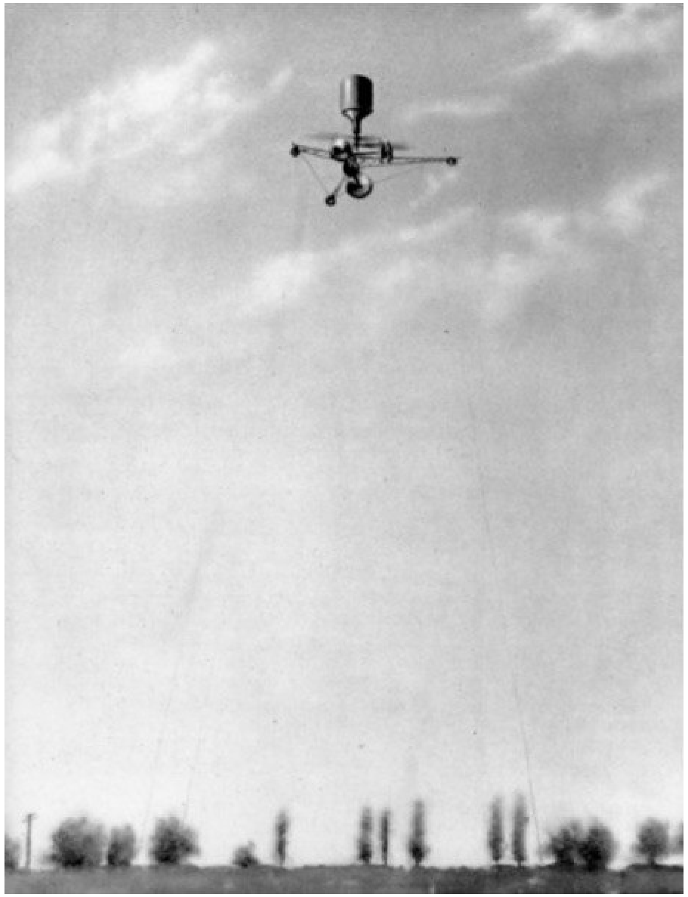
1916: first electric aircraft

PKZ - 1 - Petróczy, Kármán, Žurovec
PKZ – 2 - Žurovec (in the photos)

First electrically driven tethered observation helicopter



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Determining the required energy for flight mission of electric/ hybrid aircraft

1. Introduction
2. Preliminary consideration
3. Practical aspects
4. New approach to aircraft conceptual design
5. Energy calculations
6. Results and discussions
7. Conclusions

1. Introduction

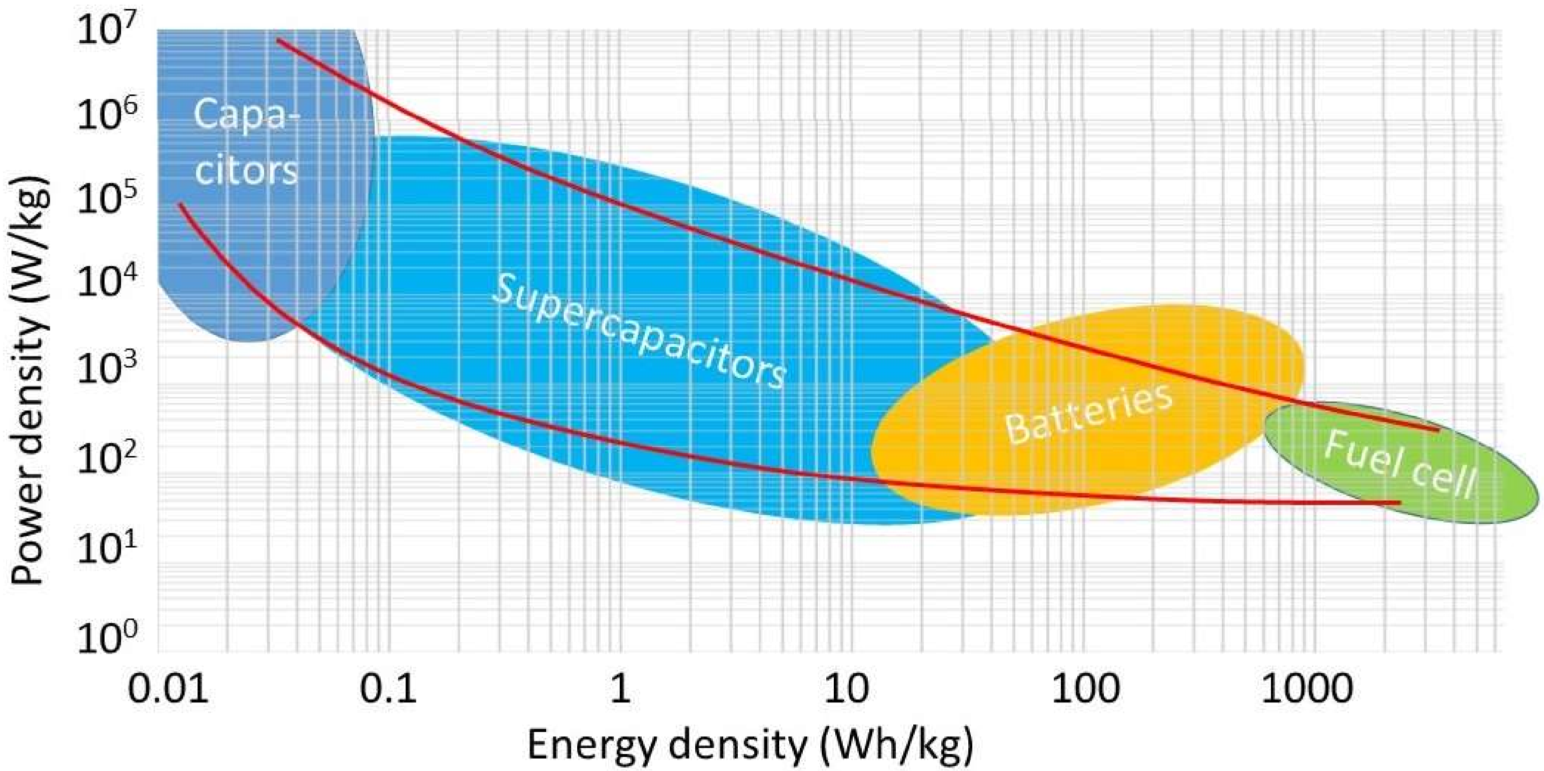
- The aircraft with electric / hybrid propulsion systems are most promising future cleaner emerging technologies.
- The low specific energy of batteries' technologies is a hard barrier in future development of the electric aircraft.
- New methods are required for conceptual design that
  - should include the energy balance evaluation and
  - managing the energy fractions for elements of the flight mission.
- This paper deals with possible estimation of the mission energy and energy fractions for elements of the flight missions.

