Development and Evaluation of a Hybrid Power Management System for Airships Intended for Infrared Thermographic Inspection of Photovoltaic Plants

Bachelor Thesis

by Patrick Lodes

Contents

1. Background

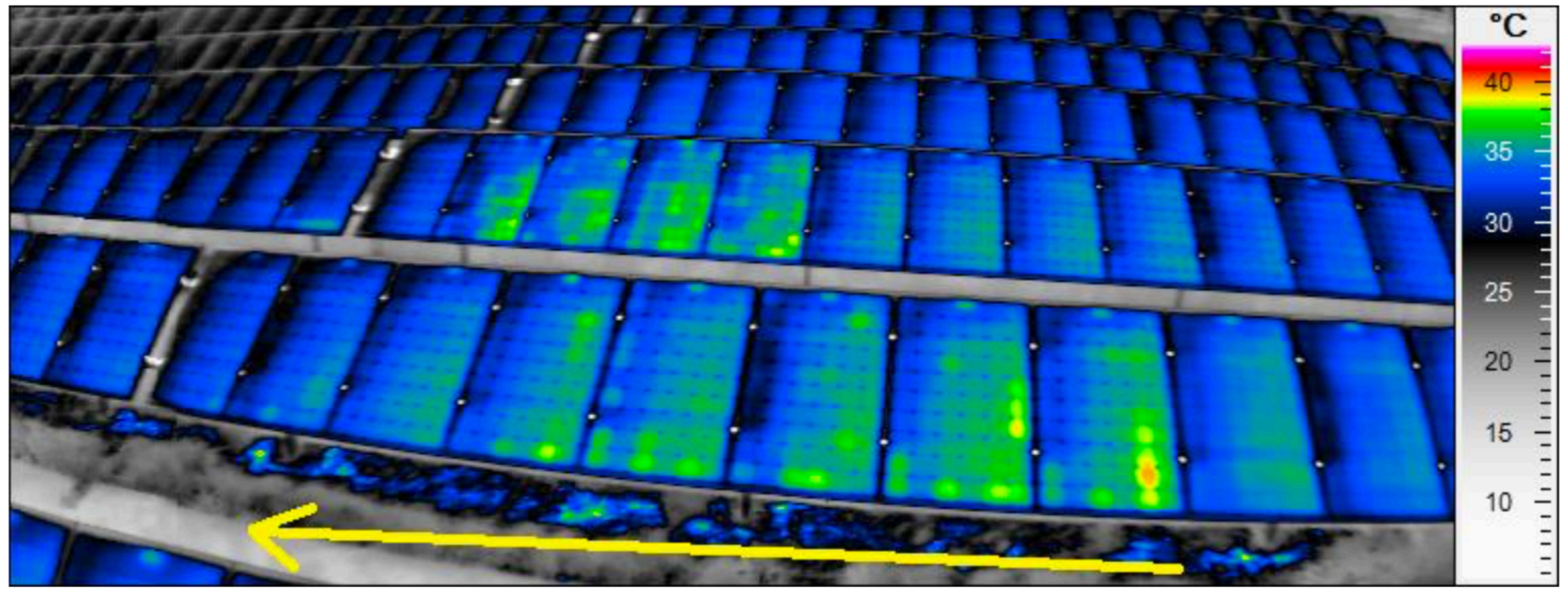
Damages of PV modules decrease performance PV plants, and thus overall power generation

Regular maintenance and fault detection required

Quantitative analysis can be done by infrared thermographic (IRT) imaging

When PV module or string is not functioning, energy is not converted to DC power.

