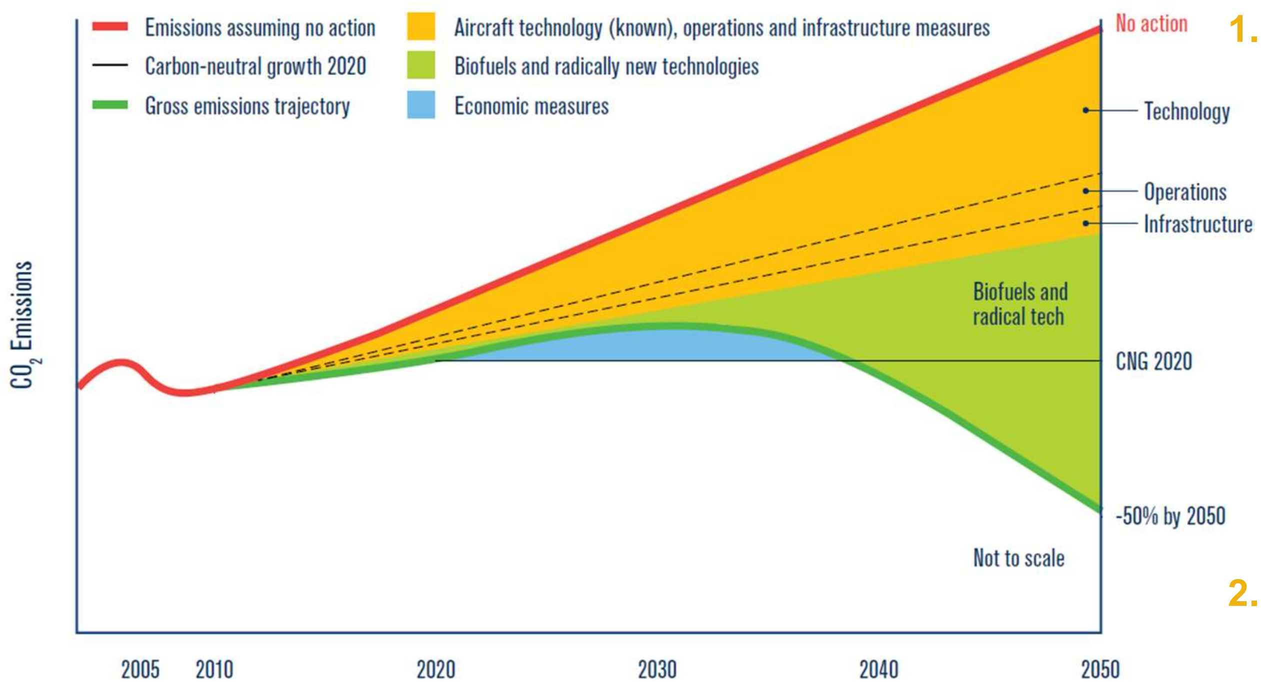


In 2015:

- Total CO_2: 36 billion tons
- Aviation-related CO_2: 781 million tons

- CO_2 emissions are expected to increase as aviation demand increases
- ICAO goals:
  1. 2% annual fuel efficiency improvement through 2050
     - CO_2 emissions are assumed to be proportional to total fuel usage
  2. Keep the net CO_2 emissions at 2020 levels (i.e. Carbon-neutral growth)
  3. Reduce net CO_2 emissions by 50% by 2050 relative to 2005 levels

Future Aircraft Emission Goals



Schematic of CO_2 emissions reduction roadmap by IATA, "IATA Technology Roadmap," 4th Edition, 2013

NASA's primary areas of technical focus:

1. **Alternative fuels**
   - Can lower the carbon use of standard turbofan engines in the near term
   - Do not help with the local air quality impact, very long lifetime of CO_2 emissions, or NO_x emissions throughout the upper troposphere and lower stratosphere
2. **Hybrid-electric and fully electric propulsion**
   - Can achieve very low to no carbon emissions

Unconventional Energy/Power Sources

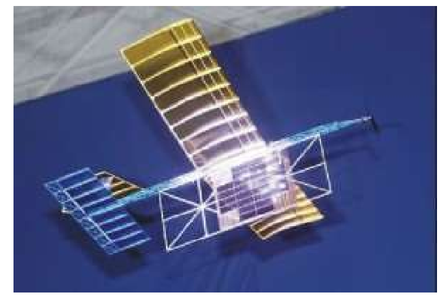
Attracting renewed attention in the past decade

Solar Cell

Lithium-Polymer Battery

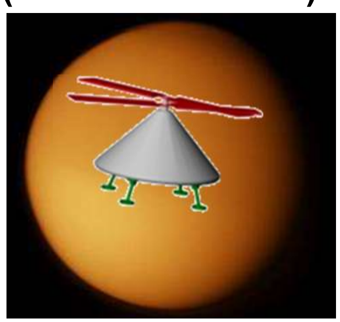
Human-Powered

Beam-Powered



Nuclear Battery

Atmosphere (Methane in Titan)



Chemical Muscle

Hydrogen

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Hybrid/Electric Aircraft Examples

Uber Elevate
Urban Air Mobility
Image Credit: uber.com

Pipistrel Alpha Electro
Electric General Aviation
Image Credit: pipistrel.si

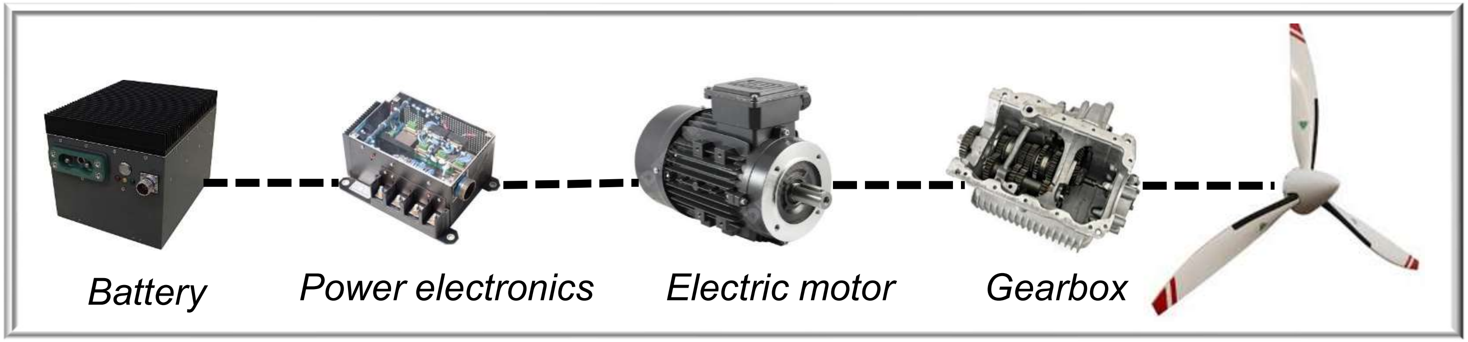
NASA X-57 Mod IV
Distributed Electric Propulsion
Image Credit: nasa.gov

Bauhaus Luftfahrt Ce-Liner
Electric Transport
Image Credit: bauhaus-luftfahrt.net

Boeing Sugar Volt
Hybrid Electric Transport
Image Credit: nasa.gov

NASA STARC-ABL
Turboelectric Transport
Image Credit: nasa.gov

Electric Propulsion System



Advantages

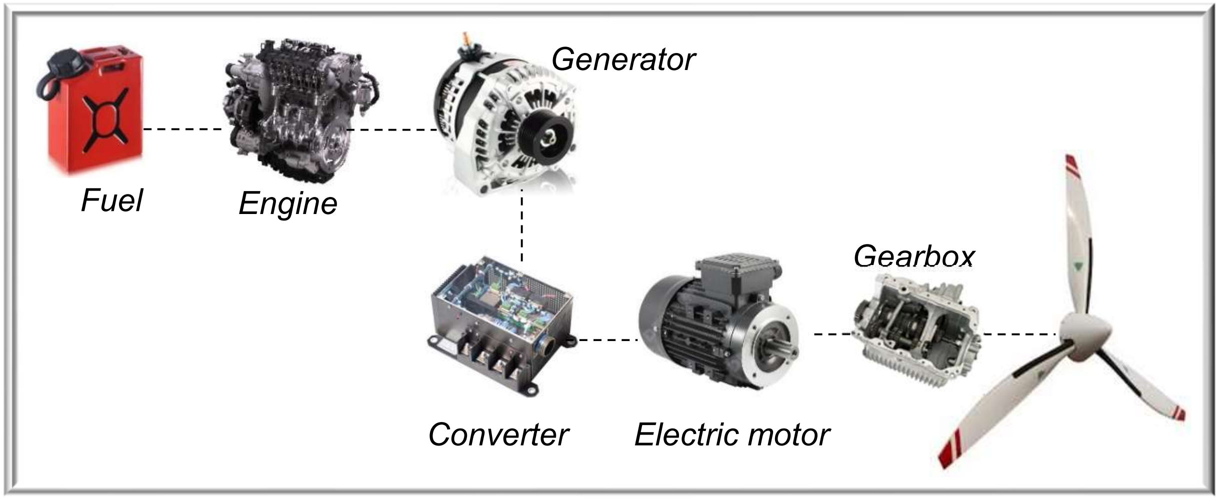
- ✓ Zero CO_2 and NO_x emissions
- ✓ Less atmospheric heat release (less global warming)
- ✓ High efficiency of the electric motor
  - ✓ No power lapse with altitude
  - ✓ Scale-free efficiency and power-to-weight ratio
- ✓ Increased reliability and maintainability
- ✓ Quieter flight

Disadvantages

- Endurance/Range penalty due to the low gravimetric specific energy* of batteries
  - Aviation Gasoline: 12.2 kWh/kg
  - Jet A: 11.9 kWh/kg
  - Lithium Ion Battery: 0.23 kWh/kg
- Increased weight sensitivity

Gravimetric Specific Energy = ratio of energy to mass of an energy source

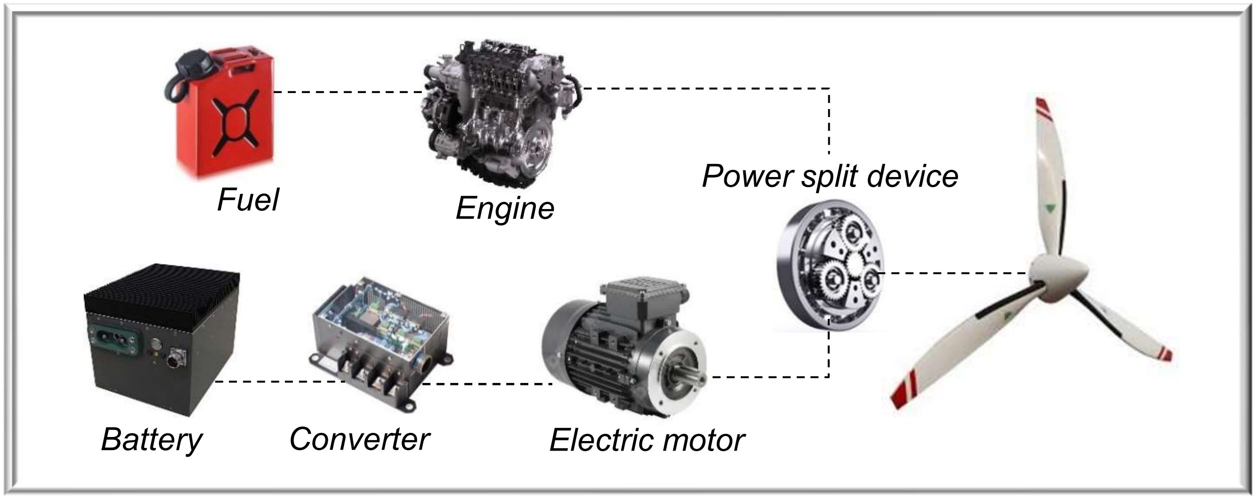
Series Hybrid Electric Propulsion System



Series configuration *(Called "turboelectric" if engine is a gas turbine engine)*

- ✓ Engine is decoupled from the transmission system; can run at its peak efficiency independent from the RPM of the transmission system
- ✓ Flexibility in terms of the location of engine-generator set
- – 3 propulsion devices (engine, motor, and generator) need to be sized for the maximum sustained power for high performance flight
- – Increased weight penalty

