Estimating the maintenance-related material cost for battery-powered aircraft propulsion systems

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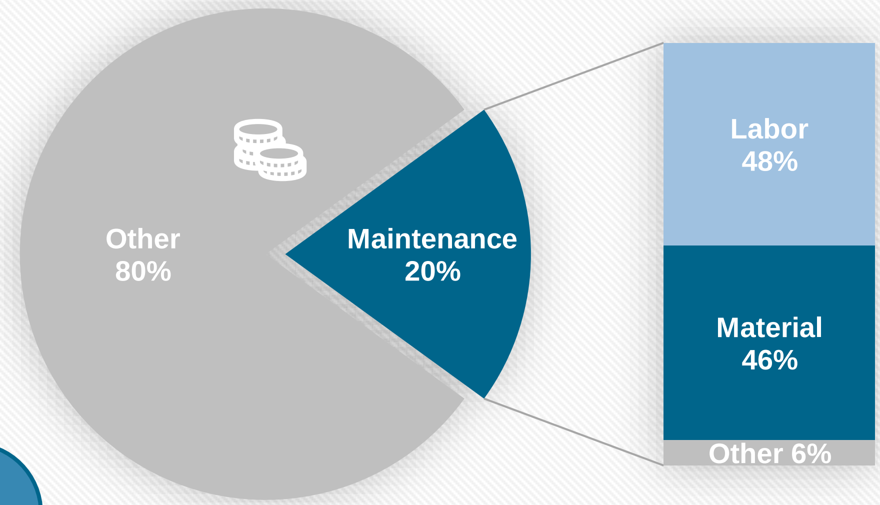
What will maintenance of new drive concepts cost?

Direct Operating Cost[1]



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Reliability-based Maintenance Assessment

1 Sources: R. Meissner et al. (2023) Towards climate-neutral aviation: Assessment of maintenance requirements for airborne hydrogen storage and distribution systems. DOI: 10.1016/j.ijhydene.2023.04.058
T. Hoff et al. (2023) Implementation of Fuel Cells in Aviation from a Maintenance, Repair and Overhaul Perspective. DOI: 10.3390/aerospace10010023

Agenda

1. Fundamentals of component reliability
2. The approach to material cost estimation
3. System architecture
4. Results
5. Main findings

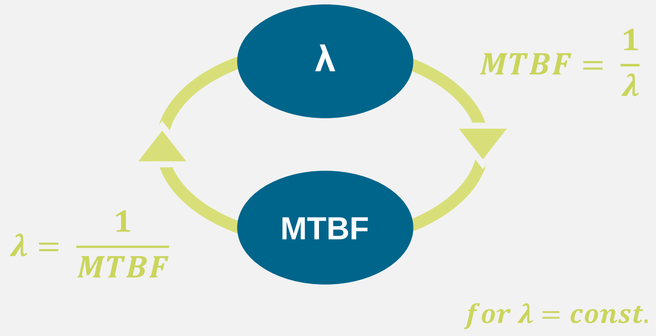
Reliability assessment of components

Measurement

A) Failure-driven

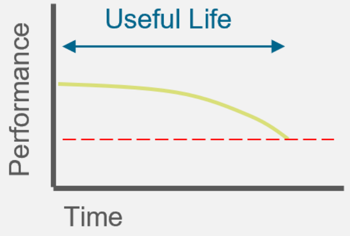
Failure Rate: Number of failures of an item in a given time interval divided by the time interval

Mean Time Between Failure: Statistical expectation of the time between failures



B) Performance-driven

Useful Life: Time interval until a limiting state of component performance is reached



