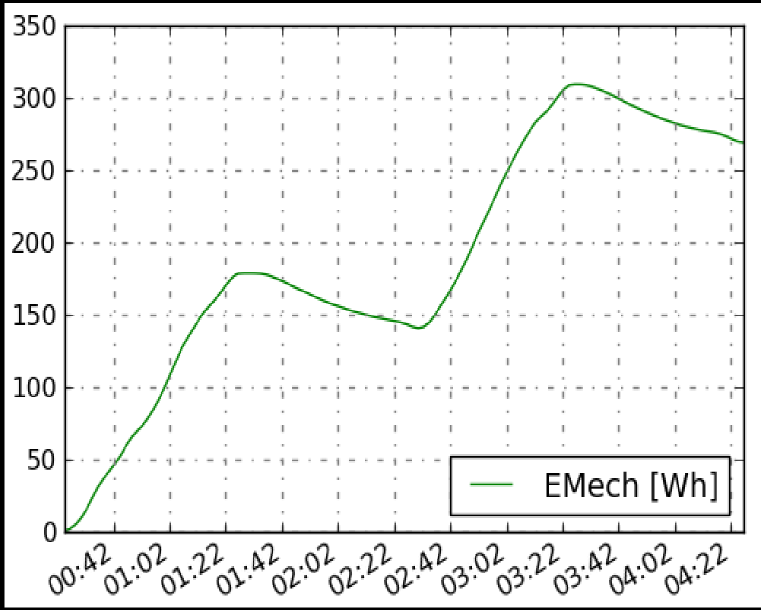

Performance factors for HAWP systems in pumping operation

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AWEC 2011, KU Leuven

TU Delft

Outline

- Motivation
- Kite power technology
- Current ground station of TU Delft
- Performace Factors
- Measurement results
- Examples
- Conclusions
- Outlook

Motivation

Performance analysis of the TU Delft kite power system

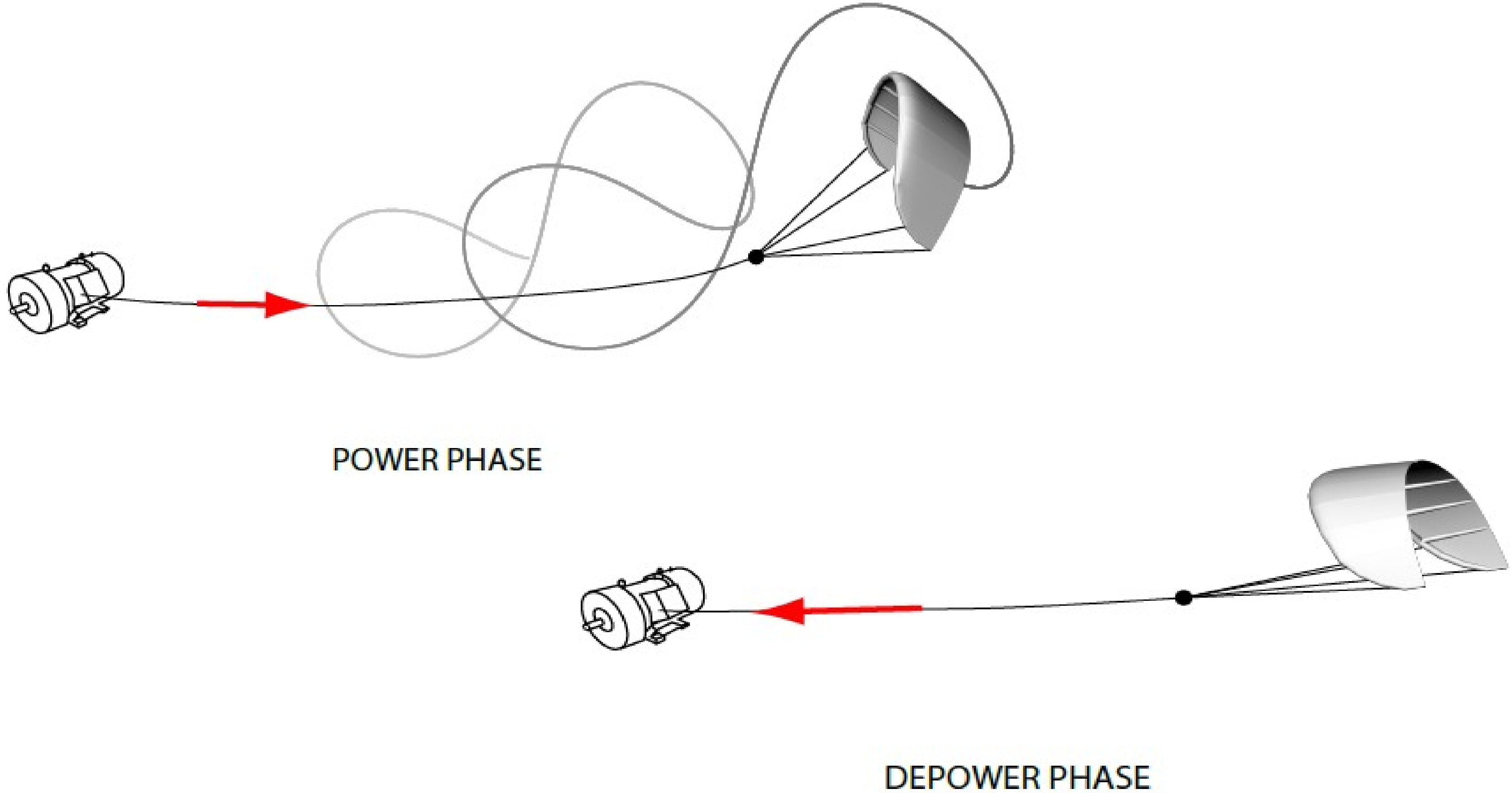
During the tests of the TU Delft kite power system in 2010 we could see an increase of the average mechanical power on nearly every test.