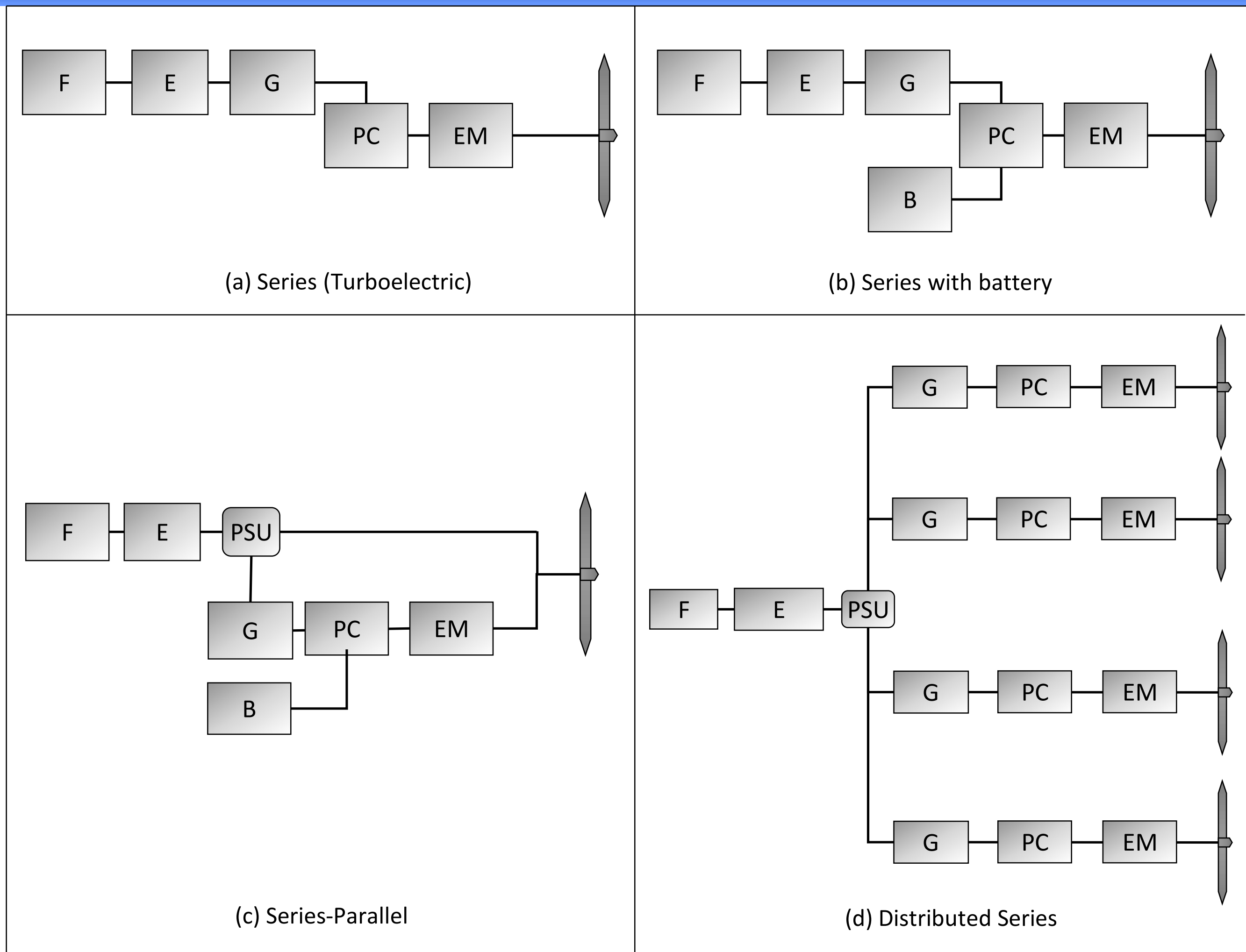
Parallel Hybrid Electric Propulsion System



Parallel configuration

- ✓ Engine and motor are coupled to the shaft; either one can be downscaled without any loss in maximum power
- ✓ Power can be delivered by only the engine (conventional propulsion), only the electric motor (fully electric propulsion) or both of them simultaneously (hybrid propulsion)
- ✓ No extra generator (motor can be used as a generator to charge the battery)
- – Increased control complexity
- – Mechanical couplings
- – Requires more complex and expensive transmission system

Example Hybrid Electric Propulsion Architectures



F: Fuel, E: Engine, G: Generator, PC: Power Converter, EM: Electric Motor, B: Battery, PSU: Power Split Unit

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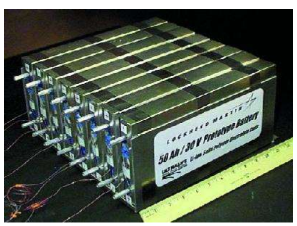
Need for Comprehensive Research

Aircraft Sizing and Synthesis

Subsystem Level

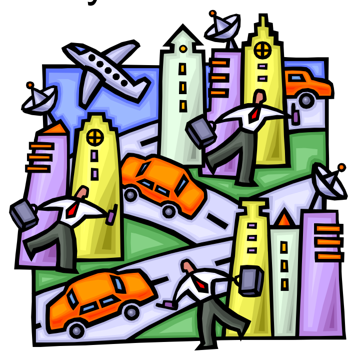


http://www.grc.nasa.gov/WWW/Electrochemistry/images/50_AH_Battery.jpg

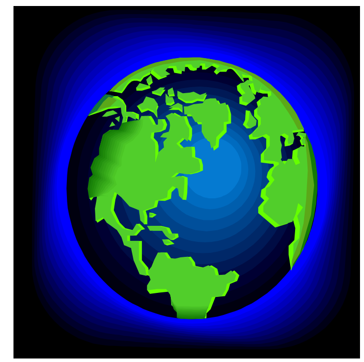
Vehicle System Level

www.boeing.com

Transportation System Level



Global System Level



- Ecological Impact
- Economics
- National Security

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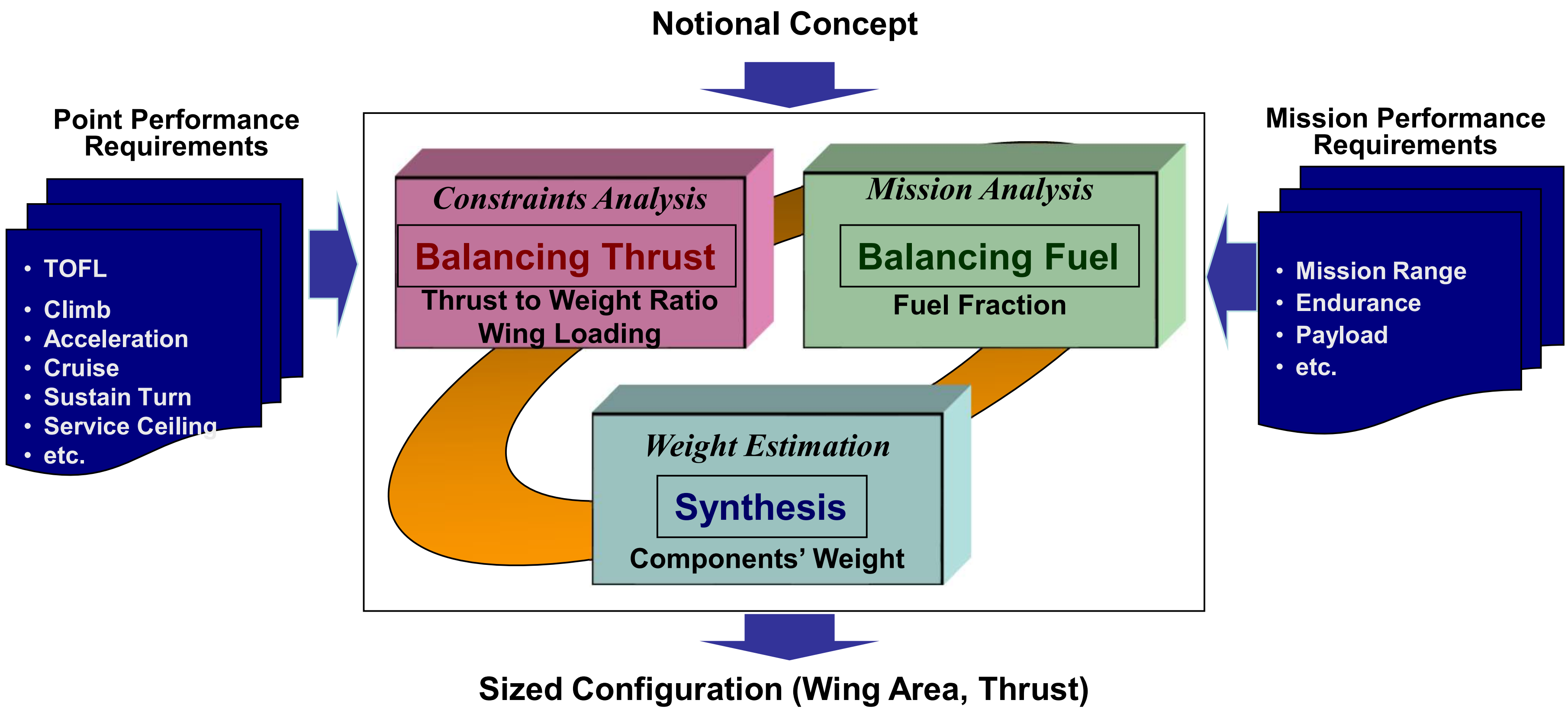
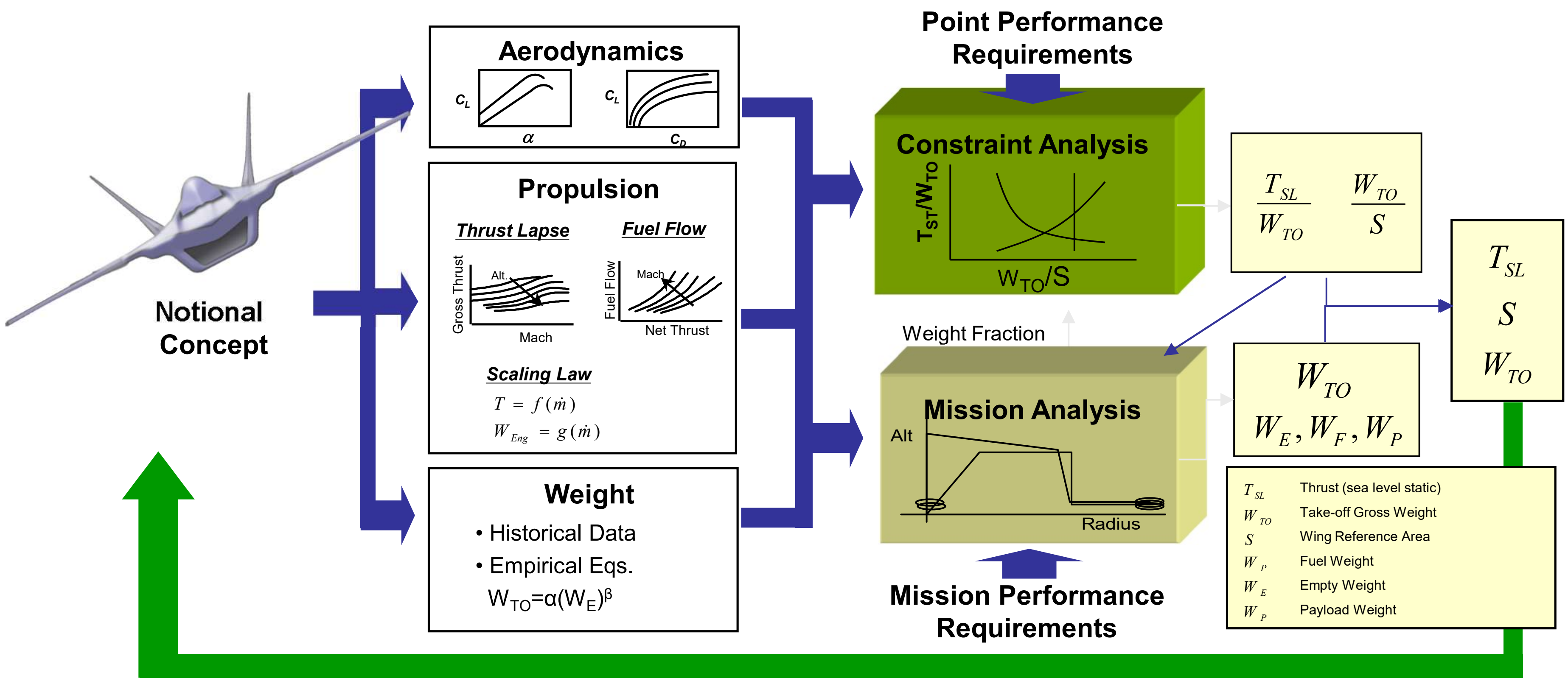
Aircraft Sizing



Traditional Aircraft Sizing Process



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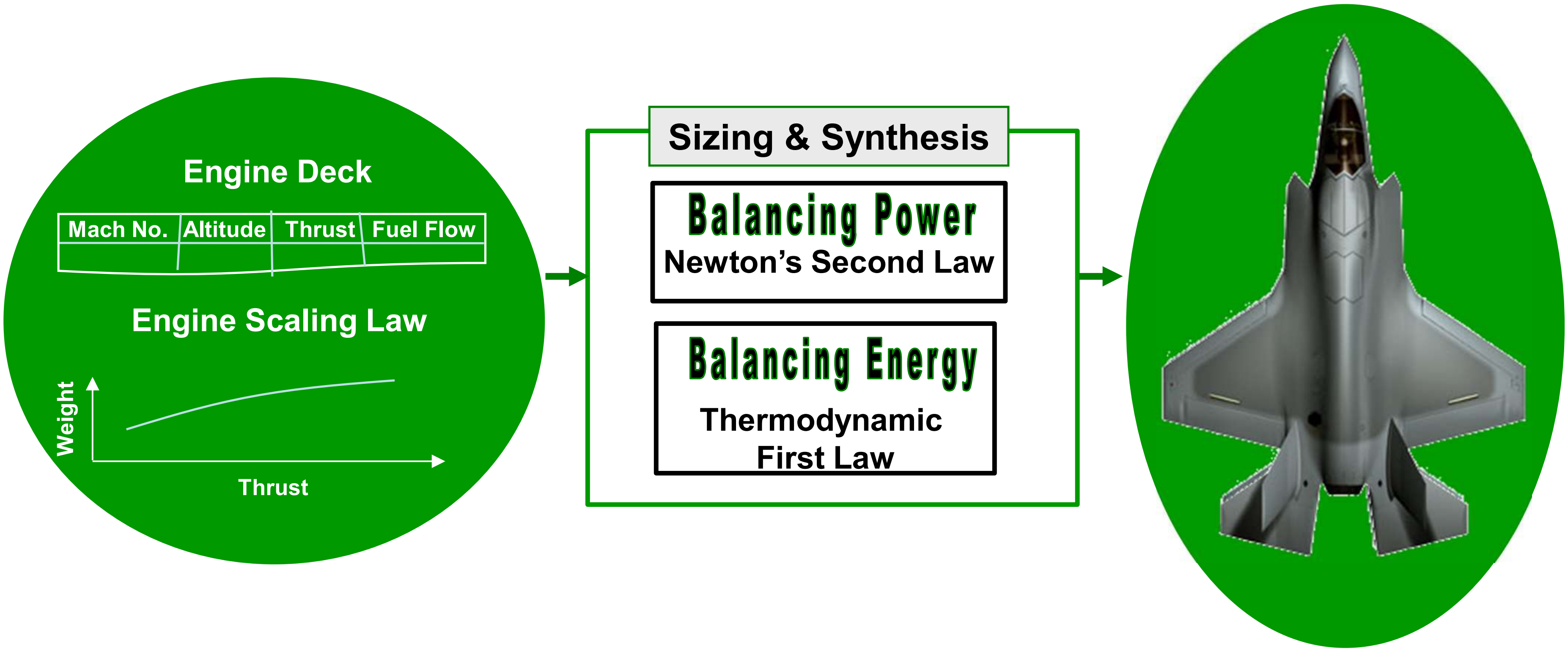
Propulsion System Integration