2. Preliminary consideration

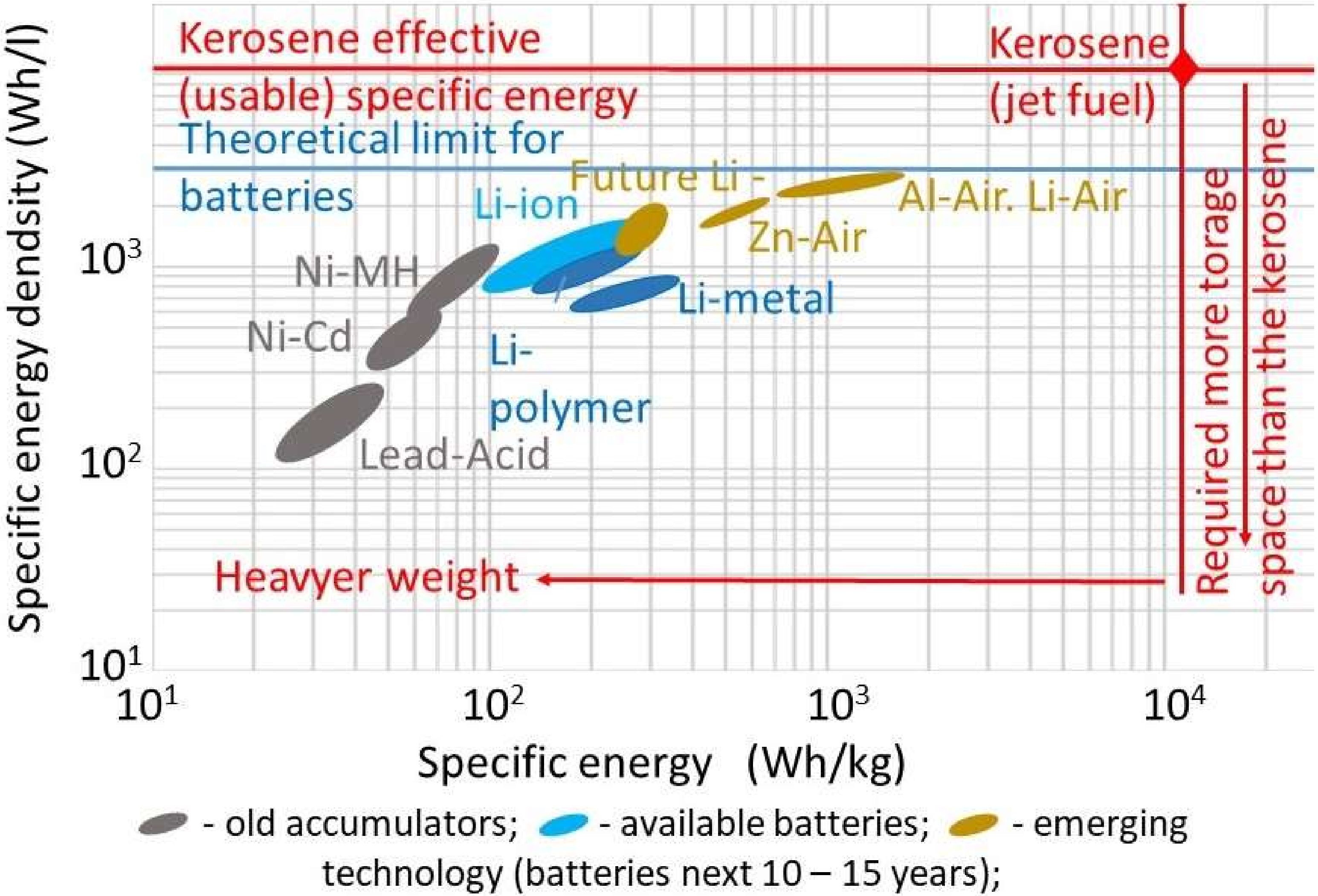
- The available batteries technologies have two serious barriers delaying their deployment:
  - low specific energy (Wh/kg)
  - thermal instability
- The aircraft with the analogical performance comparing to conventional aircraft can not be developed.
- New conceptual design approach was developed by IDEA-E project that
  - based on mass and energy balance evaluation and
  - introduction new constraints on mass and energy fractions