But we also wanted to know, how much electricity was produced and where it goes to. For this purpose we added four current sensors.

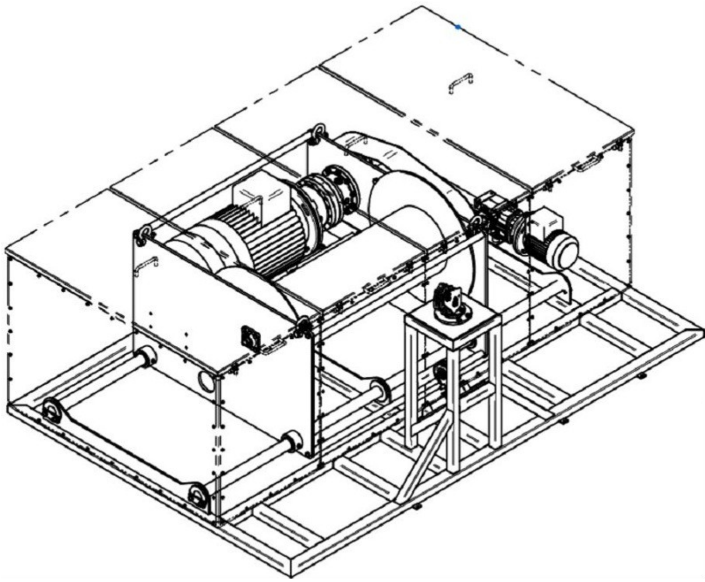
The following efficiencies were analysed:

- the friction of the drum and the gearbox
- efficiency of the motor/ generator as function of force and speed
- the efficiency of the motor controller
- the power consumption of the spindle drive, the brakes and the computers