Power released as excess heat → Raising temperature of the module

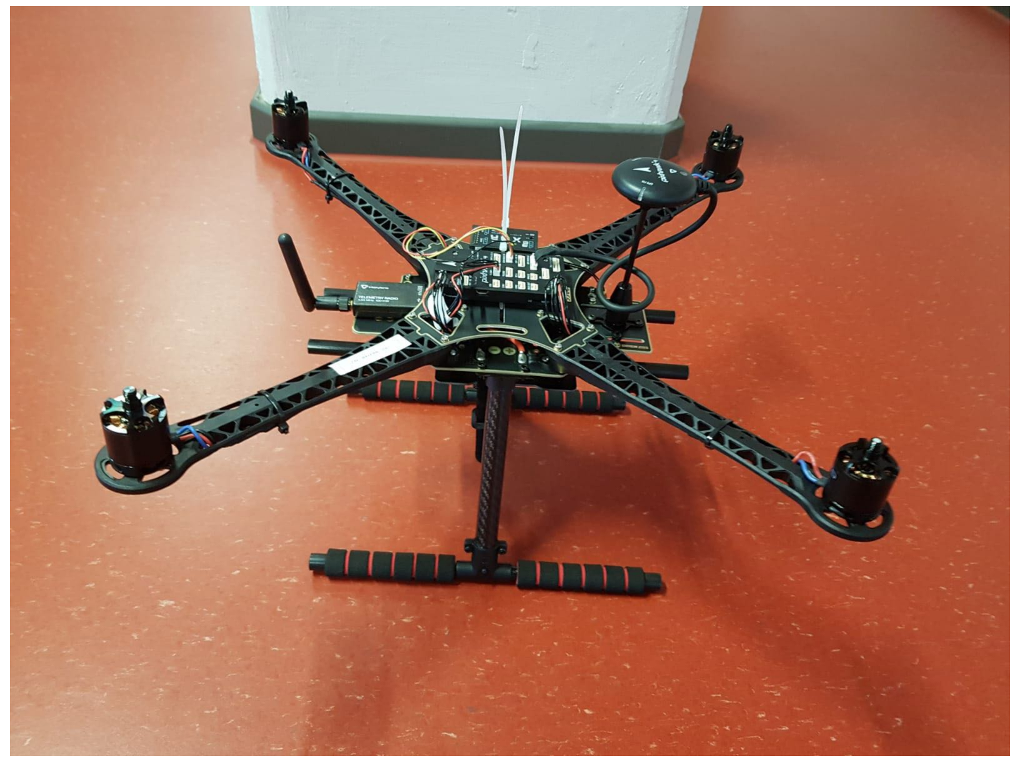


Thermal patterns formed by temperature differences point out defects.

(usually hotter than other areas)

Inspections can be done by hand.

Usage of unmanned aerial vehicles (UAV) speeds up IRT inspection process.



Standard: Multirotor Drones

Problem: Short flight times – relative to the size of the area to be monitored. (max. ca. 30min)

The total flight time of the UAV after takeoff can be shorter than the time required for the intended mission (e.g. monitoring vast outdoor area).

2. Motivation

Phases where no active IRT inspection is possible are dead time for the process (e.g. exchanging batteries)