2. Preliminary consideration

➢ **Alternatives for maximum power**

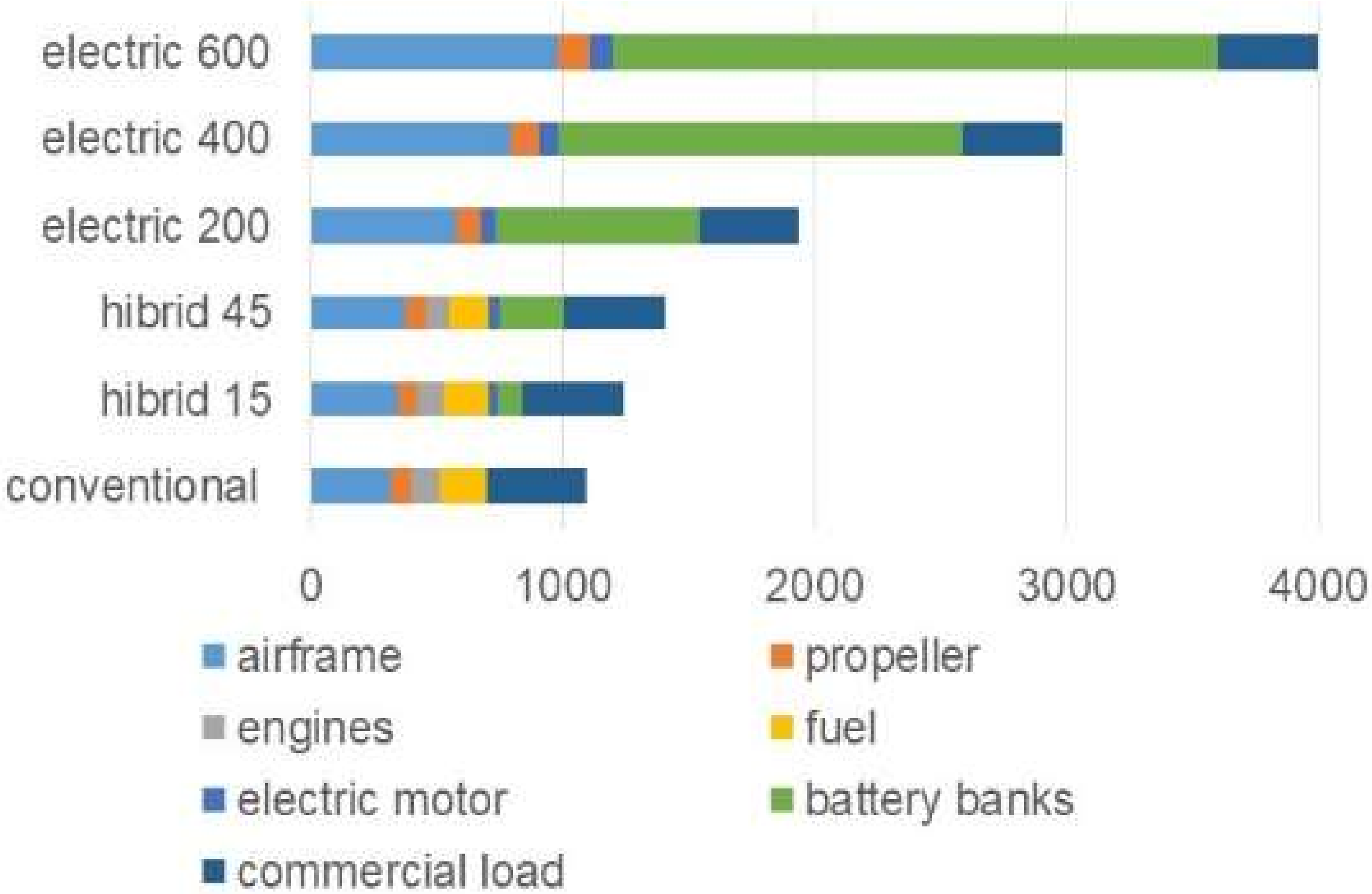


2. Preliminary consideration



2. Preliminary consideration

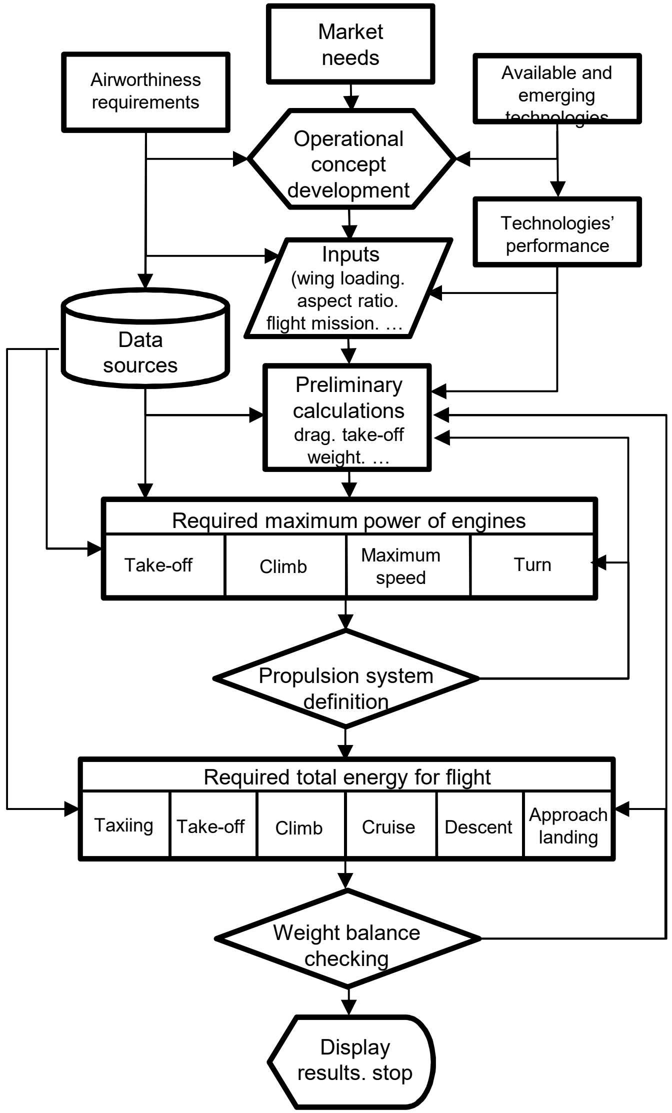
➢ **Mass breakdown → reducing the range in %**



Range reduction
41 %
60 %
72 %

3. New approach to aircraft conceptual design

- Operational concept development
- Preliminary calculations
- Required maximum power estimation
- Evaluation of the required total (mission) energy for flight
- Novelties:
  - Estimation of the mass and energy balances
  - New constraints for mass and energy fractions



3. New approach to aircraft conceptual design

- **Mass balance equation (life equation)**

$$M_{TO} = M_a + M_{sy} + M_{ps} + M_f + M_b + M_{pl} + \cdots = M_{TO} \sum_i \bar{M}_i$$

- **Its application:** $M_{TO} = \dfrac{M_e + M_{pl}}{1 - \frac{M_f}{M_{TO}} - \frac{M_b}{M_{TO}}}$

- **Energy balance equation:**

$$e_{efm} = e_{TA} + e_{TO} + e_C + e_{CR} + e_{DE} + e_{LO} + e_{AL} = e_{efm} \sum_i \bar{e}_i \ .$$

3. New approach to aircraft conceptual design

Mass balance equation

$$m_{\mathrm{TO}} = m_{\mathrm{c}} + m_{\mathrm{a}} + m_{\mathrm{e}} + m_{\mathrm{f}} + m_{\mathrm{s}} + \ldots..$$

$$1 = \overline{m}_{\mathrm{c}} + \overline{m}_{\mathrm{a}} + \overline{m}_{\mathrm{e}} + \overline{m}_{\mathrm{f}} + \overline{m}_{\mathrm{s}} + \ldots..$$

