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# Exploration of Hybrid Electric Propulsion in Regional Aircraft

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Challenge the future 1

#### Contents

Feasibility of hybrid-electric aircraft
3 Recent studies (S1,S2,S3)
Project NOVAIR
DUUC initiative
Conclusions



# Technology advancement

Technology demonstrators to validate basic assumptions and to drive technology maturations





S1: Analysis & design of a hybrid electric regional aircraft

#### Objective

Assess the potential fuel consumption reduction of hybrid-electric regional aircraft, compared to a reference aircraft by 2035

□Fuel is replaced partly by batteries as **energy source** 

□Explore design space



# S1: Reference Aircraft

Comparison between reference aircraft design and ATR-72-600:





# S1: Reference Aircraft

#### Reference aircraft design

Comparison between reference aircraft design and ATR-72-600:

Parameter	ATR-72-600	Reference aircraft	Difference
MTOM [kg]	22800	22340	- 2.0 %
Mission fuel mass [kg]	2000	2050	+ 2.5 %
Empty mass [kg]	13010	12780	- 1.8 %
Wing span [m]	27.05	26.5	- 2.0 %
Wing area [m <sup>2</sup> ]	61	58.54	- 4.2 %
Fuselage length [m]	27.17	27	- 0.6 %



# S1: Aircraft hybrid electric propulsion integration



- □ Traditional HEPS based AC layout
- Electrical motors coupled in parallel
- All additional systems and wiring taken into account



### S1: Parallel hybrid electric propulsion system architecture





#### S1: New Brequet Range Equation

Instead of traditional Brequet range equation:

$$Range = \frac{\eta_{prop}}{SFC} * \frac{C_L}{C_D} * \ln\left(\frac{m_{start}}{m_{end}}\right)$$

Adapted version for hybrid electric propulsion:

$$Range = \frac{1}{\frac{S}{\eta_{el}} + (1 - S) * SFC * e_{fuel}} * \frac{C_L}{C_D} * \eta_{prop} * \frac{1}{e_{combined}} * ln\left(\frac{e_{combined} * E_{start} + m_{empty}}{m_{empty}}\right)$$

Where:

 $\eta_{el}$  = total electrical efficiency from battery to electric motor output  $e_{\text{combined}}$  = combined specific energy of battery and fuel:

$$e_{combined} = \frac{H_E * e_{fuel} + (1 - H_E) * e_{bat}}{e_{fuel} * e_{bat}}$$

*S* = power split

 $H_E$  = degree of hybridization of energy:

$$H_E = \frac{E_{bat}}{E_{tot}} = \frac{S}{S + (1 - S) * SFC * e_{fuel} * \eta_{el}}$$



### S1: Feasible design space hybrid electric regional aircraft





#### S1: AC comparison

#### Comparison reference and hybrid-electric aircraft design

Parameter	Reference aircraft	Hybrid-electric aircraft	Difference
	22340	25470	+ 1/1 0/2
	22340	23470	+ 14 %
Mission fuel mass [kg]	2050	1470	- 28 %
Battery mass [kg]	0	2948	n/a
Battery energy density [Wh/kg]	n/a	1000	n/a
Empty mass [kg]	12780	13552	+ 6 %
Total energy stored in batteries and fuel [MWh]	26.19	21.73	- 17 %
Wing span [m]	26.5	28.8	+ 8.7 %
Wing area [m <sup>2</sup> ]	58.54	69.1	+ 18 %
Fuselage length	27	27	0 %



### S1: Conclusion

• Significant fuel saving can be achieved (up to 30 %)

- Analysis only for regional aircraft
- Results depend heavily on technological progress
- Chosen operating mode has influence on final design
- Promising results, future research recommended



S2: Integrated performance analysis applied on short-range aircraft



#### Advantages:

- Operates at optimal RPM
- Higher effective BPR
- Design freedom in positioning of engine and fan

#### Disadvantages:

- Heavy
- Less efficient

#### Advantages:

- Independent operation between engine and electrical system
- Independent design of power share between both subsystems

#### Disadvantages:

See advantages series

# S2: Simulation model: A320 with integrated HEPS





# S2: Impact of range on fuel burn



HEPS is beneficial for short ranges



#### S2: Technology development of electric components



source: Airbus (2015)



# S2: Effect of technology development on fuel burn



Based on 2030+ technology maturity level HEPS become beneficial



### S2:Effect of hybridisation on fuel burn



Take-off power split increases fuel burn (maturity 2030+)