$$\frac{t_{dead}}{t_{t_{inspect}}} \longrightarrow 0$$

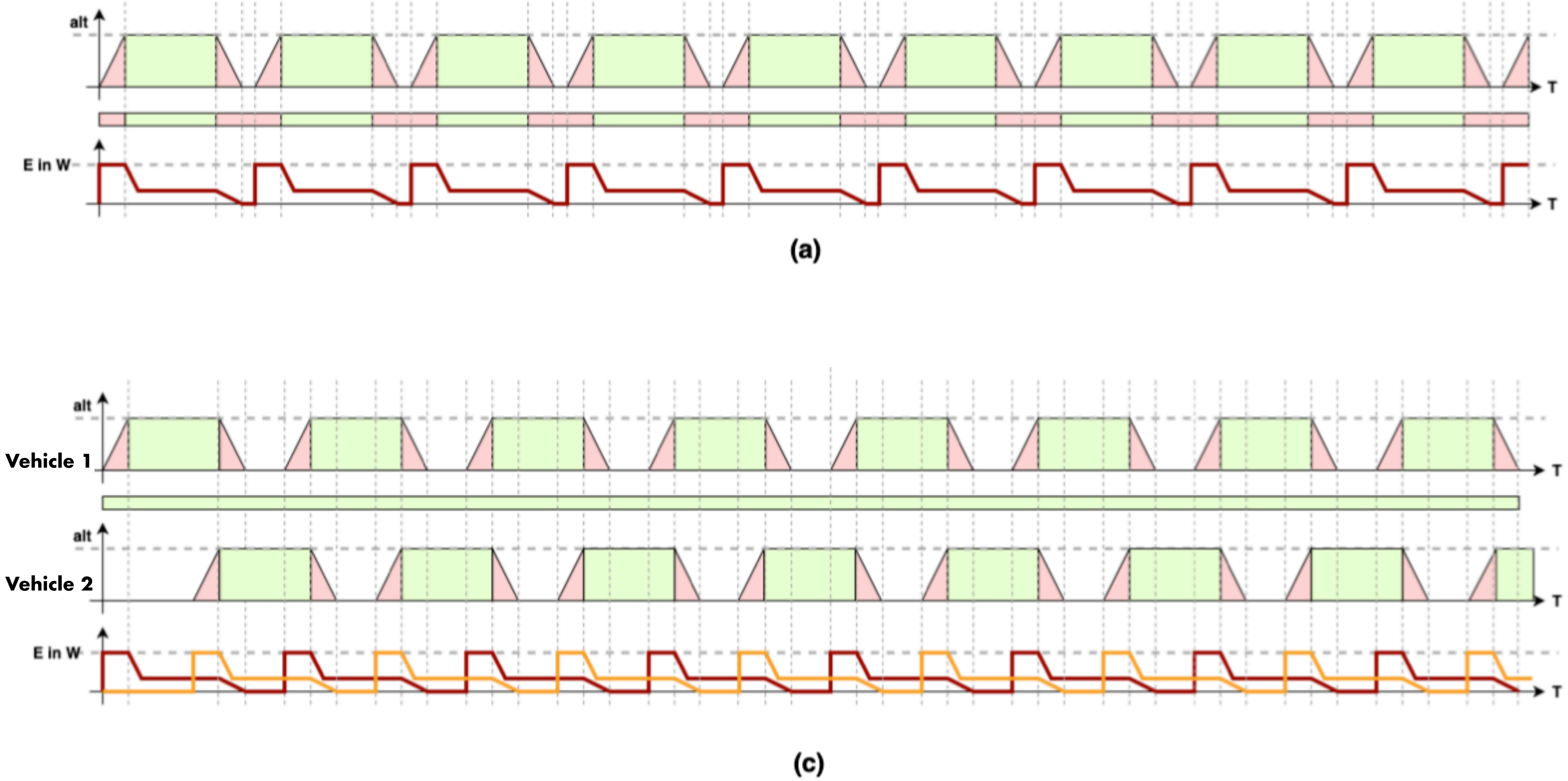
with

$$t_{dead} = \sum t_{takeoff} + \sum t_{landing}$$

Time to leave or return the flight course and to exchange the batteries are ignored.

The longer the total flight time after takeoff, the lower the fraction of dead time

Reducing the number of idle phases increases overall efficiency



Dead times are eliminated by using two alternating flight objects

Motivation: Extend flight time of UAV to increase efficiency of the IRT inspection process

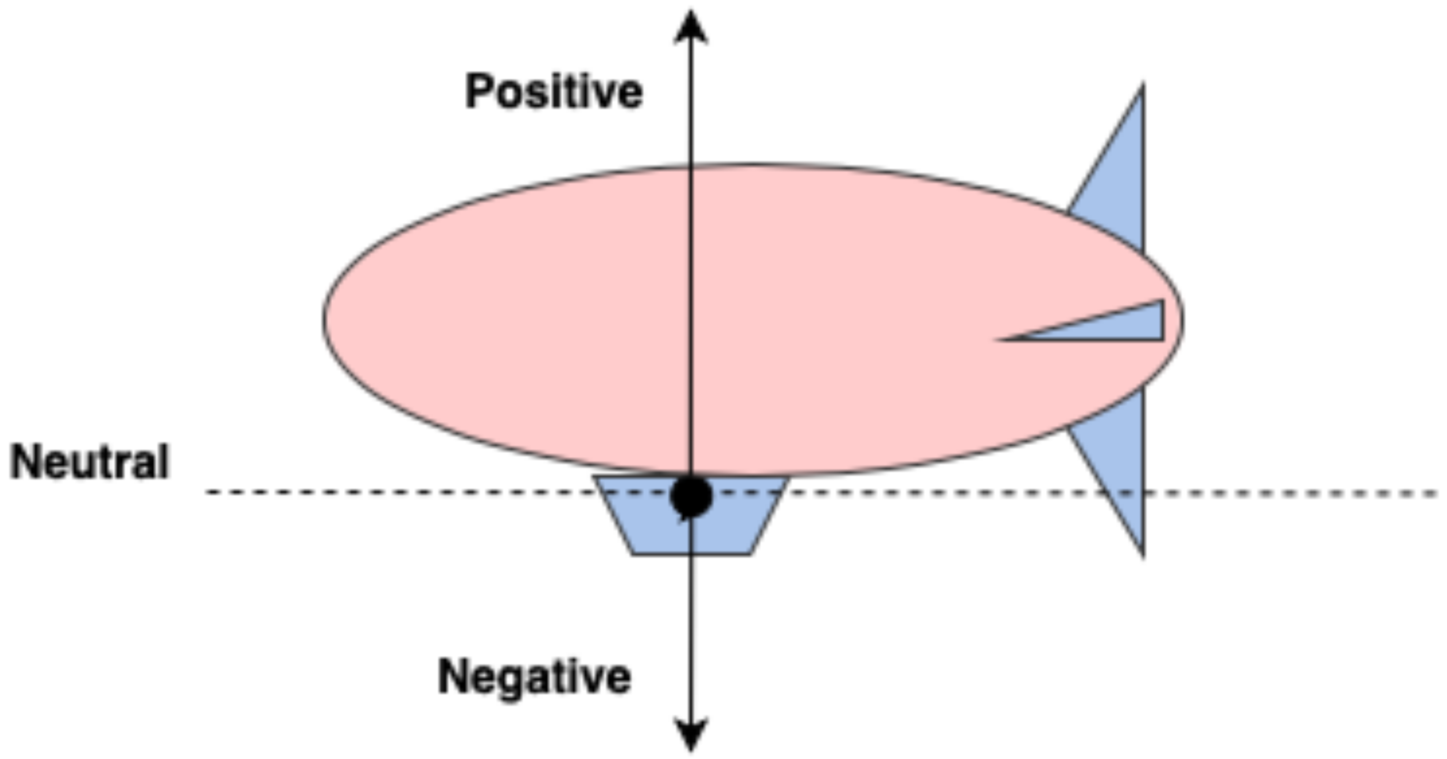
How?!