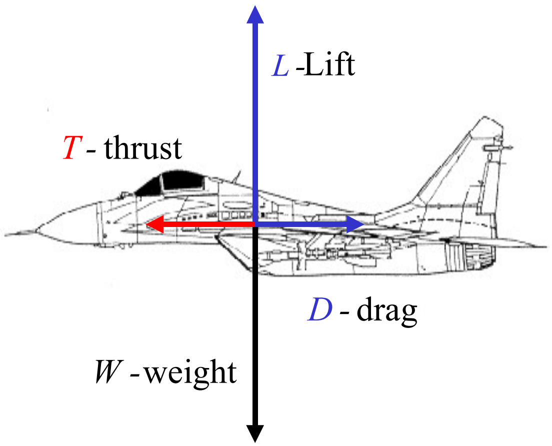
$$\overline{m}_i = \frac{m_i}{m_{\mathrm{TO}}}, \qquad \forall i$$

The relative weights depend on the applied designed methods, characteristics of the materials, technology, production culture, etc.

$\sum_{i=1}^{n} \overline{m}_i \prec 1$	The developing aircraft might be better
$\sum_{i=1}^{n} \overline{m}_i = 1$	excellent
$\sum_{i=1}^{n} \overline{m}_i \succ 1$	cannot be develoed and built

$$T = D, \qquad W = L,$$

$$T = \frac{W}{\frac{L}{D}} = \frac{mg}{\frac{C_L \frac{\rho V^2}{2} S}{C_D \frac{\rho V^2}{2} S}}$$



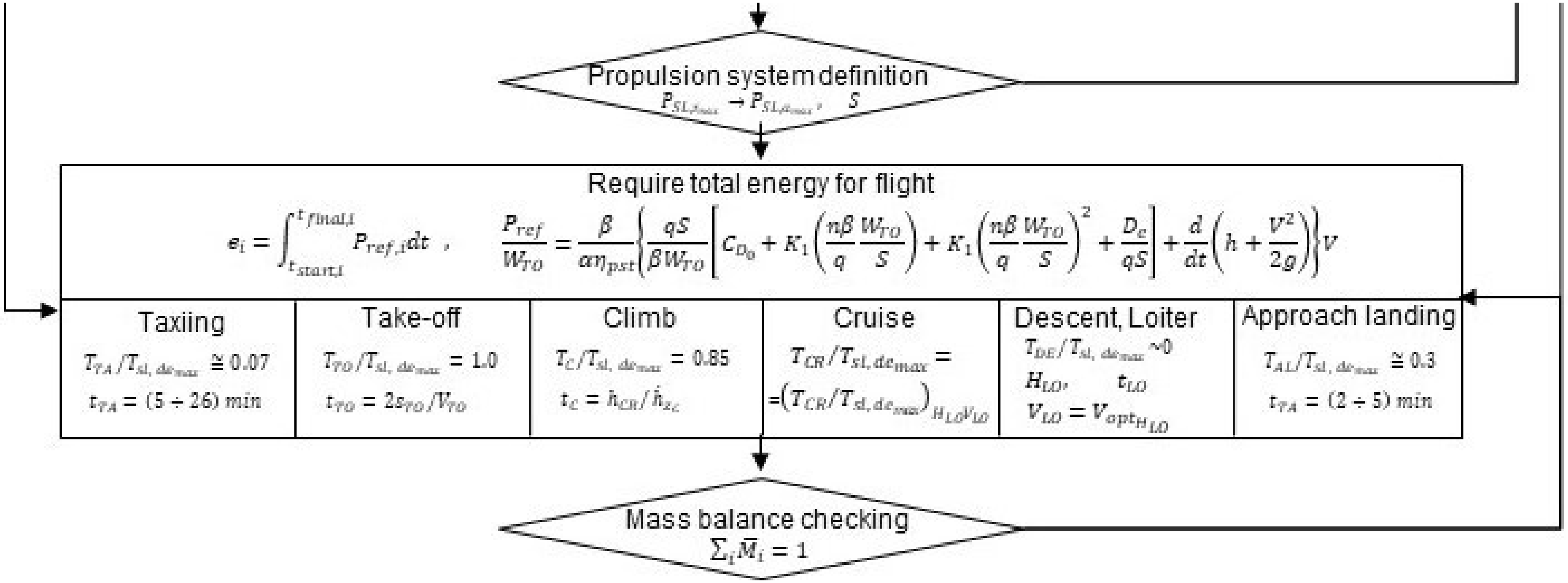
$$T = \frac{W}{\frac{C_L}{C_D}} = \frac{mg}{k},$$

$$m_e = \rho_e c T,$$

$$\overline{m}_e = \frac{m_e}{m} = \frac{\rho_e c m g}{k m g} = \frac{\rho_e c}{k}$$