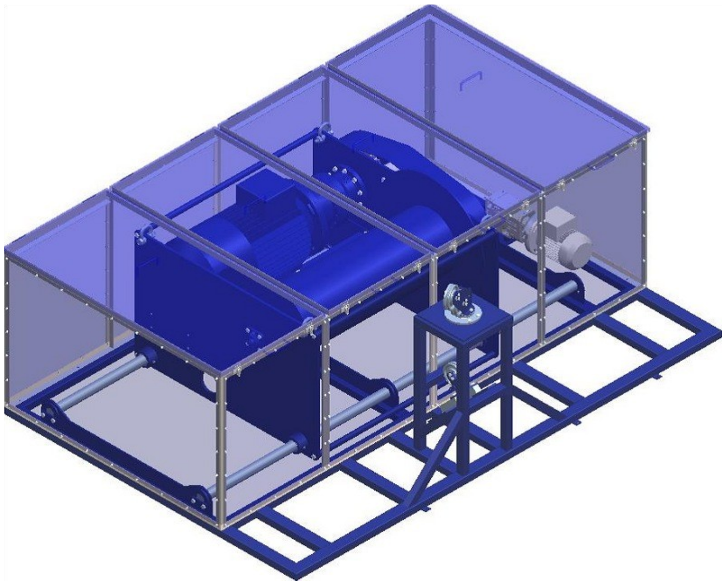
Technology
Kite Power System



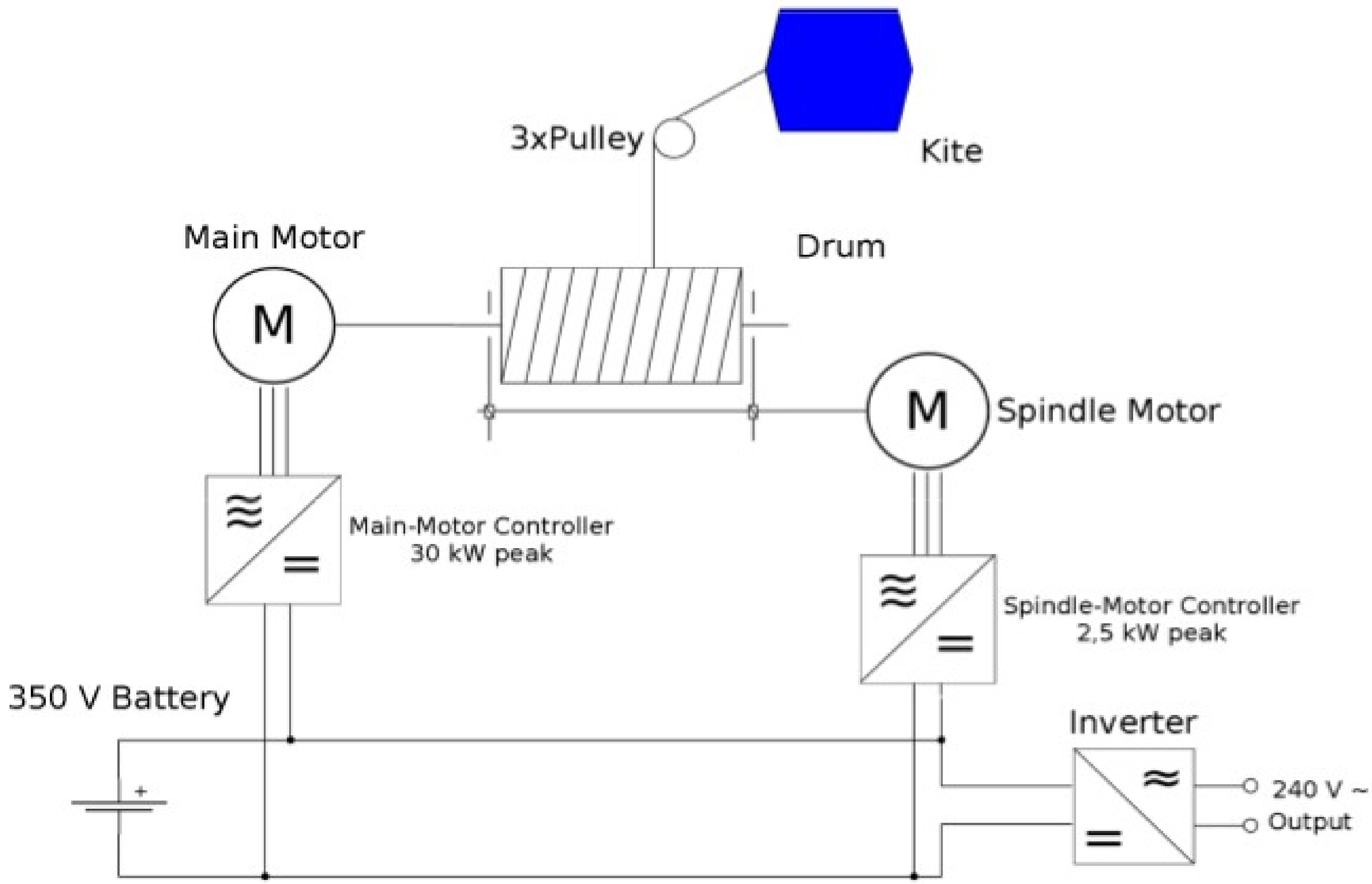
Current Ground Station



- Motor-generator for 18 kW nominal power;
- drum, synchronous belt, gearbox;
- spindle motor with gearbox and worm drive;
- pulleys, force sensor;
- electrical system.



Schematic Diagram of the Groundstation



Performance Factors for HAWP Systems in Pumping Operation (I)

Ground station

The duty cycle

$$D = \frac{t_o}{t_o + t_i} \qquad (1)$$

It is defined as the quotient of the time of the reel-out phase t_o, devided by the sum of the time of the reel-out phase and of the reel-in phase.