Conceptual Sizing



A propulsion system is characterized with numeric data sets, independent of the airframe design

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Propulsion System Integration

Detail Design
A propulsion system must be tightly integrated with airframe

Configuration Design:
- Diffuser design
- Inlet and forebody integration

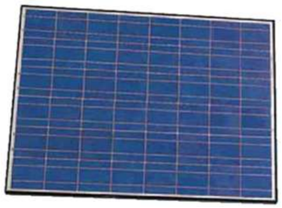
Performance:
- Thrust and fuel consumption

Structures:
- Engine mounting structures

Subsystem:
- Engine cooling
- Accessory gear box
  (PTO shaft, Bleed air)
- Secondary power system Integration

RM&S:
- Engine install and removal
- Inspection and maintenance

Propulsion System Integration



Sizing & Synthesis

- Coupling of Power and Wing Geometry
- Propulsion System Sizing
- Coupling of Energy and Wing Geometry

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Traditional Mission Analysis

$TSFC$	Thrust Specific Fuel Consumption
T	Thrust
s	distance
V	Velocity
D	Basic configuration Drag
R	Additional drag to D
β	Weight fraction
h	Altitude
g_o	Gravity constant
W_{TO}	Take-Off Gross Weight
W_F	Fuel Weight

Weight Decomposition

$$W_{TO} = W_E + W_P + W_F$$

A/C weight change equals to fuel weight change.

$$\frac{dW}{dt} = \frac{dW_F}{dt}$$

Fuel weight change (fuel flow) can be expressed as a function of thrust required.

$$\frac{dW}{dt} = \frac{dW_F}{dt} = -TSFC \times T$$

A/C weight change (fuel flow) can be expressed as a function of thrust required.

$$\frac{dW}{W} = -TSFC\ \frac{T}{W} dt = -TSFC\ \frac{T}{W}\frac{ds}{V}$$

In addition, thrust-to-weight Ratio can be related to aerodynamic performance.

Where, $$\frac{T}{W} = \left(\frac{D+R}{\beta W_{TO}}\right) + \frac{1}{V}\frac{d}{dt}\left(h + \frac{V^2}{2g_o}\right)$$

Breguet Range Equation

$$\text{Range} = \int ds = \frac{V}{TSFC}\frac{L}{D}\ln\left(\frac{W_{final}}{W_{initial}}\right)$$

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Traditional Mission Analysis

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$$\boxed{\frac{dW}{dt} = \frac{dW_F}{dt} = -TSFC \times T}$$

This assumption is no longer valid for certain types of alternative propulsion systems
- Zero Emissions Aircraft

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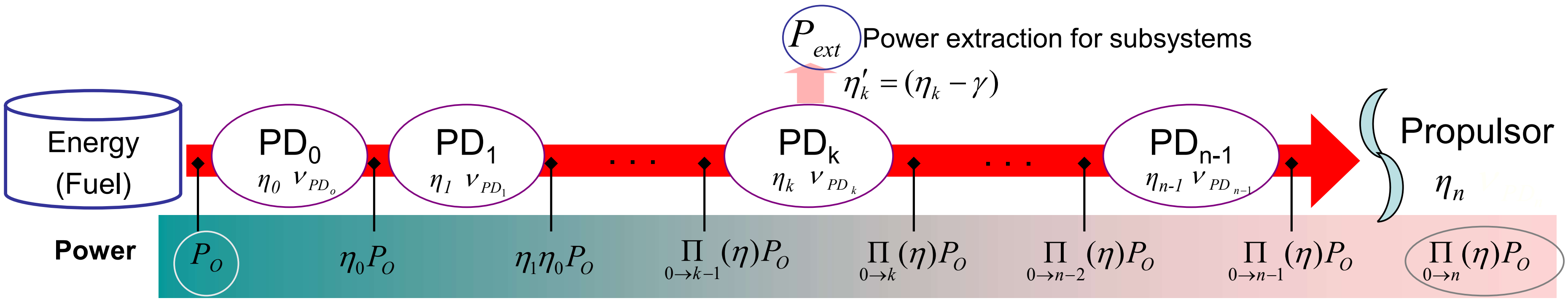
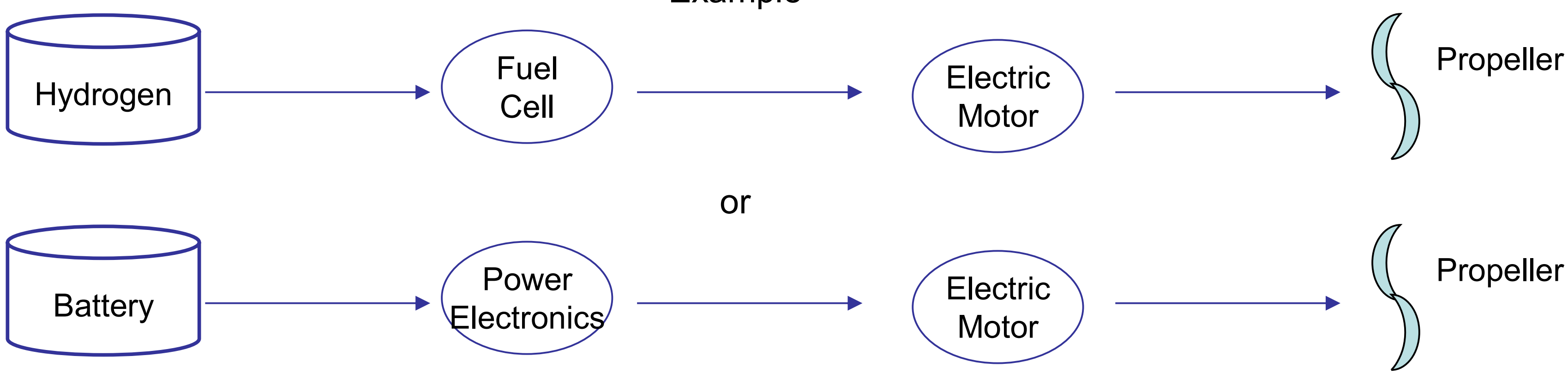
Technical Issues and Approaches

Technical Issues	*Resolution plans*
Coupling between propulsion system sizing and aircraft sizing	*Generalized propulsion system modeling*
Limited flexibility to vary "power mix" of hybrid propulsion systems	*Concept of multiple power paths*
Applicable to only limited types of fuel	*Multiple energy sources* • *Consumable energy* • *Non-consumable energy*
The time rate of change in aircraft weight does NOT necessarily equal fuel flow	*Generalized weight decomposition and weight differential equation*

Generalized Propulsion System Modeling

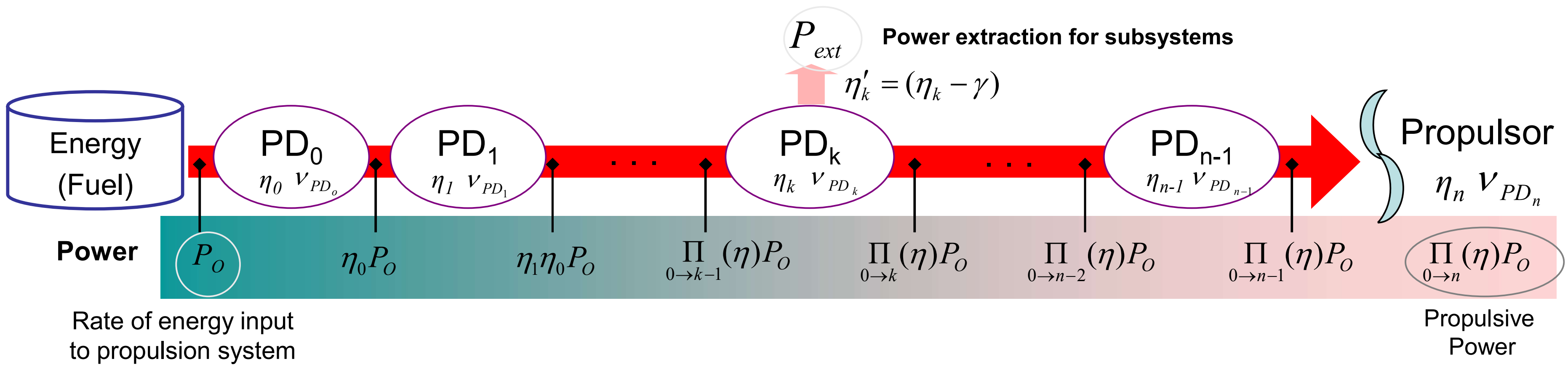


Example



Etc.

Generalized Propulsion System Modeling



Component Level

- *Efficiency Maps*
- *Specific Energy*
- *Specific Power*

$$P = \eta_n \eta_{n-1} \cdots \eta_2 \eta_1 \eta_0 P_O = \Pi(\eta) P_O$$

$$dW_{Energy} = -\frac{P}{\nu_{Energy}\,\Pi(\eta)}\,dt$$

$$W_{PS} = \sum_{i=1}^{n} W_{PD_i} = \sum_{i=1}^{n} \frac{\widehat{P}_{PD_i}}{\nu_{PD_i}}$$

System Level

- *Power*
- *Fuel Consumption*
- *System Weight*

P	Propulsive power
P_o	Component efficiency
W_{Energy}	Energy source weight
W_{PS}	Propulsion system weight
W_{PD}	Power device weight
γ	Power extraction ratio
ν_{Energy}	Specific energy
ν_{PD}	Specific power
$\Pi(\eta)$	Product of efficiencies

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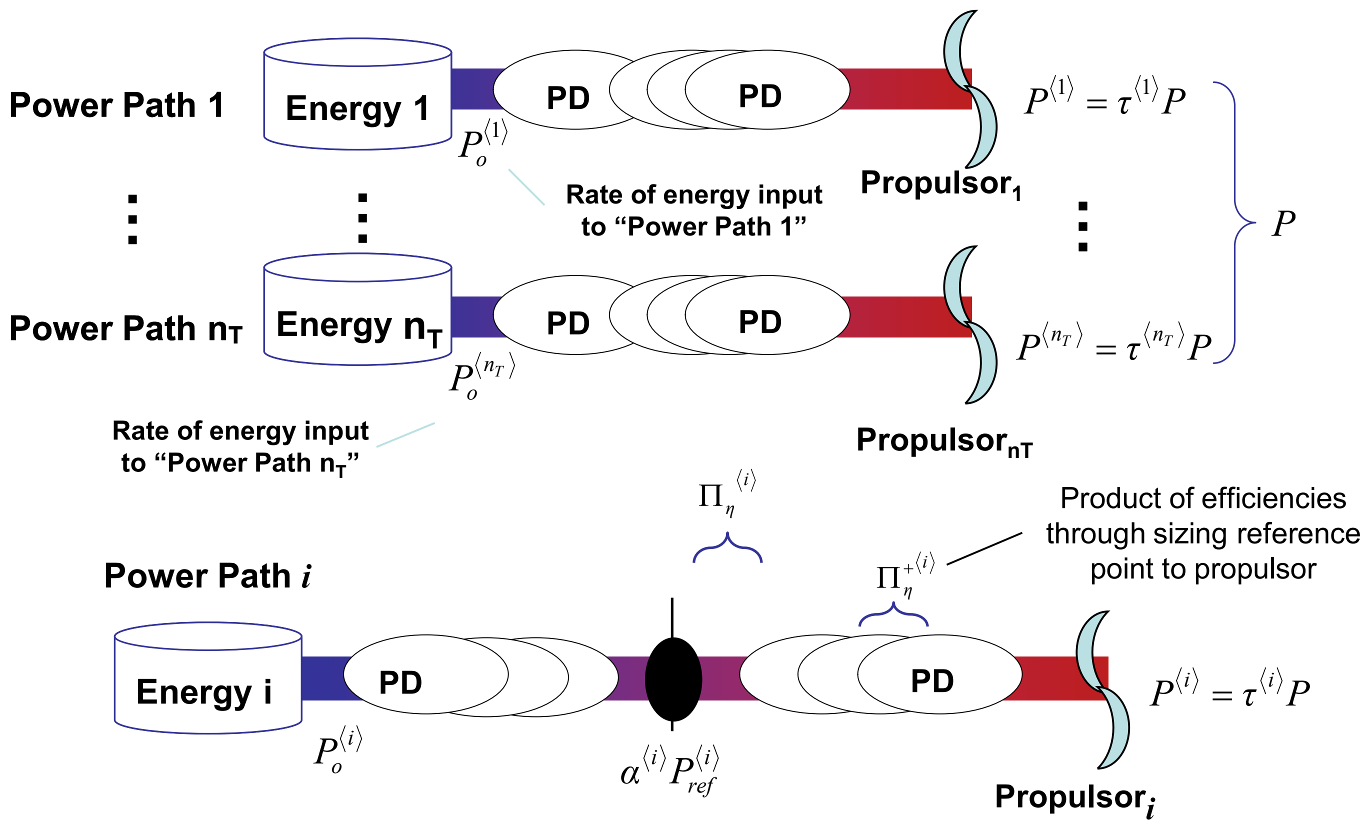
Multiple Power Paths



P	Gross propulsive power
$P^{<i>}$	i-th power path propulsive power
$\alpha^{<i>}$	Power lapse ratio measured against the sizing reference power
$\tau^{<i>}$	Power fraction of i-th power path

$$\boxed{P_{ref}^{\langle i\rangle} = \frac{\tau^{\langle i\rangle} P}{\Pi_\eta^{+\langle i\rangle} \alpha^{\langle i\rangle}}}$$