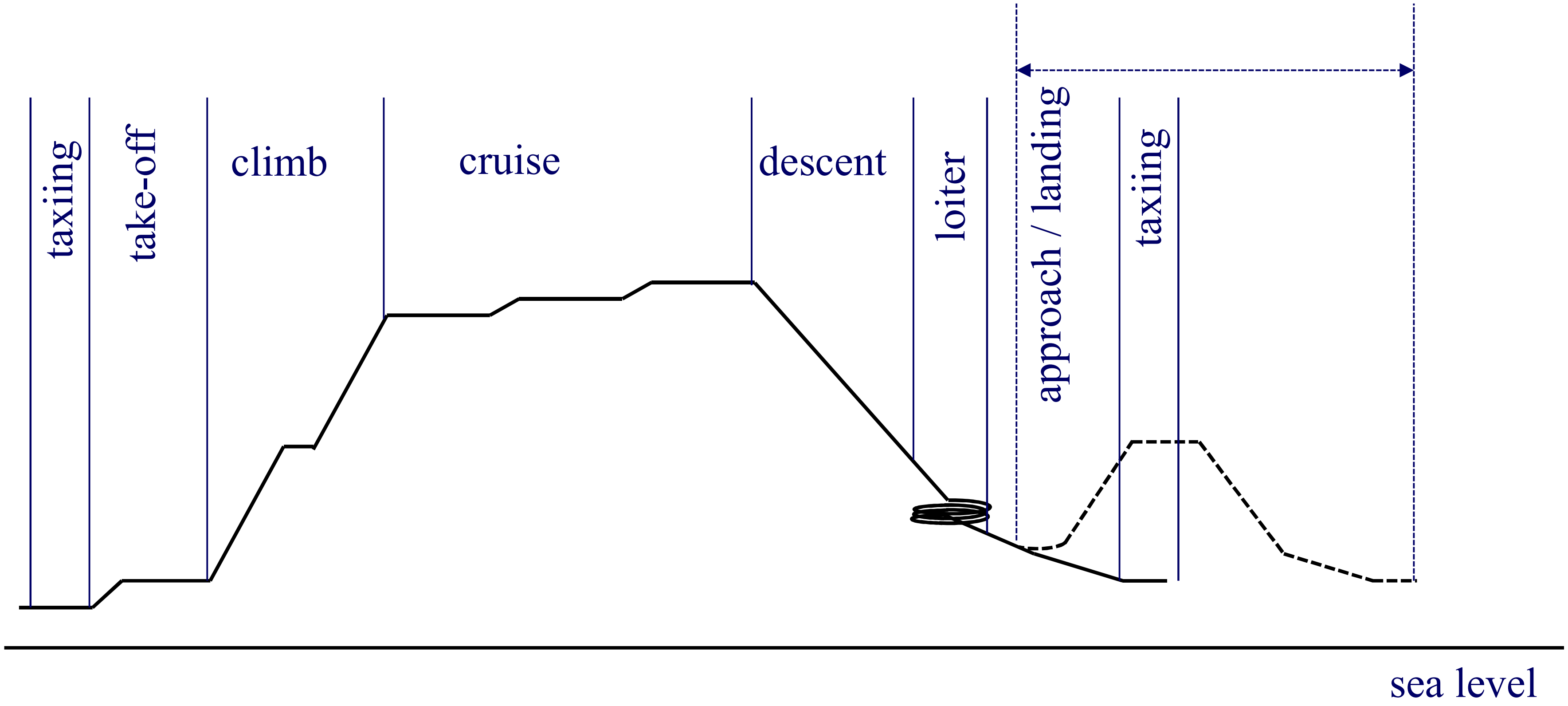
4. Energy calculations

- **Constraints should be defined for mass and energy fractions**
- **The further analysis is required**
- **The required energy for elements of the flight missions might be determined by use of these formulas.**



4. Energy calculations

➢ **Flight mission legs (elements)**



4. Energy calculations

- **Traditionally it is an easy calculation**

$$\frac{\Delta W_{f_{fm}}}{W_{TO}} = \sum_{i=1}^{n} \frac{\Delta W_{f_{fml_i}}}{W_{TO}}$$

- Used energy of 1 kg fuel (kerosene) equals to about 3 kWh (with 0. 25 total efficiency coefficient, that means
- required electric energy equals to 3.75 kWh (total electric and propeller) efficiency = 0,8) that might be stored in
- 12 – 13 kg of batteries.