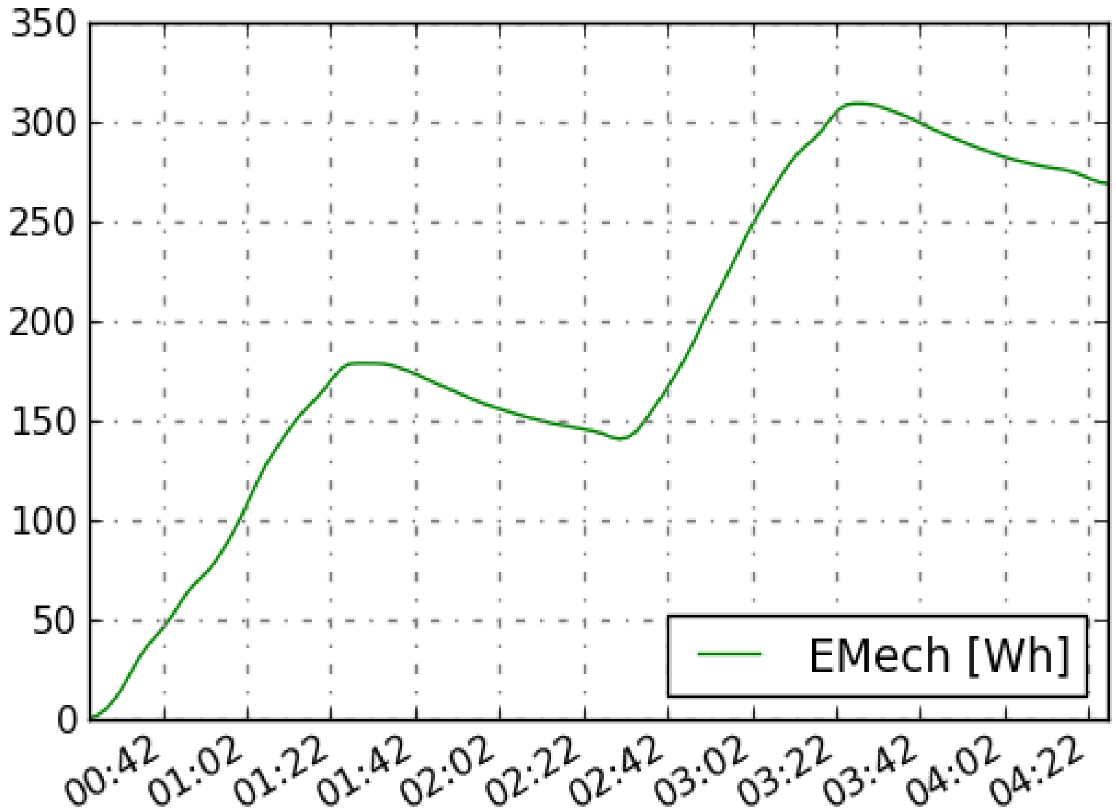
The mechanical efficiency

$$\eta_m = \frac{E_o - E_i}{E_o} \qquad (2)$$

It is defined as the quotient of the net energy, that is produced in one cycle, divided by the energy, that was produced in the reel-out phase.

Performance Factors for HAWP Systems – Example I –

Ground station



The duty cycle

$$D = \frac{70\text{s}}{70\text{s} + 60\text{s}} = 53{,}8\,\%$$

The mechanical cycle efficiency

$$\eta_m = \frac{179\,Wh - 38\,Wh}{179\,Wh} = 79\,\%$$

Performance Factors for HAWP Systems in Pumping Operation (II)

Ground station

The cycle efficiency

$$\eta_{cyc} = D \cdot \eta_m \tag{3}$$

The duty cycle and the mechanical efficiency can be combined to the cycle efficiency. It indicates, which percentage of the average mechanical power, that is produced during the reel-out phase is available as average mechanical power during the full cycle.

The electrical efficiency

$$\eta_e = \frac{E_e}{E_m} \tag{4}$$

The electrical efficiency is defined as the quotient of the electrical energy output and the mechanical energy input over the full cycle.