Sizing reference power for i^{th} power path

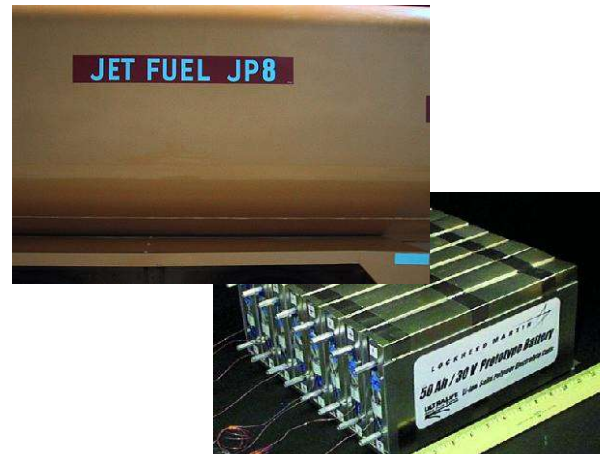
Multiple Energy Sources

- Consumable energy

  A form of energy that is derived from a source whose weight is reduced during power generation

- Non-consumable energy

  A form of energy derived from a source whose weight stays constant or changes negligibly during power generation



http://www.grc.nasa.gov/WWW/Electrochemistry/images/50_AH_Battery.jpg

$$E = \sum_{i=1}^{n_{CE}} E_{CE}^{\langle i \rangle} + \sum_{j=1}^{n_{NE}} E_{NE}^{\langle j \rangle}$$

$$W_{Energy} = \sum_{i=1}^{n_{CE}} W_{CE}^{\langle i \rangle} + \sum_{j=1}^{n_{NE}} W_{NE}^{\langle j \rangle}$$

E_{CE}	Amount of consumable onboard energy
E_{NE}	Amount of non-consumable onboard energy
W_{CE}	Consumable energy Weight
W_{NE}	Non-consumable energy Weight

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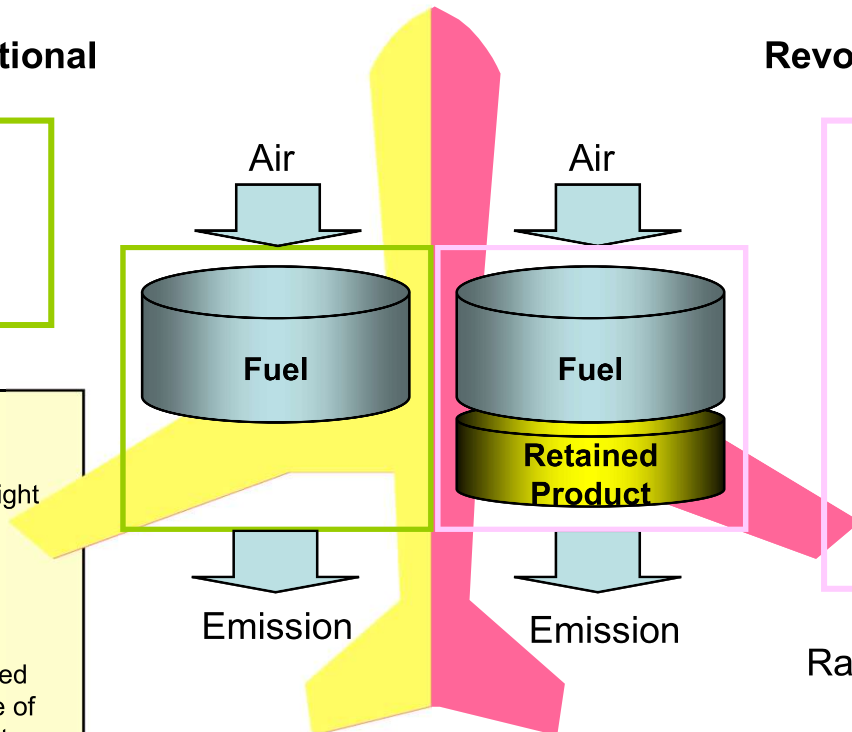
Generalized Weight Equations

Conventional

$$W = W_E + W_P + W_F$$

$$\dot{W} = \dot{W}_F$$

W_E	Empty Weight
W_R	Retained By-products Weight
W_P	Payload
$\dot{W} = \frac{dW}{dt}$	
μ	Ratio of time rate of retained product weight to time rate of consumable energy weight



Revolutionary

$$W = W_E + W_P + W_{CE} + W_R$$

$$\dot{W} = \dot{W}_{CE} + \dot{W}_R$$

$$\dot{W}_R = -\mu \dot{W}_{CE}$$

$$\dot{W} = (1-\mu)\dot{W}_{CE}$$

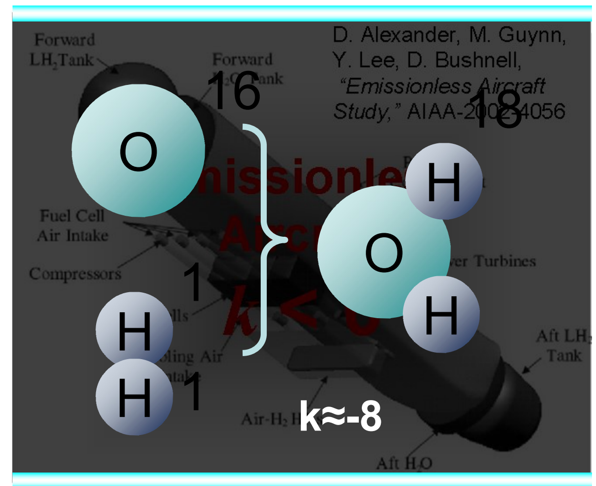
$$\dot{W} = k\dot{W}_{CE}$$

Ratio of the time rate of aircraft weight to the time rate of consumable energy weight

Generic Equation for “k” & Examples

$$k = \sum_{i=1}^{n_{CE}} \frac{1-\mu^{\langle i \rangle}}{\sum_{ii=1}^{n_{CE}} \frac{\tau^{\langle ii \rangle} \nu_{CE}^{\langle i \rangle} \Pi_{\eta}^{\langle i \rangle}}{\tau^{\langle i \rangle} \nu_{CE}^{\langle ii \rangle} \Pi_{\eta}^{\langle ii \rangle}}}$$

μ Ratio of the time rate of retained product to the time rate of consumable energy weight



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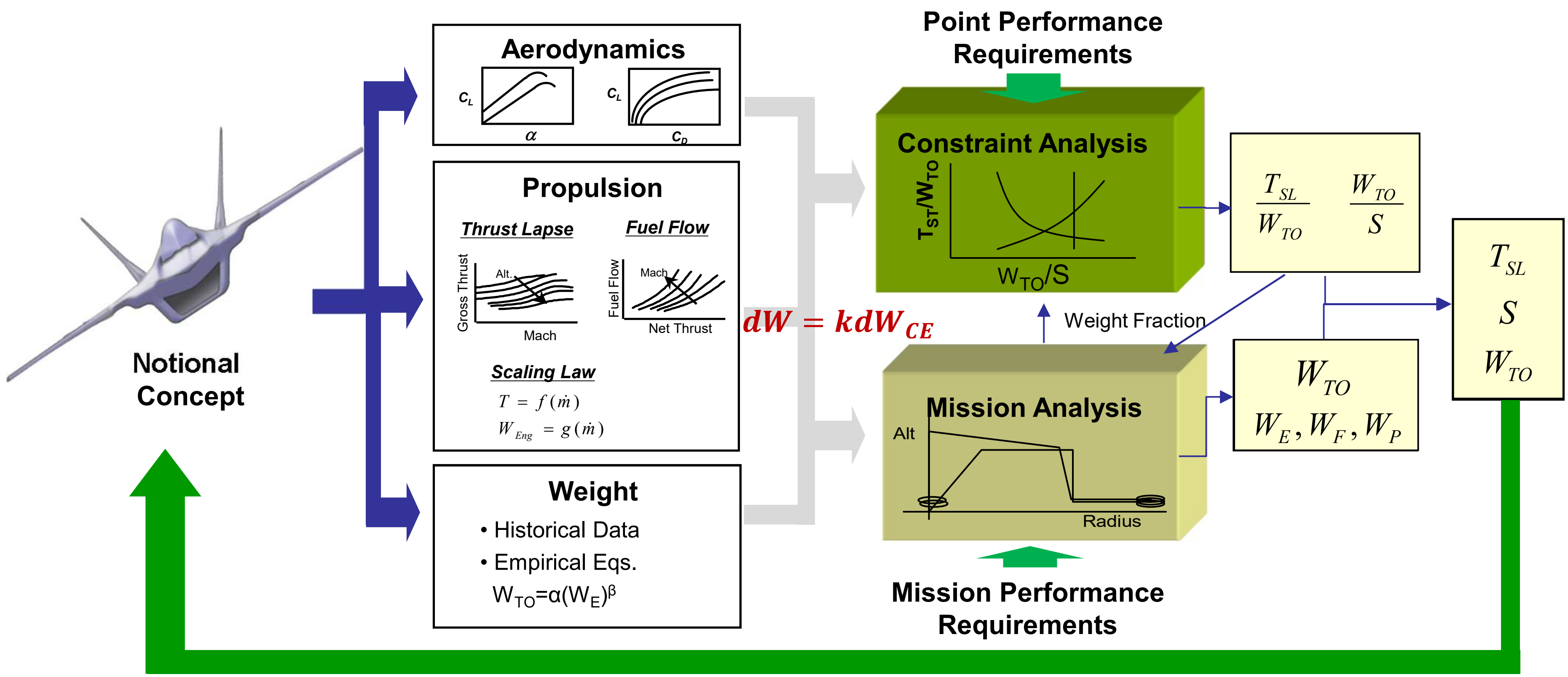
New Aircraft Sizing Process



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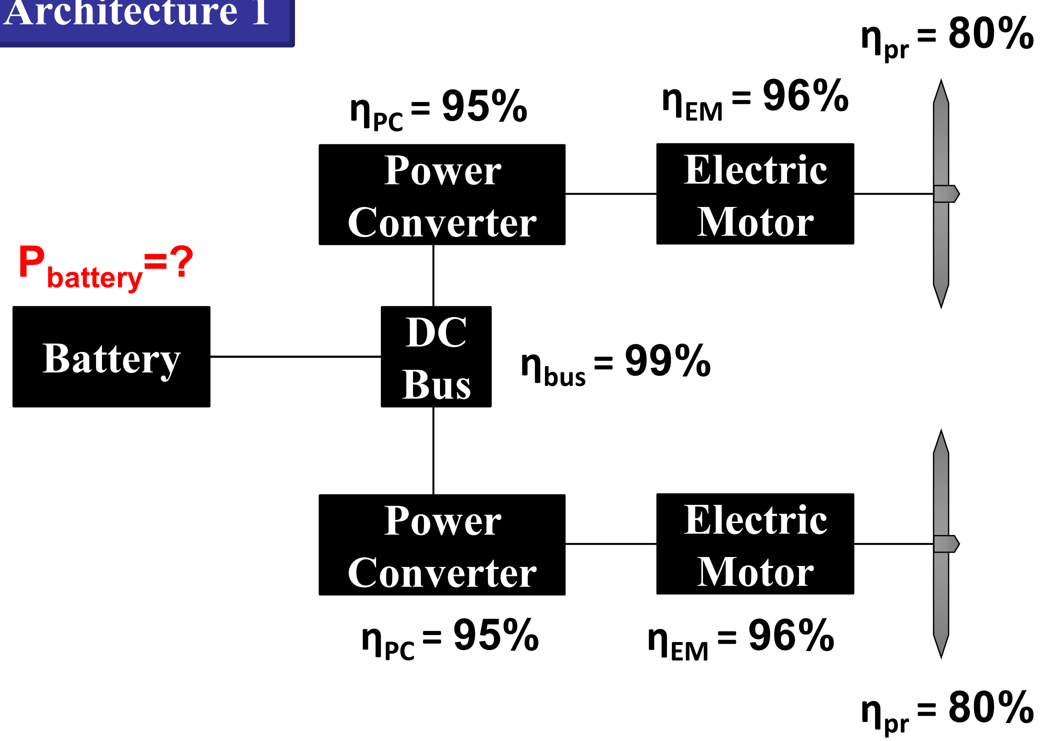
Electric Propulsion Exercise

Architecture 1

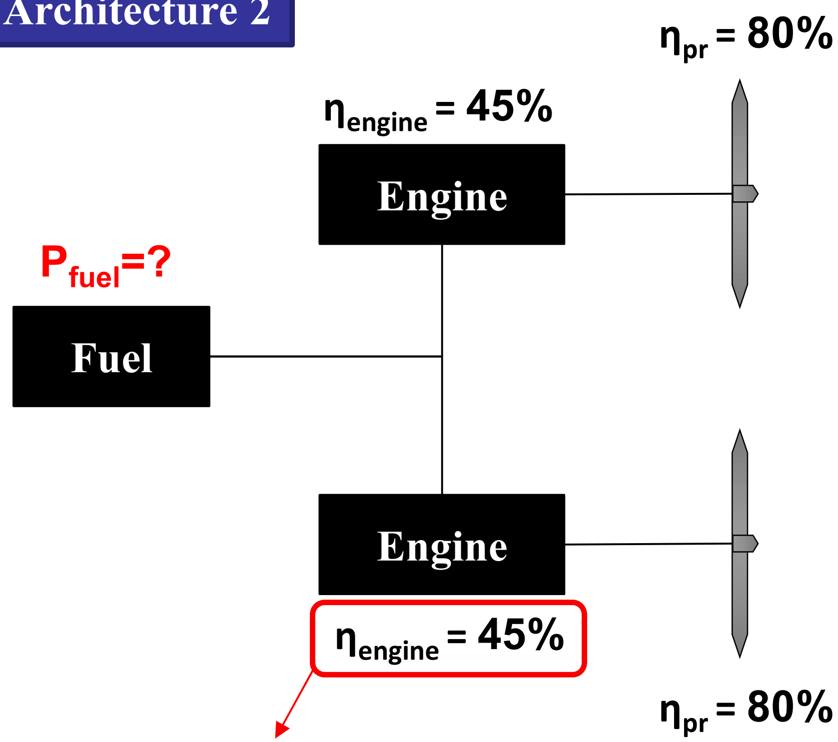


TAS = 77 m/s = 150 knots
M = 0.23
h = 2400 m
ROC = 1 m/s
dV/dt = 0.25 m/s^2
D = 860 N
m = 1360 kg
g = 9.81 m/s^2

What is the power drawn from the battery?