Source: DIN EN 13306:2010 – Maintenance terminology

Our approach of a reliability-based maintenance analysis

1 | Reliability analysis

Collecting failure rates and MTBF values from literature and operational data

Simulating useful lifetimes and degradation behavior

2 | Cost analysis

Referencing spare part prices from aircraft operation

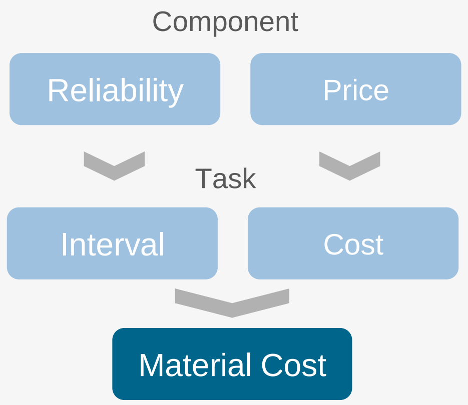
Applying cost forecasts from literature

3 | Material cost estimation

Establishing a novel reliability-based methodology for estimating material costs due to repair or replacement tasks

Component	Failure Rate ($x10^{-6}$) Min	Mean	Max
BMS	1.000	1.945	5.285
Inverter	1.912	5.746	86.000
Converter	2.044	4.035	28.660
Circuit breaker	1.967	4.821	46.000
Gearbox	1.500	5.254	17.700
El. motor	5.930	11.330	92.400
Heat exchanger	2.863	6.170	17.300
Pump	12.060	19.330	59.800
Cable	0.042	0.100	0.681

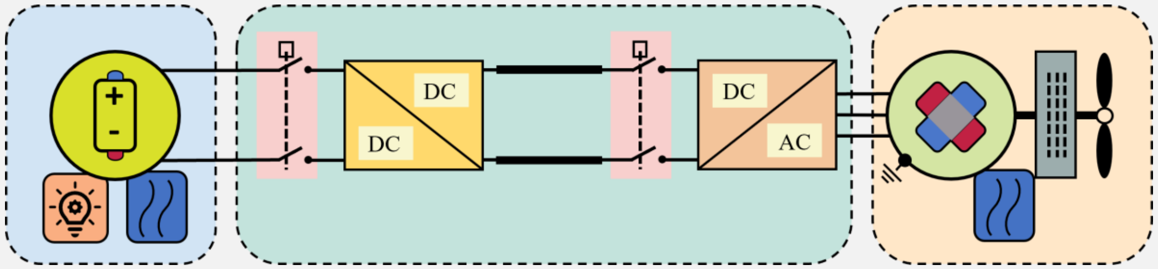
Component	Cost 2023	2050	Unit
Battery cell	112.70	64.18	\$/kWh
Inverter	129.96	51.72	\$/kW
Converter	129.96	51.72	\$/kW
Circuit breaker	129.96	51.72	\$/kW
Electric motor	63.48	20.11	\$/kW
Gearbox	63.48	20.11	\$/kW



System architecture

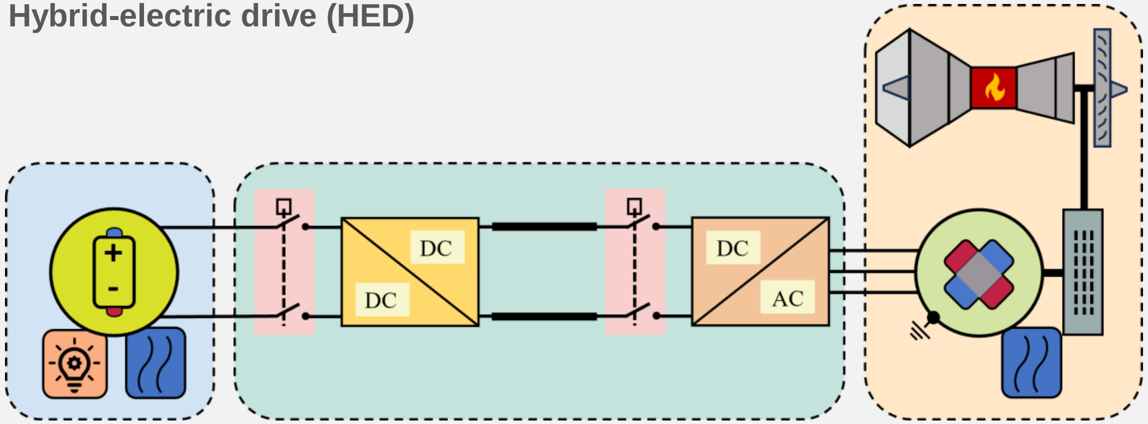
Layout for a battery-powered A320 equivalent drive train