4. Energy calculations

- **Traditionally calculation for cruise part of flight:**

$$T = D, \qquad L = W, \qquad T = D\frac{L}{L} = \frac{W}{\frac{L}{D}} = \frac{W}{k}$$

$$\frac{dW}{\mathrm{dt}} = -TSFC\,T = -TSFC\,\frac{W}{k}$$

$$\mathrm{dt} = -\frac{k}{TSFC}\frac{dW}{W}$$

$$t_{CR} = -\frac{k}{TSFC}\ln\frac{W_{CR_{initial}}}{W_{CR_{final}}}$$

$$W_{f_{CR}} = TSFC\,T_{CR}\,t_{CR} = TSFC\,T_{CR}\frac{R_{CR}}{V_{CR}}$$

$$\left(or\ W_{f_{CR}} = kT_{CR}\ln\frac{W_{CR_{initial}}}{W_{CR_{final}}}\right)$$

4. Energy calculations

- **Direct calculation (energy for cruise part)**

$$e_{CR} = P_{CR} t_{CR}$$

$$e_{CR} = P_{CR} t_{CR} = T_{CR} V_{CR} \frac{R_{CR}}{V_{CR}} = T_{CR} R_{CR}$$

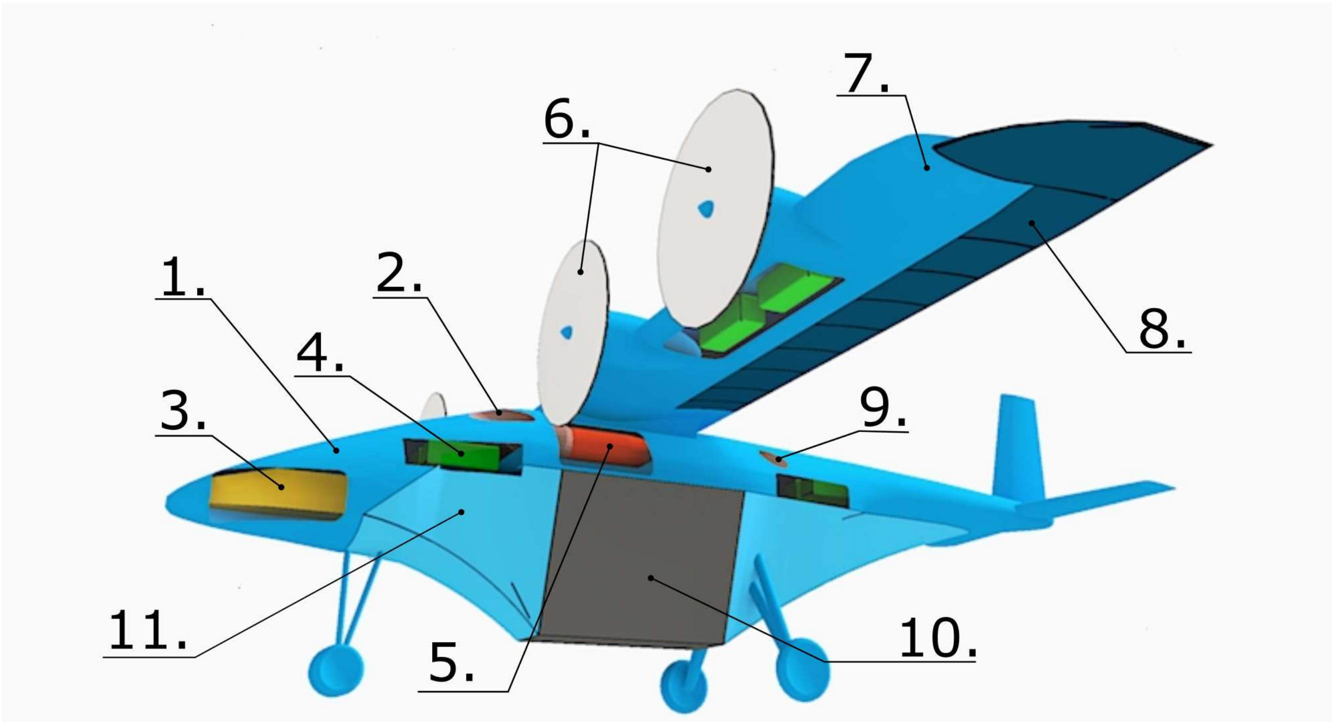
$$\frac{P_{ref}}{W_{TO}} =$$

$$= \frac{\beta}{\alpha \eta_{pst}} \left\{ \frac{qS}{\beta W_{TO}} \left[C_{D_0} + K_1 \left(\frac{n\beta}{q} \frac{W_{TO}}{S} \right) + K_1 \left(\frac{n\beta}{q} \frac{W_{TO}}{S} \right)^2 + \frac{D_e}{qS} \right] + \frac{d}{dt} \left(h + \frac{V^2}{2g} \right) \right\} V$$