Conventional Propulsion Exercise

Architecture 2



Notice the efficiency drop
Why?

TAS = 77 m/s = 150 knots
M = 0.23
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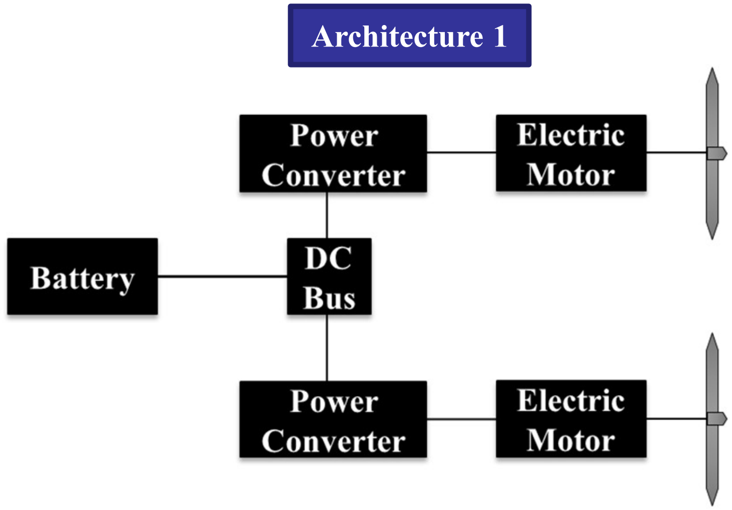
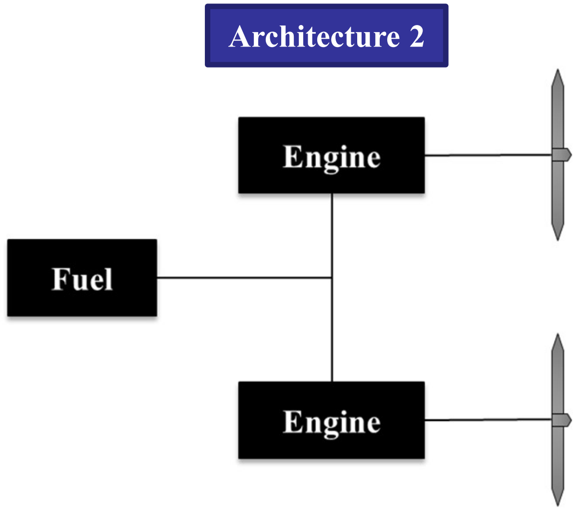
How does the power requirement from the energy storage change compared to the previous example?

Electric to Conventional Comparison





- Assume that:
  - Flight goes on for 1 minute at constant rate of climb and acceleration
  - Battery specific energy = 0.2 kWh/kg
  - Fuel specific energy = 12.2 kWh/kg
- What is the minimum required weight of the two energy sources?
  - Can you calculate the energy source weight with the given information?

Generalized Constraint Analysis Equation

Rate of Mechanical Energy Input	=	Storage Rate Of Potential Energy	+	Storage Rate Of Kinetic Energy

$$\{T-(D+R)\}V = W\frac{dh}{dt} + \frac{W}{g_o}\frac{d}{dt}\left(\frac{V^2}{2}\right)$$

Mattingly Constraint Equation

$$\boxed{\frac{T_{SL}}{W_{TO}} = \frac{\beta}{\alpha}\left\{\frac{qS}{\beta W_{TO}}\left[K_1\left(\frac{n\beta}{q}\frac{W_{TO}}{S}\right)^2 + K_2\left(\frac{n\beta}{q}\frac{W_{TO}}{S}\right) + C_{D_o} + \frac{R}{qS}\right] + \frac{1}{V}\frac{d}{dt}\left(h + \frac{V^2}{2g_o}\right)\right\}}$$

Generalized Constraint Equation

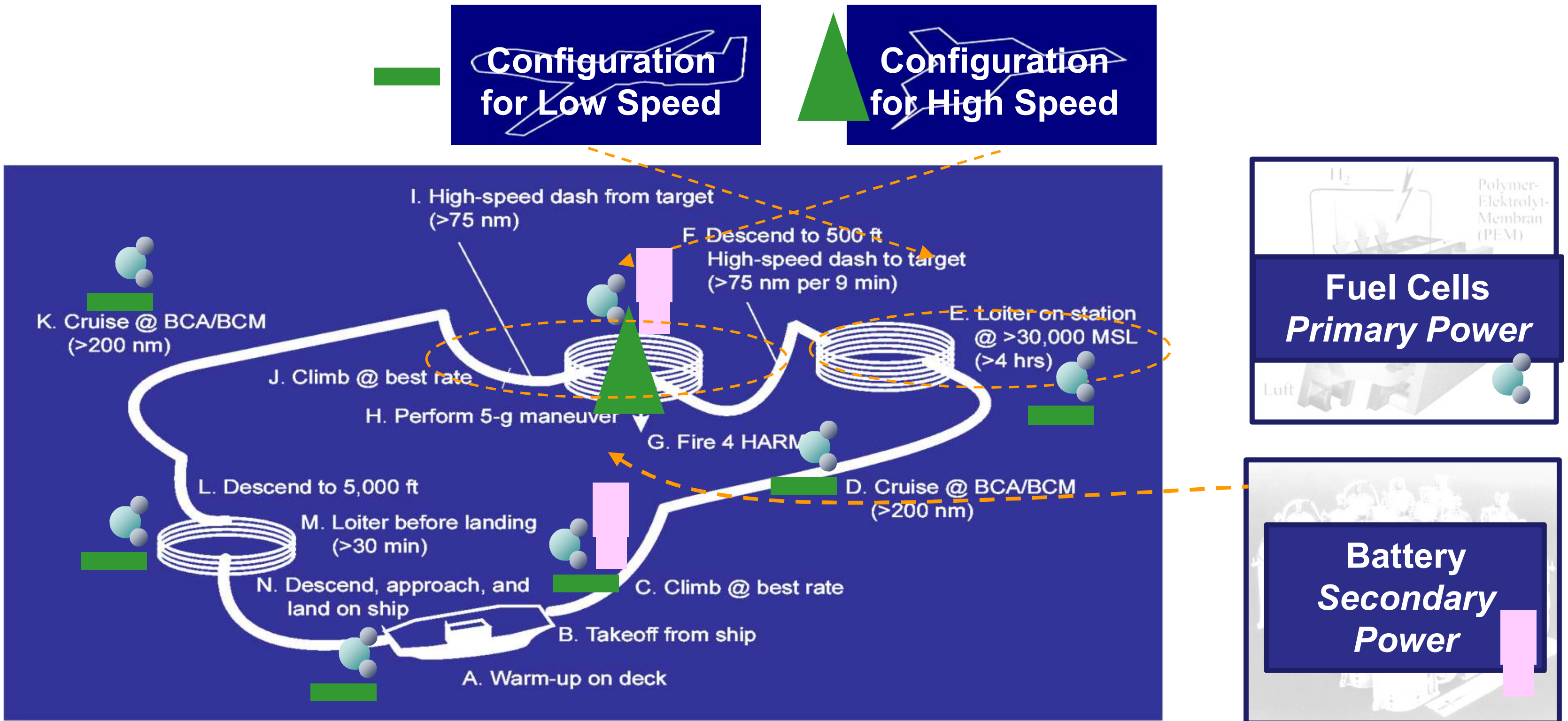
$$\boxed{\frac{P_{ref}^{\langle i\rangle}}{W_{TO}} = \frac{\tau^{\langle i\rangle}\beta}{\prod_{\eta}^{+\langle i\rangle}\alpha^{\langle i\rangle}}\left\{\frac{qS}{\beta W_{TO}}\left[K_1\left(\frac{n\beta}{q}\frac{W_{TO}}{S}\right)^2 + K_2\left(\frac{n\beta}{q}\frac{W_{TO}}{S}\right) + C_{D_o} + \frac{R}{qS}\right] + \frac{1}{V}\frac{d}{dt}\left(h + \frac{V^2}{2g_o}\right)\right\}V}$$

Constraint Equations

$$\boxed{\frac{P_{ref}^{\langle i\rangle}}{W_{TO}} = \frac{\tau^{\langle i\rangle}\beta}{\Pi_{\eta}^{+\langle i\rangle}\alpha^{\langle i\rangle}}\left\{\frac{qS}{\beta W_{TO}}\left[K_1\left(\frac{n\beta}{q}\frac{W_{TO}}{S}\right)^2 + K_2\left(\frac{n\beta}{q}\frac{W_{TO}}{S}\right) + C_{D_o} + \frac{R}{qS}\right] + \frac{1}{V}\frac{d}{dt}\left(h + \frac{V^2}{2g_o}\right)\right\}V}$$

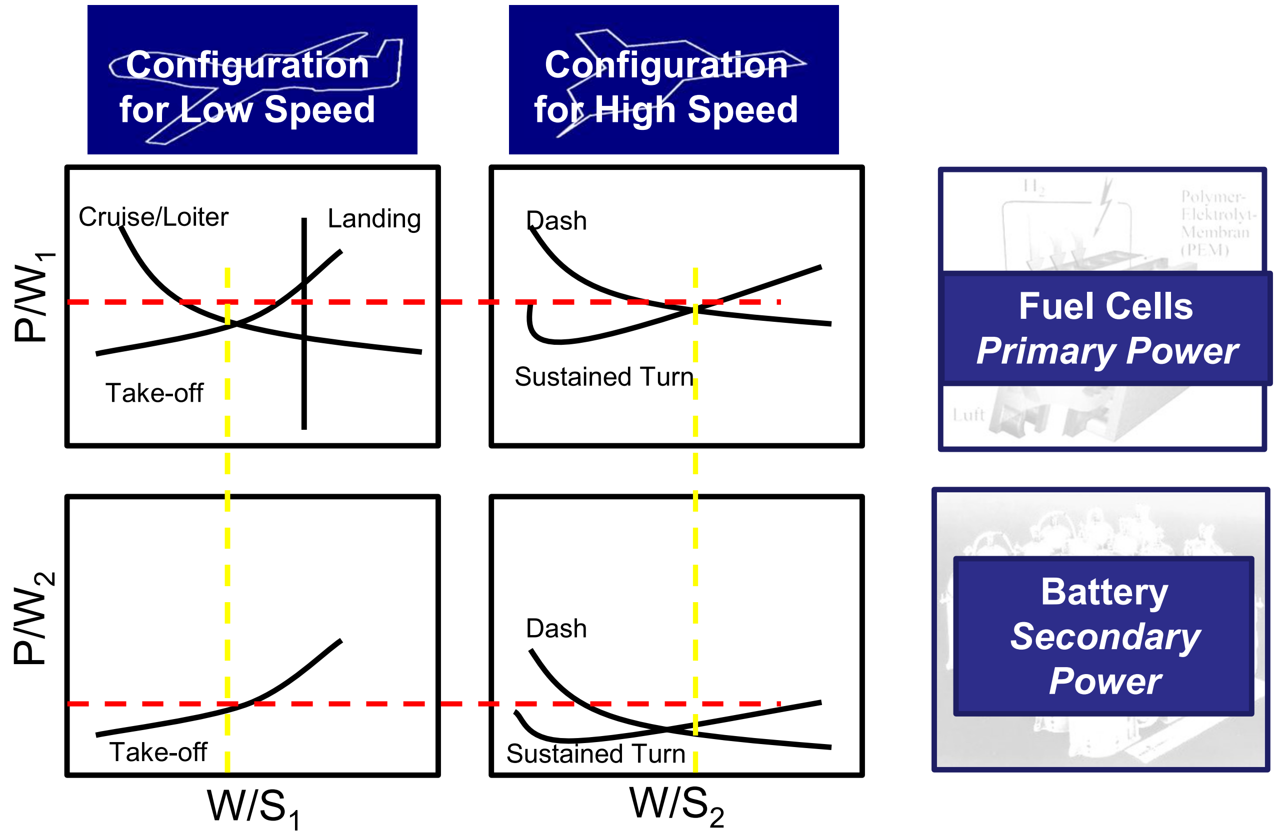
	Assumption	Constraint Equation
Take-off	$P >> (D+R)V$ $\quad \frac{dh}{dt}=0 \quad n=1$ $V_{TO} = k_{TO}V_{STALL}$	
Constant Speed Climb	$\frac{dV}{dt}=0 \quad n \approx 1$	
Cruise	$\frac{dV}{dt}=0 \quad \frac{dh}{dt}=0 \quad n=1$	
Sustained Turn	$\frac{dV}{dt}=0 \quad \frac{dh}{dt}=0$ $n=\left\{1+\left(\frac{V}{g_o R_c}\right)^2\right\}^{\frac{1}{2}} \quad n=\left\{1+\left(\frac{\Omega V}{g_o}\right)^2\right\}^{\frac{1}{2}}$	
Service Ceiling	$\frac{dh}{dt}=100\text{ ft/min} \quad \frac{dV}{dt}=0 \quad n=1$	

Constraint Analysis Matrix for Morphing Aircraft



Source: Georgia Tech, 2005 AIAA Graduate Design Competition

Constraint Analysis Matrix for Morphing Aircraft



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New Mission Analysis

Discretize the Mission Profile

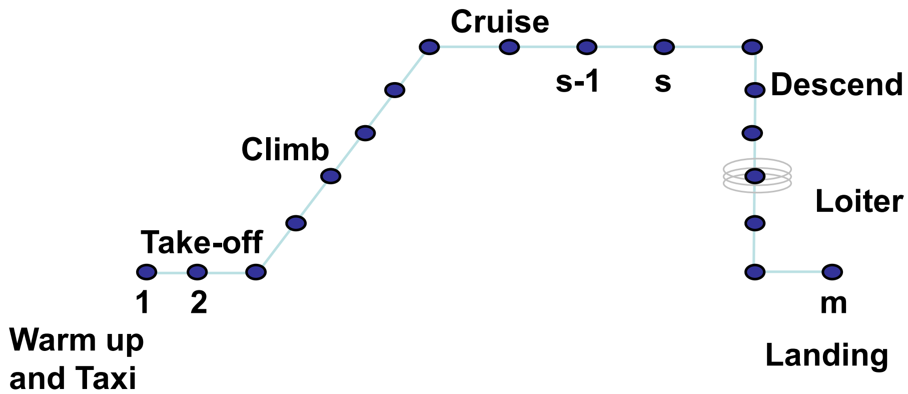
Calculate Energy Consumptions for Each Mission Segment