Calculating the electrical efficiency

Ground station

When the partial efficiencies have been measured or calculated, e.g. with datasheet based models, then the overall electrical efficiency can be calculated. We define:

η_{eo} : *Electrical efficiency of the generator, incl. gearbox (if any) and controller*

η_{ei} : *Electrical efficiency of the motor, incl. gearbox (if any) and controller*

η_{batt} : *Electrical efficiency of the battery (or other storage device)*

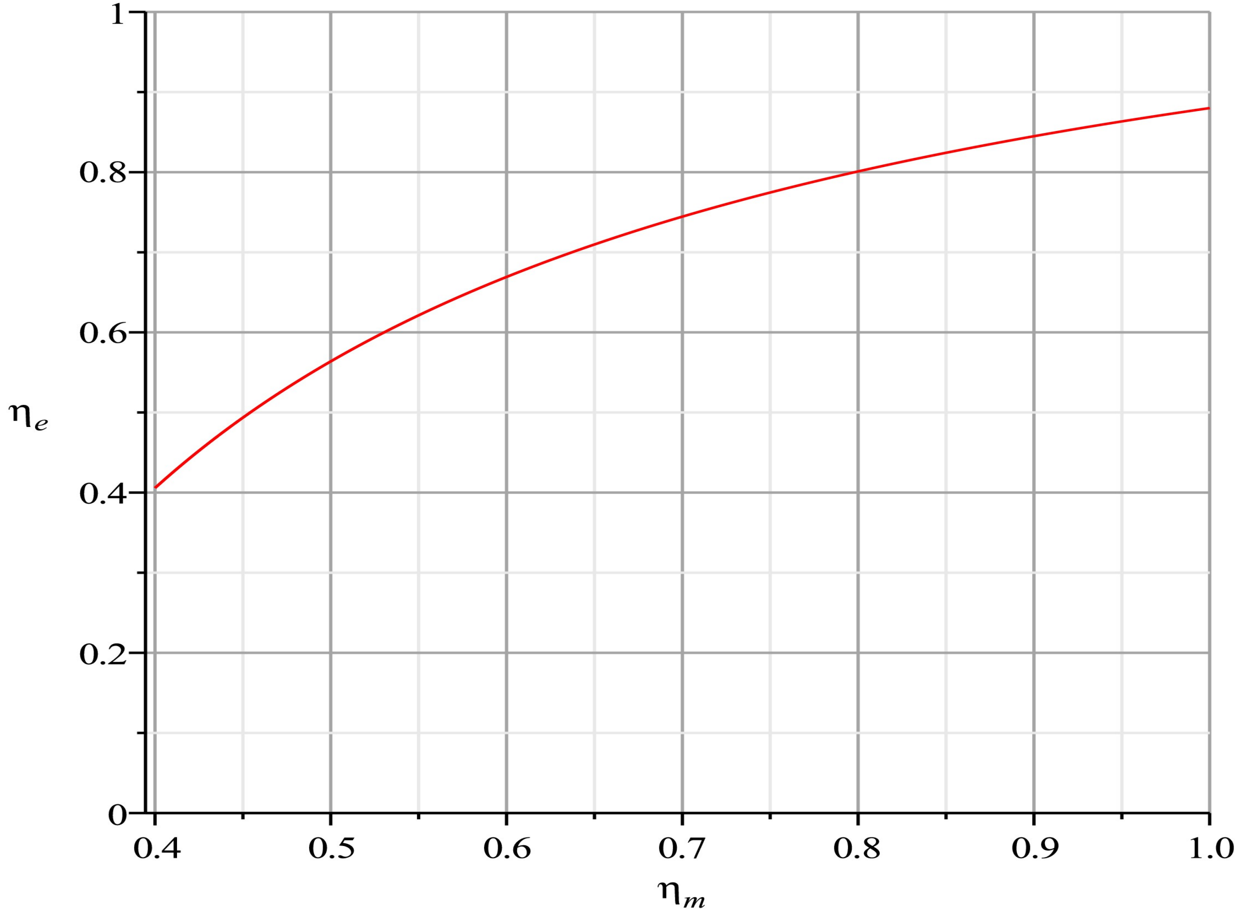
η_{sys} : *Electrical efficiency due to the power, needed for the spindle motor, the brakes etc.*

With these definitions the electrical efficiency, as defined in (4) can be calculated:

$$\eta_e = \frac{E_e}{E_m} = \eta_{sys} \cdot \frac{\eta_{eo}\eta_{ei}\eta_{batt} - 1 + \eta_m}{\eta_{ei}\eta_{batt}\eta_m} \qquad (5)$$

Electrical Winch efficiency

High efficient ground station with separate motor and generator



$$\eta_{eo} = 88\%$$

$$\eta_{ei} = 88\%$$

$$\eta_{batt} = 95\%$$

Performance Factors for HAWP Systems in Pumping Operation (III)