All-electric drive (AED)



Storage system | Distribution system | Propulsion system

Hybrid-electric drive (HED)



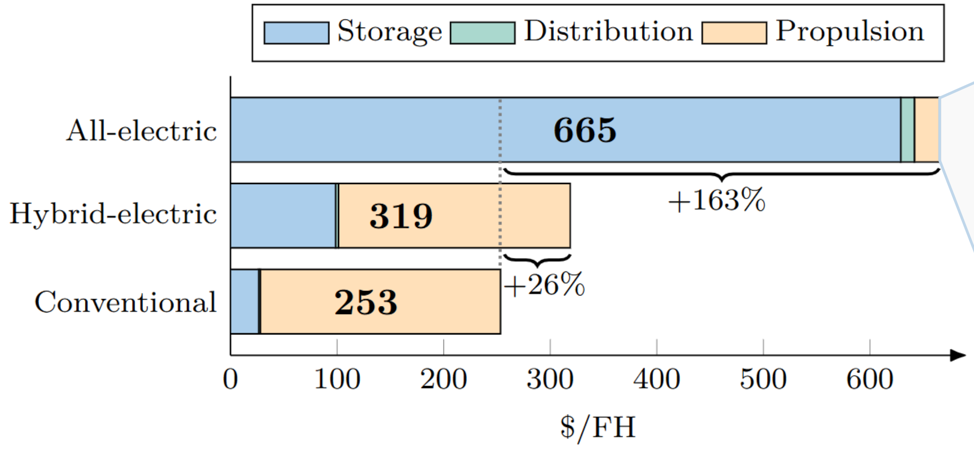
Storage system | Distribution system | Propulsion system

Key aspects

- Battery sizing results in unfeasible system mass for AED configuration
- Parallel HED allows additional usage of electric motors and results in a manageable battery mass