✓ Consumable Energy

1. *Variable Aircraft Weight ($k \neq 0$)*
2. *Constant Aircraft Weight ($k = 0$)*

✓ Non-consumable Energy

1. *With Consumable Energy*
2. *Without Consumable Energy ($k=0$)*



Integrate the Results of All Mission Segments

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Summary of Mission Analysis

Consumable Energy

Vehicle weight at the end of s-th segment

$$\Omega_{CE} = \frac{W_{CE}}{W_{TO}} = (1+\epsilon_{CE}) \sum_{s=1}^{m} \frac{W_{CE}^{(s)}}{W_{TO}}$$

$k \neq 0$

$$\frac{W_{CE}^{(s)}}{W_{TO}} = \frac{\beta^{(s-1)}}{k} \left(1 - \frac{W^{(s)}}{W^{(s-1)}} \right)$$

$$\frac{W^{(s)}}{W^{(s-1)}} = \exp\left(-k^{(s)} \Upsilon^{(s)} \Xi_{CE}^{(s)} \right)$$

$k = 0$

$$\frac{W_{CE}^{(s)}}{W_{TO}} = \beta^{(s-1)} \Upsilon^{(s)} \Xi_{CE}^{(s)}$$

$$\Xi_{CE}^{(s)} = \sum_{i=1}^{n_{CE}} \frac{\tau^{\langle i \rangle}}{\nu_{CE}^{\langle i \rangle} \Pi_{\eta}^{\langle i \rangle}}$$

$$\Upsilon^{(s)} = \int_{t^{(s-1)}}^{t^{(s)}} \left(\frac{P}{W} \right) dt$$

Ω_{CE} Consumable energy weight fraction

$\Xi_{CE}^{(s)}$ Overall power-specific fuel consumption at s-th mission segment

$\Upsilon^{(s)}$ Weight-specific work down

Non-consumable Energy

$$\Omega_{NE} = \frac{W_{NE}}{W_{TO}} = (1+\epsilon_{NE}) \sum_{s=1}^{m} \beta^{(s-1)} \Upsilon^{(s)} \Xi_{NE}^{(s)}$$

Note that $\Upsilon^{(s)}$ must not be confused with γ, which represents power extraction ratio

Mission Analysis : Consumable Energy Sizing

1. Variable Aircraft Weight ($k \neq 0$)

$$dW = k\,dW_{CE} \qquad dW_{CE_i}^{\langle i \rangle} = -\frac{\tau^{\langle i \rangle} P}{\nu_{CE_i} \Pi_\eta^{\langle i \rangle}} dt$$

$$\frac{dW}{W} = -\sum_{i=1}^{n_{CE}} \frac{k\tau^{\langle i \rangle}}{\nu_{CE}^{\langle i \rangle} \Pi_\eta^{\langle i \rangle}} \left(\frac{P}{W}\right) dt$$

$$\frac{W^{(s)}}{W^{(s-1)}} = \exp\left(-k^{(s)} \Upsilon^{(s)} \Xi_{CE}^{(s)}\right)$$

$$\frac{W_{CE}^{(s)}}{W_{TO}} = \frac{\beta^{(s-1)}}{k^{(s)}} \left(1 - \frac{W^{(s)}}{W^{(s-1)}}\right)$$

Weight specific work done

$$\Upsilon^{(s)} = \int_{t^{(s-1)}}^{t^{(s)}} \frac{P}{W} dt \approx \begin{cases} \dfrac{\Delta z_e^{(s)}}{1-u} & \text{(Positive excess power)} \\ \left(\dfrac{D+R}{W}\right) V dt \;\; or \;\; \left(\dfrac{D+R}{W}\right) ds & \text{(Zero excess power)} \end{cases}$$

Overall power-specific fuel consumption

$$\Xi_{CE}^{(s)} = \sum_{i=1}^{n_{CE}} \frac{\tau^{\langle i \rangle}}{\nu_{CE}^{\langle i \rangle} \Pi_\eta^{\langle i \rangle}}$$

Drag to thrust ratio

$$u = \frac{D+R}{T} = nV\left(\frac{C_D + C_{DR}}{C_L}\right) \Big/ \sum_{i=1}^{n_T} \frac{\Pi_{\eta_i} \alpha_i}{\beta} \frac{P_{io\,SL}}{W_{TO}}$$

Energy height

$$z_e = h + \frac{V^2}{2g_o}$$

Weight fraction

$$\beta^{(s-1)} = \frac{W^{(s-1)}}{W_{TO}} \qquad \text{(Normal case)}$$

$$= \frac{W^{(s-1)} - W_P^{(s-1)}}{W_{TO}} \qquad \text{(Payload drop)}$$

Note that $\Upsilon^{(s)}$ is displayed as $\mathrm{Y}^{(s)}$

Mission Analysis : Consumable Energy Sizing

2. Constant Aircraft Weight (k= 0)

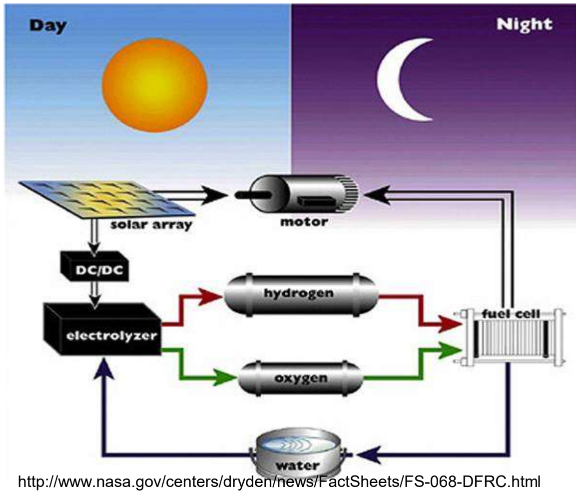
$$\frac{dW_{CE}}{W} = -\sum_{i=1}^{n_{CE}} \frac{\tau^{\langle i \rangle}}{\nu_{CE_i} \Pi_{\eta}^{\langle i \rangle}} \left(\frac{P}{W} \right) dt$$

$$\frac{W_{CE}^{(s)}}{W} = \int_{t^{(s)}}^{t^{(s-1)}} \sum_{i=1}^{n_{CE}} \frac{\tau^{\langle i \rangle}}{\nu_{CE_i} \Pi_{\eta}^{\langle i \rangle}} \left(\frac{P}{W} \right) dt$$

$$\frac{W_{CE}^{(s)}}{W_{TO}} = \beta^{(s-1)} \Upsilon^{(s)} \Xi_{CE}^{(s)}$$

$$\frac{W_{CE}}{W_{TO}} = \Omega_{CE} = (1 + \varepsilon_{CE}) \sum_{s=1}^{m} \frac{W_{CE}^{(s)}}{W_{TO}}$$

http://www.dfrc.nasa.gov/Gallery/Photo/Helios/Small/ED03-0152-2.jpg



http://www.nasa.gov/centers/dryden/news/FactSheets/FS-068-DFRC.html

Note that $\Upsilon^{(s)}$ is displayed as $\Upsilon^{(s)}$

Mission Analysis: Non-consumable Energy Sizing

1. Presence of Consumable Energy

$$dE_{NE}^{\langle j\rangle} = \frac{\tau^{\langle j\rangle}}{\tau^{\langle i\rangle}} \frac{\Pi_{\eta}^{\langle i\rangle}}{\Pi_{\eta}^{\langle j\rangle}} \nu_{CE}^{\langle i\rangle} dW_{CE}^{\langle i\rangle}$$

$$\left(\frac{E_{NE}^{\langle j\rangle}}{W_{TO}}\right)^{(s-1)} - \left(\frac{E_{NE}^{\langle j\rangle}}{W_{TO}}\right)^{(s)} = \frac{\tau^{\langle j\rangle}}{\tau^{\langle i\rangle}} \frac{\Pi_{\eta}^{\langle i\rangle}}{\Pi_{\eta}^{\langle j\rangle}} \frac{\nu_{CE}^{\langle i\rangle} W_{CE}^{(s)}}{W_{TO}}$$

2. Non-consumable Energy Only

$$dE_{NE}^{\langle j\rangle} = -p_o^{\langle j\rangle} dt = -\frac{\tau^{\langle j\rangle} P}{\Pi_{\eta}^{\langle j\rangle}} dt \qquad \frac{dE_{NE}^{\langle j\rangle}}{\beta W_{TO}} = -\frac{\tau^{\langle j\rangle}}{\Pi_{\eta}^{\langle j\rangle}} \frac{P}{W} dt$$

$$\left(\frac{E_{NE}^{\langle j\rangle}}{W_{TO}}\right)^{(s-1)} - \left(\frac{E_{NE}^{\langle j\rangle}}{W_{TO}}\right)^{(s)} = \int_{t^{(s-1)}}^{t^{(s)}} \frac{\beta^{(s-1)} \tau^{\langle j\rangle}}{\Pi_{\eta}^{\langle j\rangle}} \frac{P}{W} dt$$

$$\frac{E_{NE}^{\langle j\rangle}}{W_{TO}} = \sum_{s=1}^{m} \frac{\beta^{(s-1)} \Upsilon^{(S)} \tau^{\langle j\rangle}}{\Pi_{\eta}^{\langle j\rangle}}$$

$$W_{NE} = \sum_{j=1}^{n_{NE}} W_{NE}^{\langle j\rangle} = \sum_{j=1}^{n_{NE}} \frac{E_{NE}^{\langle j\rangle}}{\nu_{NE}^{\langle j\rangle}}$$

$$\frac{W_{NE}}{W_{TO}} = \Omega_{NE} = (1+\varepsilon_{CE}) \sum_{s=1}^{m} \beta^{(s-1)} \Upsilon^{(s)} \Xi_{NE}^{(s)}$$

Note that $\Upsilon^{(s)}$ is displayed as $\Upsilon^{(s)}$

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Aircraft Weight Estimation

$$W_{TO} = W_E + W_{CE} + W_P$$

Traditional

$$W_E = \Gamma W_{TO}$$

New Formulation

$$W_E = W'_E + \delta W_E + W_{NE} + W_{PS}$$

Requirements

Mission Analysis

$$W_{TO} = \frac{W_P}{1 - \Gamma' - \Delta - \Phi - \Omega_{CE} - \Omega_{NE}}$$

$$W_{CE} = \Omega_{CE} W_{TO}$$

$$W_{NE} = \Omega_{NE} W_{TO}$$

Physics Based Analysis

$$W_{PS} = \Phi W_{TO}$$

$$\delta W_E = \Delta W_{TO}$$

Historical Database

$$W'_E = \Gamma' W_{TO}$$

$$W_{TO} = \frac{W_P}{1 - \Gamma' - \Delta - \Phi - \Omega_{CE} - \Omega_{NE}}$$

W'_E Empty weight excluding propulsion system weight

W_{PS} Weight of propulsion systems

δW_E Correction to traditional empty weight

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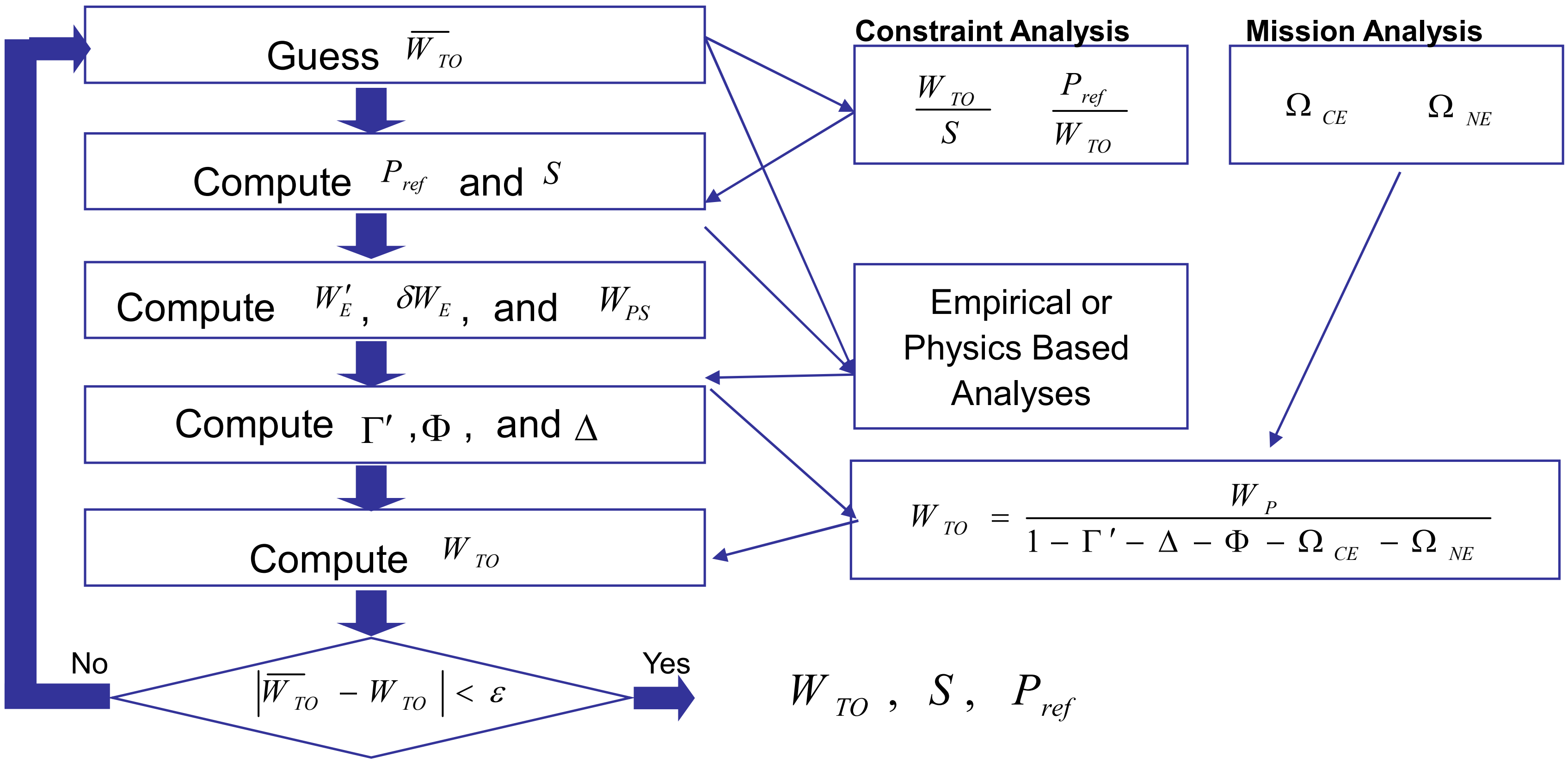
Weight Estimation Process