Ground station

The total efficiency

$$\eta_{tot} = \eta_{cyc} \cdot \eta_e = D \ \eta_{sys} \frac{\eta_{eo}\eta_{ei}\eta_{batt} - 1 + \eta_m}{\eta_{ei}\eta_{batt}} \quad (6)$$

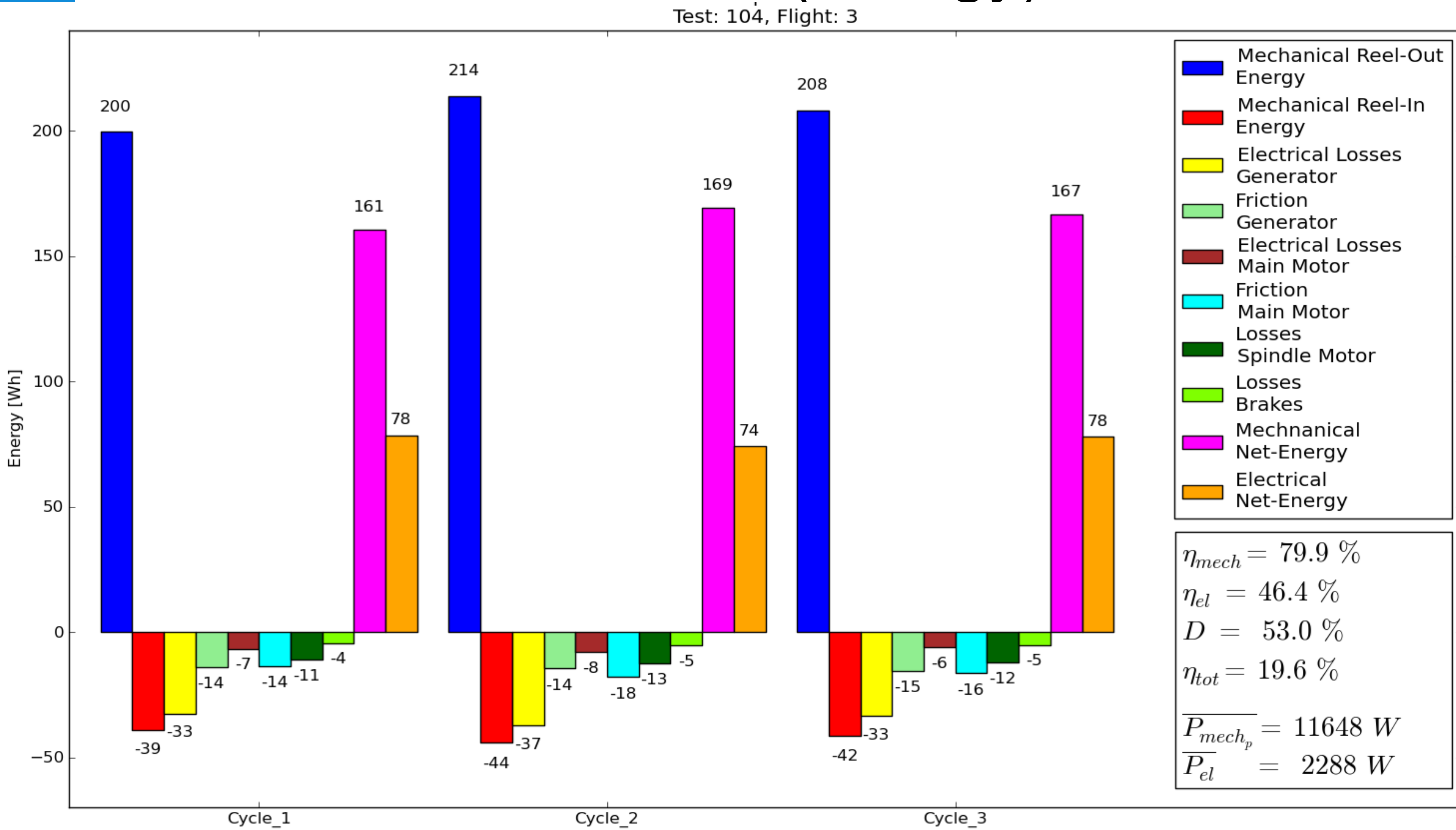
The total efficiency is the product of the cycle efficiency and the electrical efficiency. It indicates, which percentage of the average mechanical power, that is produced during the reel-out phase is available at the electrical output in average during the full cycle.