Material scope – All-electric system

Comparison of material cost for a battery-powered A320 equivalent drive train



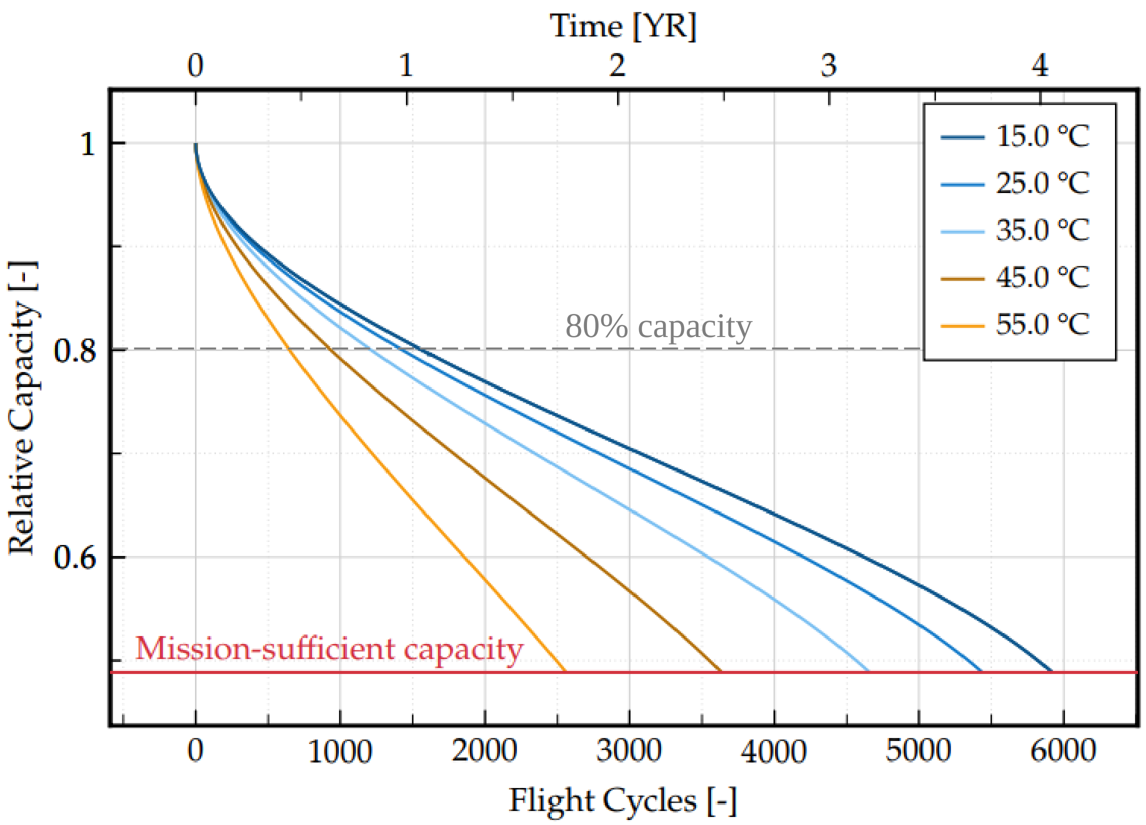
System	Component	Cost	Unit	Share
Storage	Battery cells	627.15	$/FH	94.2%
	BCS	1.66	$/FH	0.2%
	BMS	0.08	$/FH	0.01%
	Sub-total	**628.89**	**$/FH**	**94.5%**
Distribution	Circuit breakers	6.43	$/FH	1.0%
	Inverters	3.73	$/FH	0.6%
	Converters	2.68	$/FH	0.4%
	Sub-total	**12.84**	**$/FH**	**1.9%**
Propulsion	Propeller units	16.41	$/FH	2.4%
	Electric motors	3.52	$/FH	0.5%
	MCS	2.21	$/FH	0.3%
	Gearboxes	1.62	$/FH	0.2%
	Sub-total	**23.76**	**$/FH**	**3.6%**
Total		**665.49**	**$/FH**	**100%**

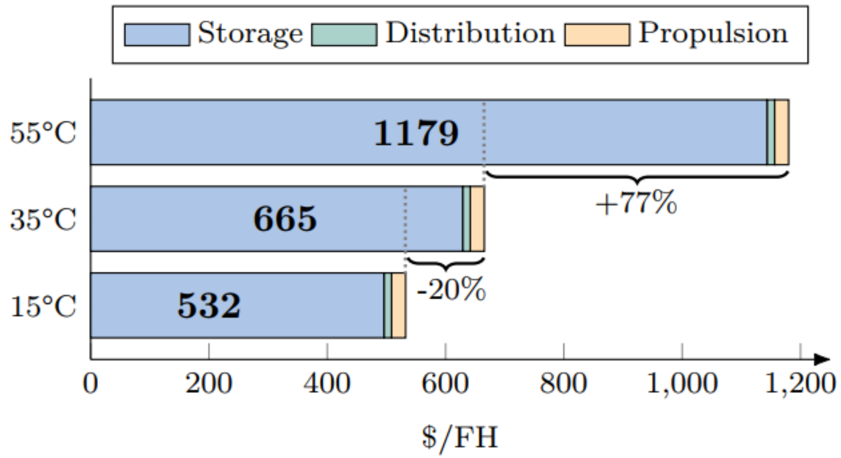
Expected impact

- **Battery cells** are responsible for **94%** of the material cost due to their enormous number and strong degradation effects
- Components of the **propulsion system** have only a **minor impact** due to reliable and cost-effective electric motors

Estimating the useful lifetime of the battery cells

Applying a semi-empirical degradation model[1]