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Comparison

	Old Formulation	New Formulation
Weight Decomposition	$W = W_E + W_F + W_P$	$W = W_E + W_P + W_{CE} + W_R$ $W_E = W_E' + W_{PS} + W_{NE} + \delta W_E$
Weight Diff. Equation	$dW = dW_F$	$dW = kdW_{CE}$
Onboard Energy Weight	$W_F = (1+\varepsilon)(1-\Pi)W_{TO}$	$W_{CE} = \Omega_{CE} W_{TO}$ $where\ \Omega_{CE} = (1+\varepsilon_{CE})\sum_{s=1}^{m} \frac{W_{CE}^{(s)}}{W_{TO}}$ $When\ k \neq 0$ $\frac{W_{CE}^{(s)}}{W_{TO}} = \frac{\beta^{(s-1)}}{k^{(s)}}\left(1-\frac{W^{(s)}}{W^{(s-1)}}\right)$ $\frac{W^{(s)}}{W^{(s-1)}} = \exp\left(-k^{(s)}\Upsilon^{(s)}\Xi_{CE}^{(s)}\right)$ $When\ k = 0$ $\frac{W_{CE}^{(s)}}{W} = \beta^{(s-1)}\Upsilon^{(s)}\Xi_{CE}^{(s)}$ $W_{NE} = \Omega_{NE} W_{TO}$ $where\ \Omega_{NE} = (1+\varepsilon_{NE})\sum_{s=1}^{m} \beta^{(s-1)}\Upsilon^{(s)}\Xi_{NE}^{(s)}$
Take-Off Gross Weight	$W_{TO} = \frac{W_P}{1-\Gamma-\frac{W_F}{W_{TO}}}$	$W_{TO} = \frac{W_P}{1-\Gamma'-\Delta-\Phi-\Omega_{CE}-\Omega_{NE}}$

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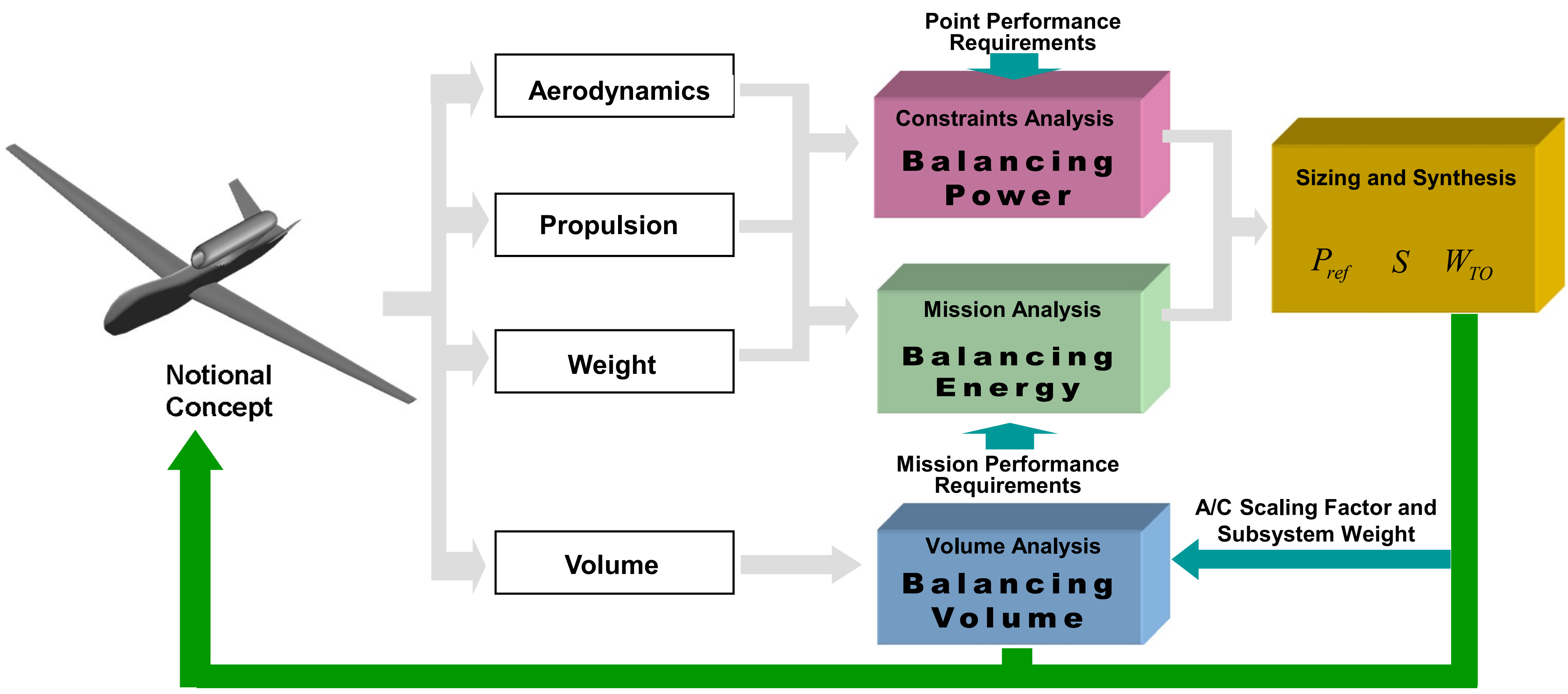
Comprehensive Aircraft Sizing Method



Generalized Breguet Range Equation (GBRE)

Consumable Energy

When k ≠ 0

$$R = \frac{\nu_{CE}\Pi_\eta}{k}\frac{L}{D}\ \ln\left(\frac{1}{1-k\frac{W_{CE}}{W_{TO}}}\right)$$

When k = 0

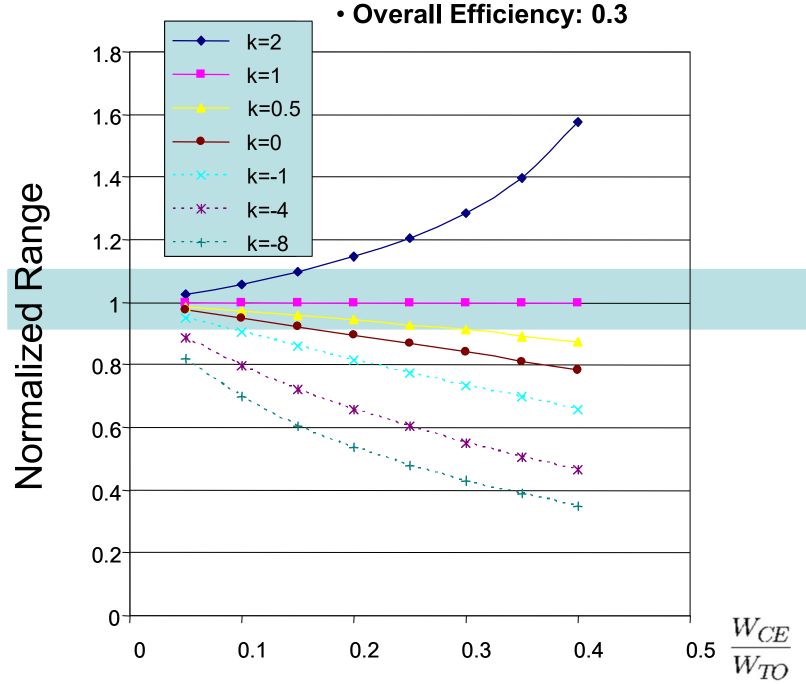
$$R = \nu_{CE}\Pi_\eta\frac{L}{D}\frac{W_{CE}}{W_{TO}}$$

Non-consumable Energy

$$R = \nu_{NE}\Pi_\eta\frac{L}{D}\frac{W_{NE}}{W_{TO}}$$

Useful for a first order estimate of range when limited information is available

- Hydrogen Fuel
- L/D : 15
- Overall Efficiency: 0.3



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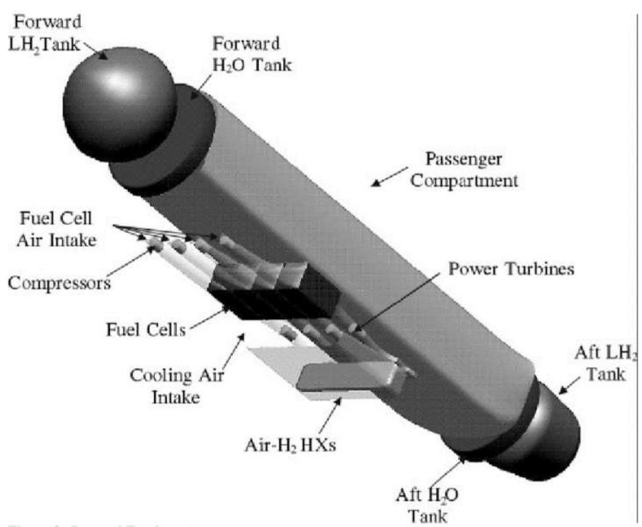
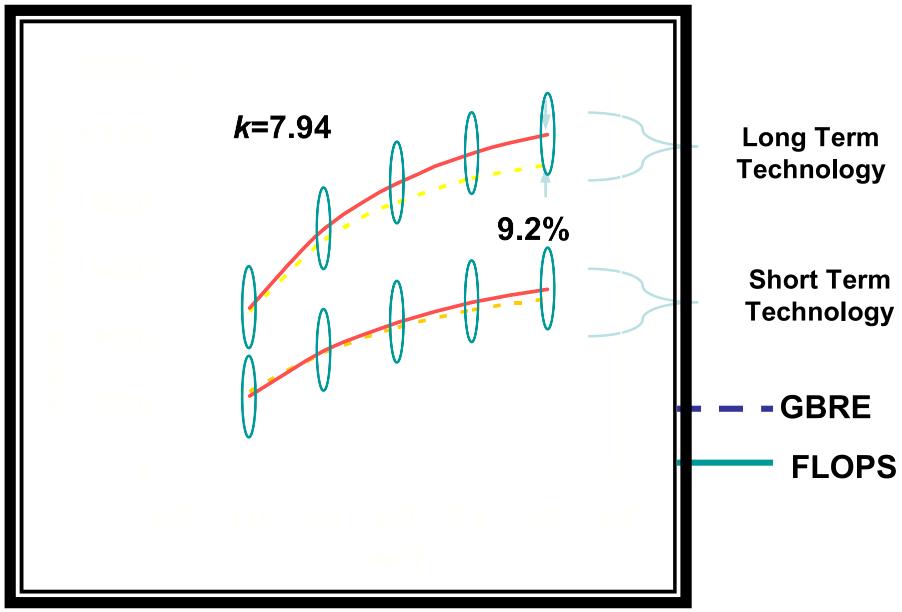
Application of GBRE

Zero Emission Aircraft Study Performed by MSE Technology Applications Inc. and NASA LaRC

- 300 PAX subsonic transport fueled by LH_2
- Electric ducted fan engines powered by a PSOFC (planar solid oxide fuel cell) system
- Water vapor is stored in two cylindrical water tanks
- Analyzed by a customized version of FLOPS modified by NASA LaRC





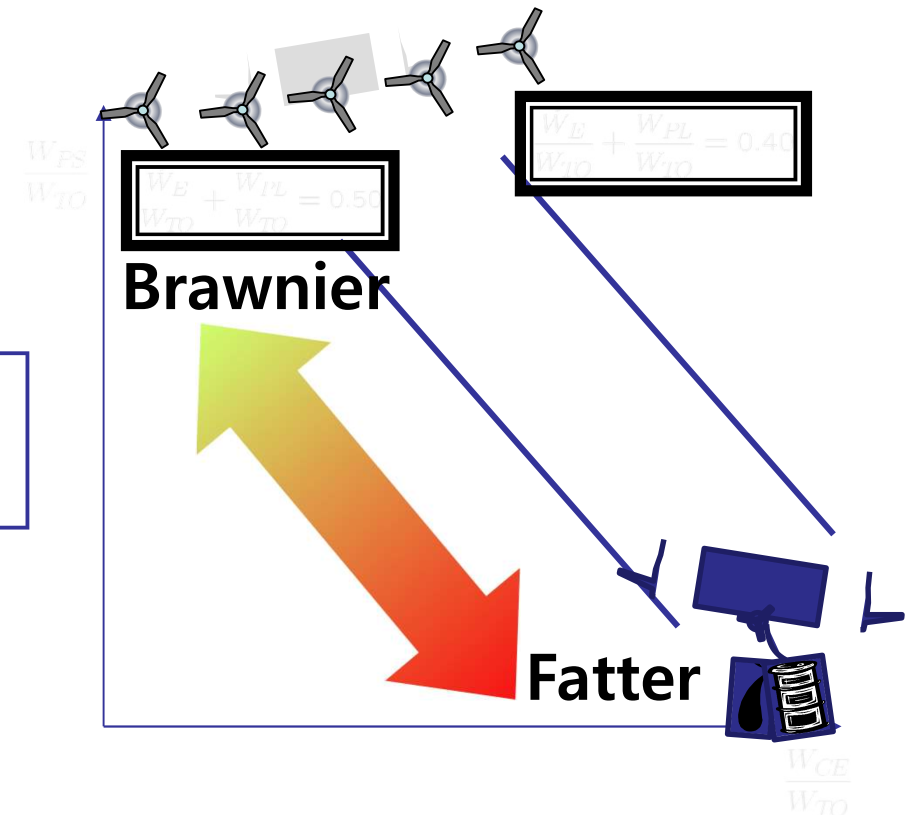
Duality between Energy Source and Propulsion System Weight

$$W_{TO} = W_E + W_{PS} + W_{CE} + \delta W_E + W_{PL}$$

$$(1+e_{PS})\frac{W_{PS}}{W_{TO}} + (1+e_{CE})\frac{W_{CE}}{W_{TO}} = 1 - \frac{W_E}{W_{TO}} - \frac{W_{PL}}{W_{TO}}$$