The cost factor

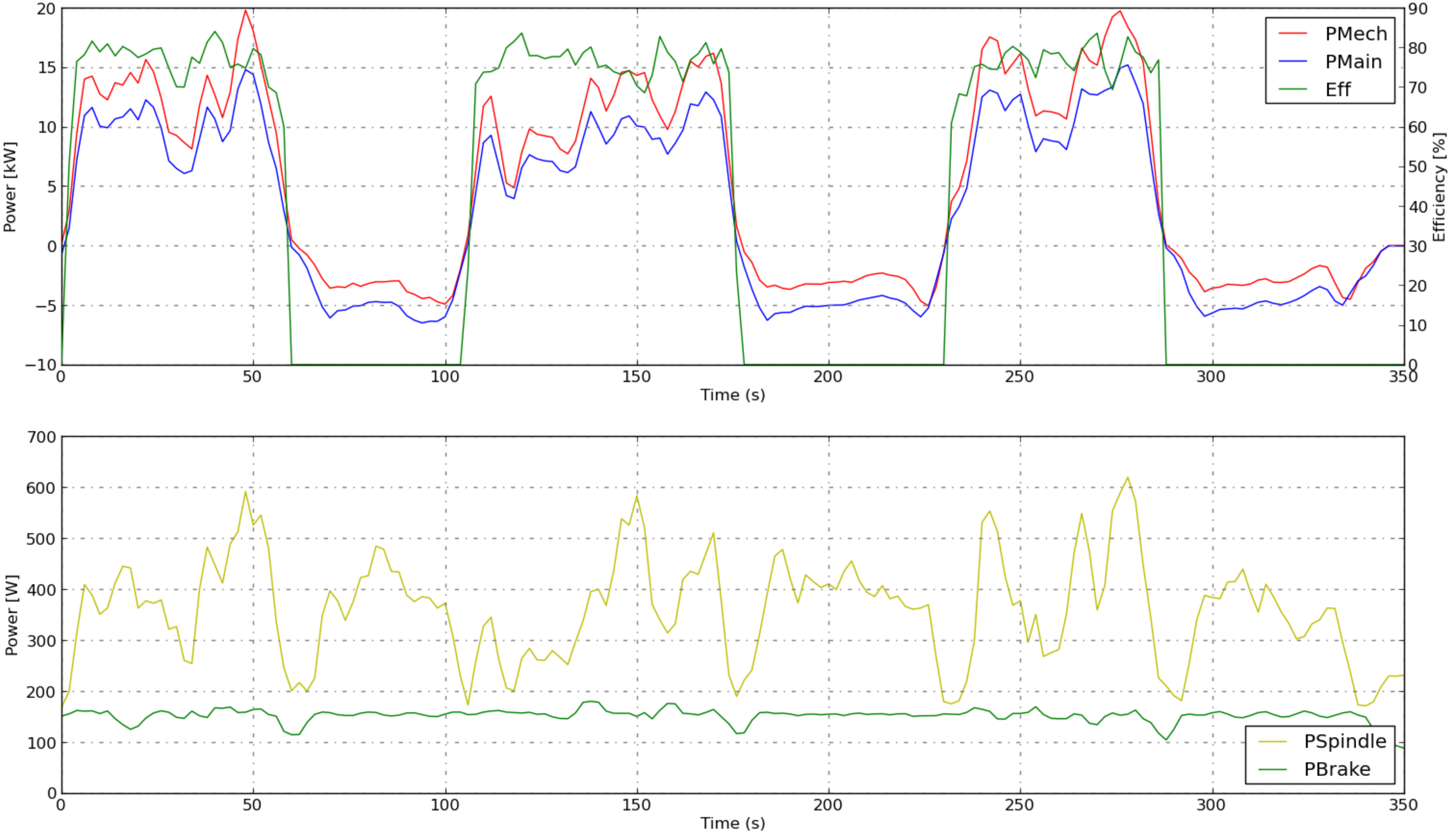
$$CF = \frac{P_{inst}}{P_e} \approx \frac{1}{\eta_{tot}} \quad (7)$$

The cost factor is defined as the relation between the total installed electrical machine power and the average electrical output at the optimal wind speed. It gives an indication of the relative costs of the ground station (not of the overall kite power system!), compared with a (theoretical) optimal system, that constantly reels out and does not need any reel-in time and energy.