Useful lifetime is highly dependent on

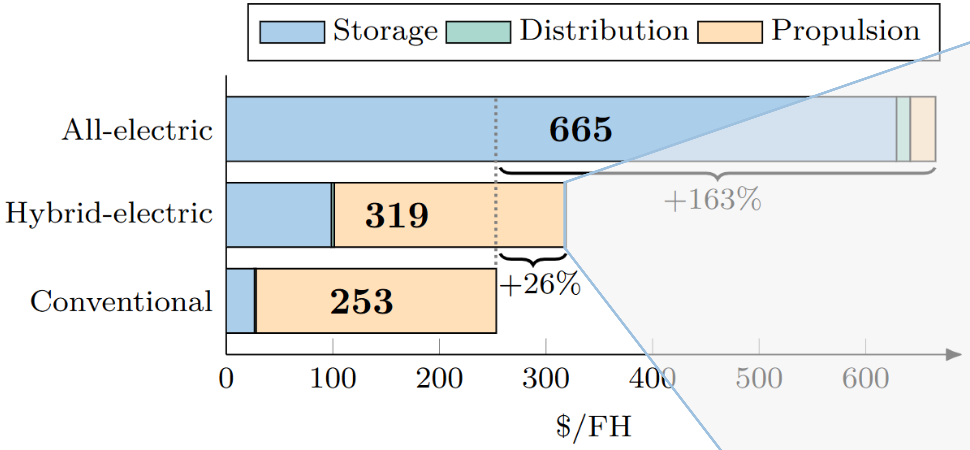
a) Operating temperature
→ Lever: Powerful cooling system

b) Depth of discharge
→ Lever: Battery over-sizing, hybridization

1 Model: J. Schmalstieg et al. (2014) A holistic aging model for Li(NiMnCo)O2 based 18650 lithium-ion batteries. DOI: 10.1016/j.jpowsour.2014.02.012
M. Clarke et al. (2021) Lithium–Ion Battery Modeling for Aerospace Applications. DOI: 10.2514/1.C036209

Material scope – Hybrid-electric system

Comparison of material cost for a battery-powered A320 equivalent drive train



System	Drive train	Component	Cost	Unit	Share
Storage	Conventional	–	–	–	–
	Electric	**Battery cells**	96.91	$/FH	**30.4%**
		BCS	1.66	$/FH	0.5%
		BMS	0.08	$/FH	0.03%
	Sub-total		**98.65**	**$/FH**	**30.9%**
Distribution	Conventional	FQIC	0.83	$/FH	0.3%
		Miscellaneous	0.65	$/FH	0.2%
	Electric	Circuit breakers	0.62	$/FH	0.2%
		Inverters	0.36	$/FH	0.1%
		Converters	0.26	$/FH	0.1%
	Sub-total		**2.72**	**$/FH**	**0.9%**
Propulsion	Conventional	**Main engines**	204.91	$/FH	**64.3%**
		ECU	4.08	$/FH	1.3%
		TRU	3.08	$/FH	1.0%
		Miscellaneous	3.79	$/FH	1.2%
	Electric	MCS	1.11	$/FH	0.3%
		Electric motors	0.34	$/FH	0.1%
		Gearboxes	0.15	$/FH	0.05%
	Sub-total		**217.46**	**$/FH**	**68.2%**
Total			**318.83**	**$/FH**	**100%**

Expected impact

- **85% lower battery** cost compared to all-electric drive train due to a smaller system and less degradation [1]
- **11% lower engine cost** compared to conventional drive train due to hybridization and less engine load [2]

1: Assuming battery usage mainly during taxi and takeoff
2: Assuming 10% degree of hybridization during takeoff

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Main findings

Material cost for a **fully-battery powered** A320-equivalent is expected to **increase by 163%** compared to the conventional configuration

➡ Not economically and technologically viable

Cost of a **hybrid-electric** version is expected to **increase by 26%** without a major increase in battery mass

➡ Economical and technological potential for a quicker market entry

Battery cells show to be one of the **greatest cost drivers** and cost-optimizing decisions should focus on their design and operation

➡ Over-sizing by a certain reserve capacity and low operating temperature

THANK YOU FOR YOUR ATTENTION

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Pre-published paper

Imprint

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