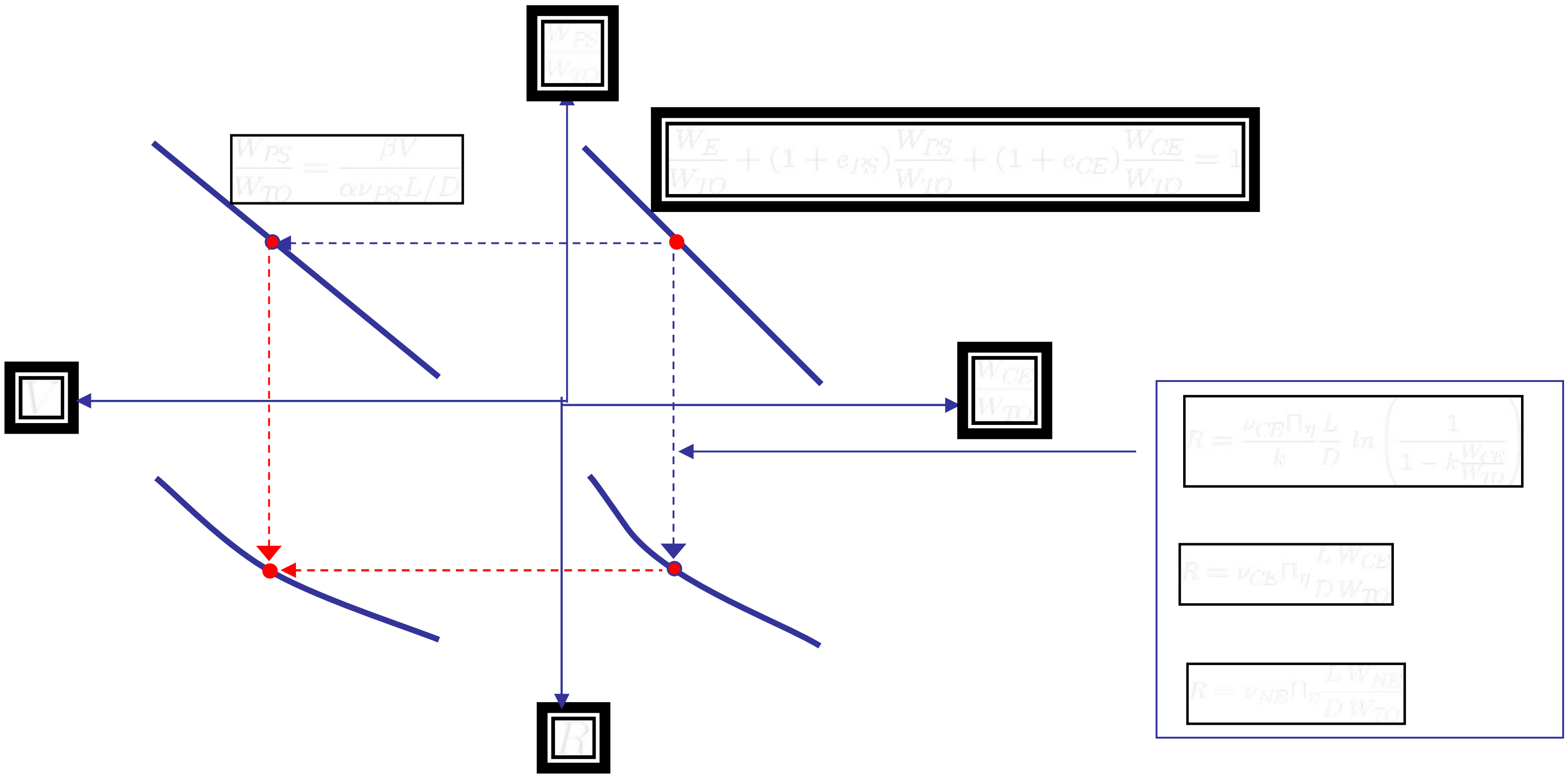
Expresses a set of allowable values for :

- **Propulsion system weight fraction**
- **Energy weight fraction**



The impact on the empty weight from integrating an alternative propulsion system and an consumable energy source, all normalized by the take-off gross weight.

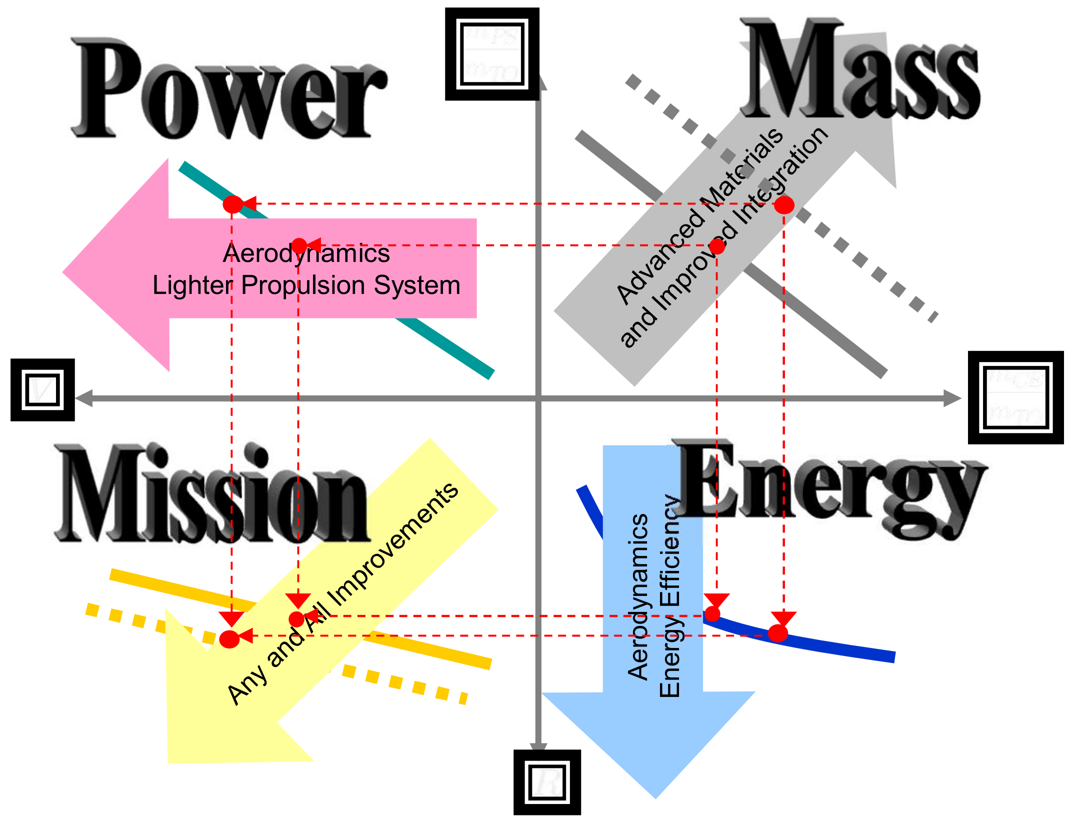
Mapping Weight Fractions to Performance



Non-dimensional Aircraft Mass (NAM) Ratio Diagram

For a given energy-propulsion system architecture, this diagram:

- Develops ***the performance frontiers*** in terms of range and velocity
- Enables a designer to rapidly examine ***a fleet of aircraft designs***
- Identifies ***the most appropriate mission***



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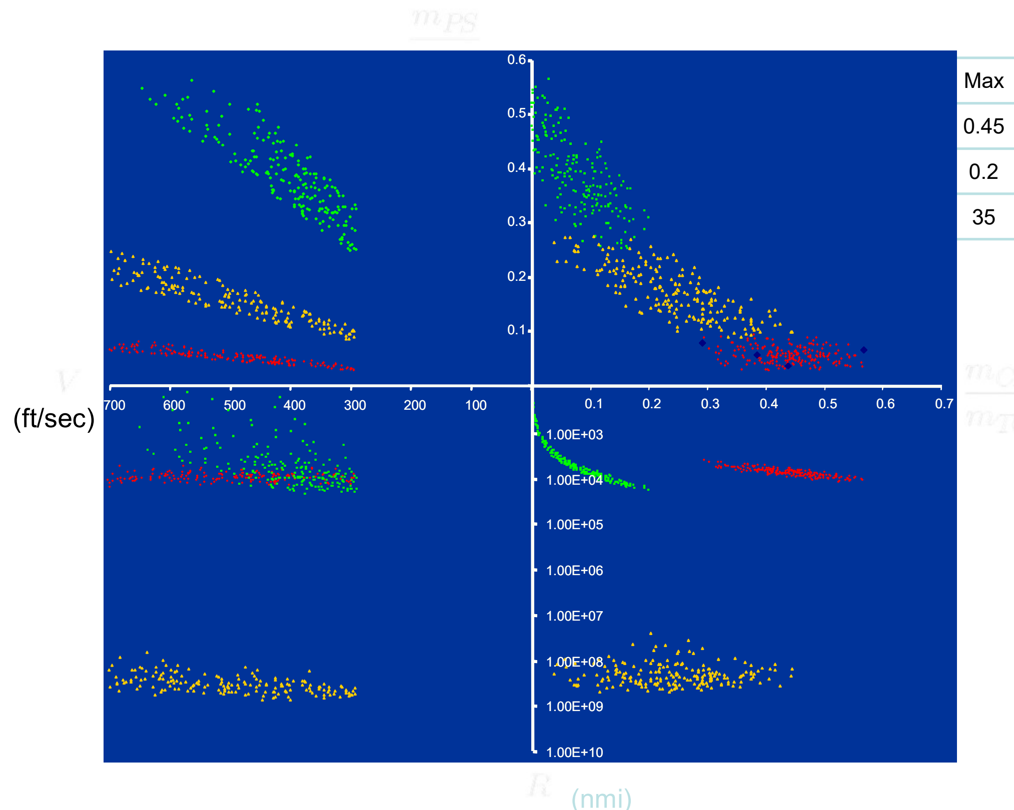
Example: Comparison of Three Architectures

- **Architecture A**: Conventional turbo prop engine fueled with jet fuel
- **Architecture B**: PEMFC-powered electric propulsion system fueled with liquid hydrogen
- **Architecture C**: Triggered isomer heat exchanger engine (TIHE) fueled isomers of hafnium (^{178}Hf)

Architecture	A	B	C
e_{PS}	0	0	0.51
e_{CE} (e_{NE})	0	0.5	0
Π_η	0.16 - 0.2	0.38 - 0.43	0.35 - 0.5
ν_{CE} (ν_{NE}) (ft)	1.786×10^{7}	4.464×10^{7}	5.653×10^{11}
ν_{PS} (ft/sec)	1400	138	421
α	0.27	0.3	0.3



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Symbols (1/2)

C_D	Coefficient of clean configuration drag
C_{D_o}	Zero lift drag coefficient
C_{DR}	Coefficient of additional drag
D	Basic configuration drag
E	Amount of stored onboard energy
E_{CE}	Amount of consumable onboard energy
E_{NE}	Amount of non-consumable onboard energy
g_o	Gravity constant
h	Altitude
k	Ratio of the time rate of aircraft weight change to the time rate of consumable energy weight change
K_1	Drag polar coefficient for 2nd order term
K_2	Drag polar coefficient for 1st order term
m	Number of total mission segments
n	Load factor
n_T	Number of total power paths
n_{CE}	Number of consumable power paths
n_{NE}	Number of non-consumable power paths
n_{PD}	Number of power devices
P	Power available

P_o	Power input from original energy source
P_{ref}	Sizing reference power
q	Dynamic pressure
R	Additional drag to D
s	Travel distance
S	Wing area
S_G	Ground roll
t	Time
T	Thrust
u	Drag to thrust ratio
V	Free stream velocity
V_{stall}	Stall speed
V_{TO}	Take-off speed
W	Instantaneous aircraft weight
W_{CE}	Consumable energy weight
W_{energy}	Total stored energy weight
W_E	Empty weight
W_F	Fuel weight
W_{NE}	Non-consumable energy weight
W_P	Payload weight
W_{PS}	Propulsion system weight
W_{TO}	Take-off gross weight
z_e	Energy height

Symbols (2/2)

α	Power lapse ratio
β	Weight fraction
Δ	Weight correction factor
ϵ_{CE}	Consumable energy allowance ratio
ϵ_{NE}	Non-consumable energy allowance ratio
η	Component efficiency
η_P	Propulsor efficiency
Γ	Empty weight fraction
$\tilde{\Gamma}$	Fraction of empty weight excluding propulsion system weight
μ	Stored product to fuel ratio
ν_{CE}	Specific energy of consumable energy
ν_{NE}	Specific energy of non-consumable energy
ν_{PD}	Specific power of power devices

Ω_{CE}	Consumable energy weight fraction
Ω_{NE}	Non-consumable energy weight fraction
Φ	Power devices weight fraction
Π_η	Overall efficiency of individual power path
ρ	Free-stream air density
τ	Power fraction of individual power path
Υ	Weight-specific mechanical energy of aircraft
Ξ_{CE}	Overall power specific fuel consumption
Superscript	
$\langle i \rangle$	ID number of a power path powered by consumable energy sources
$\langle j \rangle$	ID number of a power path powered by non-consumable energy sources
(s)	Mission segment number

$\Pi_\eta^{+\langle i \rangle}$ **Product of efficiencies from sizing reference point to propulsor**