# S2: Energy consumption



From an energy consumption perspective, HEPS are only slightly beneficial with technology development predicted by 2030+



#### S2: Fuel burn vs. Energy consumption





### S2: Effect of engine sizing on performance





### S2: Optimised HEPS overall efficiency





□ Climb powersplit of 14%

Turboshaft engine down scaled to 80%

 Significant efficiency increment during taxi-out, take-off and climb and efficiency also increases during cruise



# S2: Fuel burn and energy consumption of optimised HEPS



Fuel burn saving: 11%Energy consumption saving: 6%



#### S2: Emissions



Fuel burn dependent emissions can be reduced with 11%
 Engine dependent emissions can be reduced with 3% of which NO<sub>x</sub> with 1%



### S2: Conclusions

□ Investigation on HEPS as `retro-fit' in A320

- □ Applied HEPS is beneficial for short ranges
- The application of HEPS in mid/long-term is heavily dependent on the technology maturity level of electric components (specific energy/power)
- □ Fuel burn can be reduced, but total energy consumption increases
- □ The parallel HEPS architecture allows a better sized engine, which is more efficient
- Optimal' power management control strategy (with power split of 14%) including 80% scaled engine yields in fuel burn reduction of 11% and total energy saving of 6% for a 1000km flight mission
- $\Box$  CO<sub>2</sub> and NO<sub>x</sub> emissions can be reduced with 11% and 1% respectively (during taxi-phase zero CO<sub>2</sub> emission).



S3: Well (source) to propeller efficiency





#### S3: Series Hybrid Electric Aircraft





#### Results

# $\eta_{WTP}$

Well-to-propeller Efficiency	$R^2$	Lower Value	Mean Value	Upper Value
$\eta_{WTP_{baseline}}$	0.75	12.5	14.3	16.1
$\eta_{WTP_{nobatteries}}$	0.70	9.2	10.8	12.4
$\eta_{WTP_{current,naturalgas}}$	0.70	11.2	13.2	15.2
$\eta_{WTP_{current,renewable}}$	0.70	11.3	13.3	15.3
$\eta_{WTP_{theoretical,naturalgas}}$	0.70	12.2	14.4	16.6
$\eta_{WTP_{theoretical,renewable}}$	0.70	13.1	15.5	17.9



### S3: Conclusions

From an environmental perspective it is not a good idea to develop a Series Hybrid Electric Aircraft (SHEA)

- The well-to-propeller efficiency of a conventional aircraft is <u>14.3 with</u>  $\frac{R^2 = 0.75}{R^2 = 0.75}$
- □ The well-to-propeller efficiency of a SHEA is 14.4 with  $R^2 = 0.7$  (natural gas)
- □ The well-to-propeller efficiency of a SHEA is 15.4 with R<sup>2</sup> = 0.7 (renewables)
- From literature study it is known:
  - Design cost will go up
  - Maintenance cost will go up
  - Sustainability battery technology uncertain
- Parameters that maximise the viability of Hybrid Electric Aircraft are:
  - Increasing the bus-voltage
  - Renewable energy as source
  - Not using distributed propulsion as the benefits are not proven
  - New technologies



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# CS2 project: NOVAIR



#### Novel Aircraft Configurations and Scaled Flight Testing Instrumentationn





CleanSky 2 project: NOVAIR (start December 2016)



The development logic of NOVAIR



**NOVU** 

#### CS2 project: NOVAIR



**Point-based designs** 



Top-level approach to the assessment of radical hybrid-electric aircraft configurations



#### Delft University Unconventional Concept (DUUC) TUD: Pioneering Innovations Project







# Delft University Unconventional Concept (DUUC)

#### □ Towards Scaled Flight Testing

- of Unconventional AC
- □ Propulsive empennage concept
  - ✓ Increased propulsive efficiency
  - ✓ Safe propeller operation
  - ✓ Enhanced upset recovery
  - $\checkmark\,$  Noise shielding
  - ✓ Increased cabin comfort
  - ✓ Hybrid Electric Vehicle?

**TUD:** Pioneering Innovations Project





DUUC-0.1 flight from Woensdrecht AFB

- Preliminary design and analysis ongoing
- First data set expected by end 2016



### Concluding remarks

- Results on overall benefits of a hybrid electric propulsion system (HEPS) in regional aircraft seem inconclusive
- Next step in power density of subsystem and their efficiency is crucial before application can be considered
- Benefits of HEPS is mostly associated with opportunities for distributed propulsion
- NOVAIR and the Delft University DUUC project will contribute to this analysis in the coming years