- **This methods applicable to all mission legs**

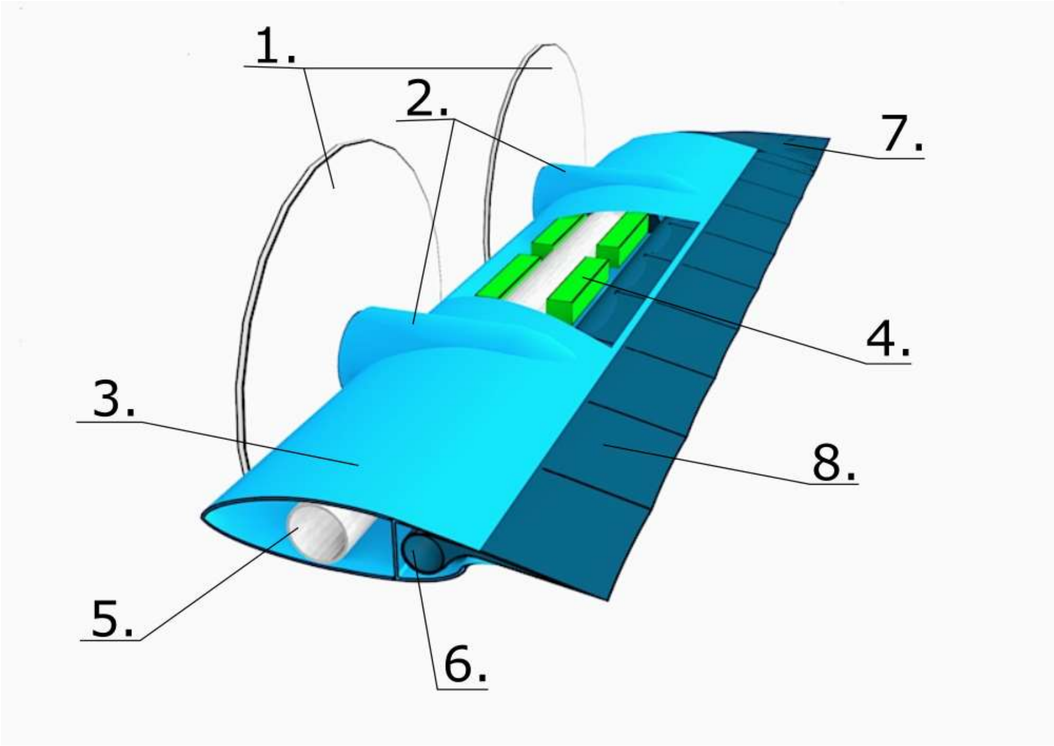
5. Results and discussions

➢ **Unconventional hybrid UAV is designed conceptually.**



Layout of the developed small cargo UAV with hybrid propulsion system (1.- fuselage, 2.- engine inlet, 3.- control box, 4.- batteries, 5.- gas turbine with electric generator, 6.- propellers, 7.- fix wing, 8.- flexible part of wing, 9.- exhaust gas inlet, 10.- containers, 11.- covering linen)

5. Results and discussions



Wing principal structure (1.- propellers, 2.- electric motors, 3.- hard (composite) wing section, 4.- batteries, 5.- beam – tube, 6.- rod rolling the linen, 7.- flexible (composite), deflectable tip rod, 8.- flexible part of wing (linen))

5. Results and discussions

➢ Energy balance of developed hybrid UAV

flight phases	energy (kWh)	electric energy (kWh)	fossil used energy (kWh)	battery mass (kg)	total fuel (l)
taxiing	0.07	0.07		0.29	0.05
take-off (finished at 500 m - that is 4 minutes on P_{max})	3.67	3.67		14.67	2.29
climb to 3000 m (climb rate 3 m/s and 0.9 P_{max})	11.46		11.46		7.16
cruise (altitude 3 km. speed 25 m/s (90 km/h.))	20.32		20.32		12.70
descent	0.00				
approach /landing (from 500 m)	1.80	1.80		7.20	1.13
reserve	12.40	4.13	8.27	16.53	5.17
total	49.72	9.67	40.05	38.69	28.49

6. Conclusions

- The electric / hybrid aircraft will be entered into operation after 2020 (small aircraft) and 2030
- The aircraft conceptual design methodology can not applied because the low specific energy of batteries that increases mass of aircraft radically.
- New concept is developed by using the mass and energy balance estimation and introducing new constraints.
- The energy balance might be determined by the describing equations.
- The developed unconventional hybrid UAV demonstrated the applicability of the developed conceptual design methodology.

7. Acknowledgement

This work was supported by

Hungarian national EFOP-3.6.1-16-2016-00014 project titled by "Investigation and development of the disruptive technologies for e-mobility and their integration into the engineering education" (IDEA-E)