Measurement results (Energy)



Measurement results (Power)



Examples I

Performance factors for HAWP systems in pumping operation

	Current system – measured –	Current system – simulated –	New system	
v_{gnd}	6 m/s	8 m/s	8 m/s	wind speed at 6 m height
v_i^{max}	8 m/s	8 m/s	14 m/s	maximal reel-in speed of the winch
v_{ot}^{max}	5.8 m/s	8 m/s	7 m/s	maximal reel-out speed of the tether
η_m	80 %	80 %	80 %	mechanical efficiency
η_{tot}	19.7 %	18.1 %	42.6 %	total efficiency
D	53 %	48 %	67 %	duty cycle

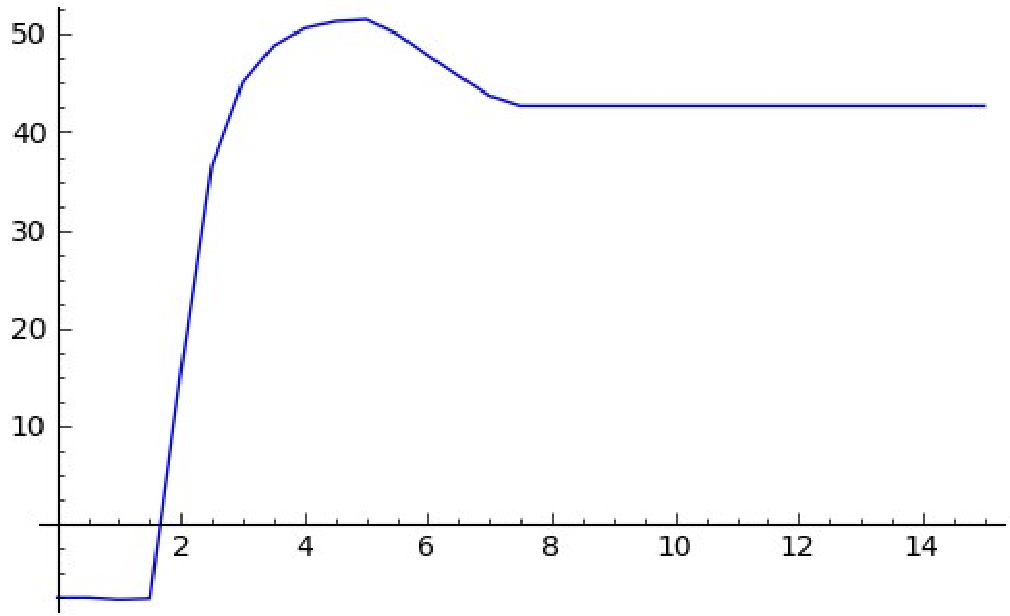
Examples II

Performance factors for HAWP systems in pumping operation

	Current system – measured –	Current system – simulated –	New system	
C_i^v	1.85	1.85	1.50	crest factor of the reel-in speed
C_o^v	1.71	1.71	1.50	crest factor of the reel-out speed
C_f	1.15	1.15	1.15	crest factor of the reel-out force
P_{inst}	13.0 kW	18.4 kW	55.0 kW	installed machine power
P_e	2.29 kW	2.90 kW	20.4 kW	average electrical output over 3 cycles
CF	5.66	6.36	2.70	cost factor

Total Efficiency as function of windspeed

Efficiency in % vs. windspeed in 6 m height, new groundstation



The total efficiency depends on the windspeed.

At lower wind speeds the optimal duty cycle is higher, because the reel-out speed is lower, and the reel-in speed can be kept constant.

In this design we reach a total efficieny of 50% at a windspeed of 5 m/s.

Conclusions

Performance factors of HAWP systems

1. The electrical efficiency of a HAWP system in pumping mode of operation depends heavily on the mechanical efficiency of the system.
2. As a rule of the thumb, the losses in the ground station are two times as high, as the losses in the generator alone.
3. To get a high duty cycle, a groundstation that is optimized for a high reel-in speed and a low reel-out speed (with a high force) is needed.
4. With a good design a cost factor of 2.7 for a system with 20 kW nominell output might be achievable.

Outlook

Main goals of the research of TU Delft in the coming year

1. Develop and implement a new groundstation with up to 20 kW average electrical output.
2. Develop a fully automated control system for the kite and the winch, based on wireless control of the kite and the open robotics software OROCOS.
3. Develop and validate a real-time dynamic kite system model.
4. Develop a new kite with a pulling force of 1200 kgf and an improved lift over drag ratio.

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