1. Vehicle with low power consumption
2. Solar power as secondary power supply
3. Dedicated hardware for power management in flight

An airship meets some of the vehicle requirements

1. Lighter-than-air (LTA) characteristics results in less energy required to maintain altitude.

2. Helium body of the airship has big surface area.
→ Additional space to mount organic photovoltaic (OPV)



Goal: **Development of hybrid power management system (HPMS)**

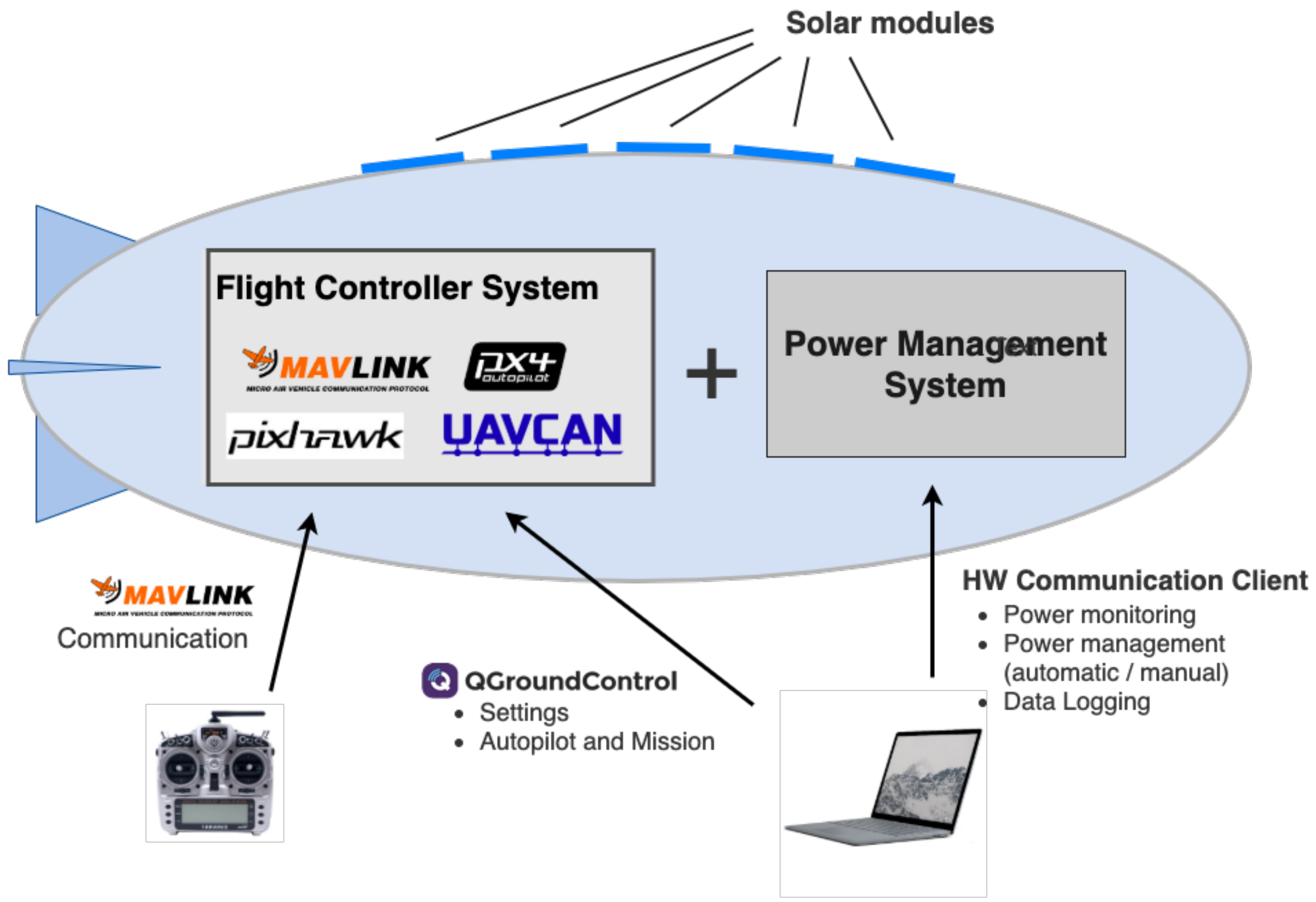
Comprising hardware, firmware and software

Interfere with, control and improve the power management of the flight system

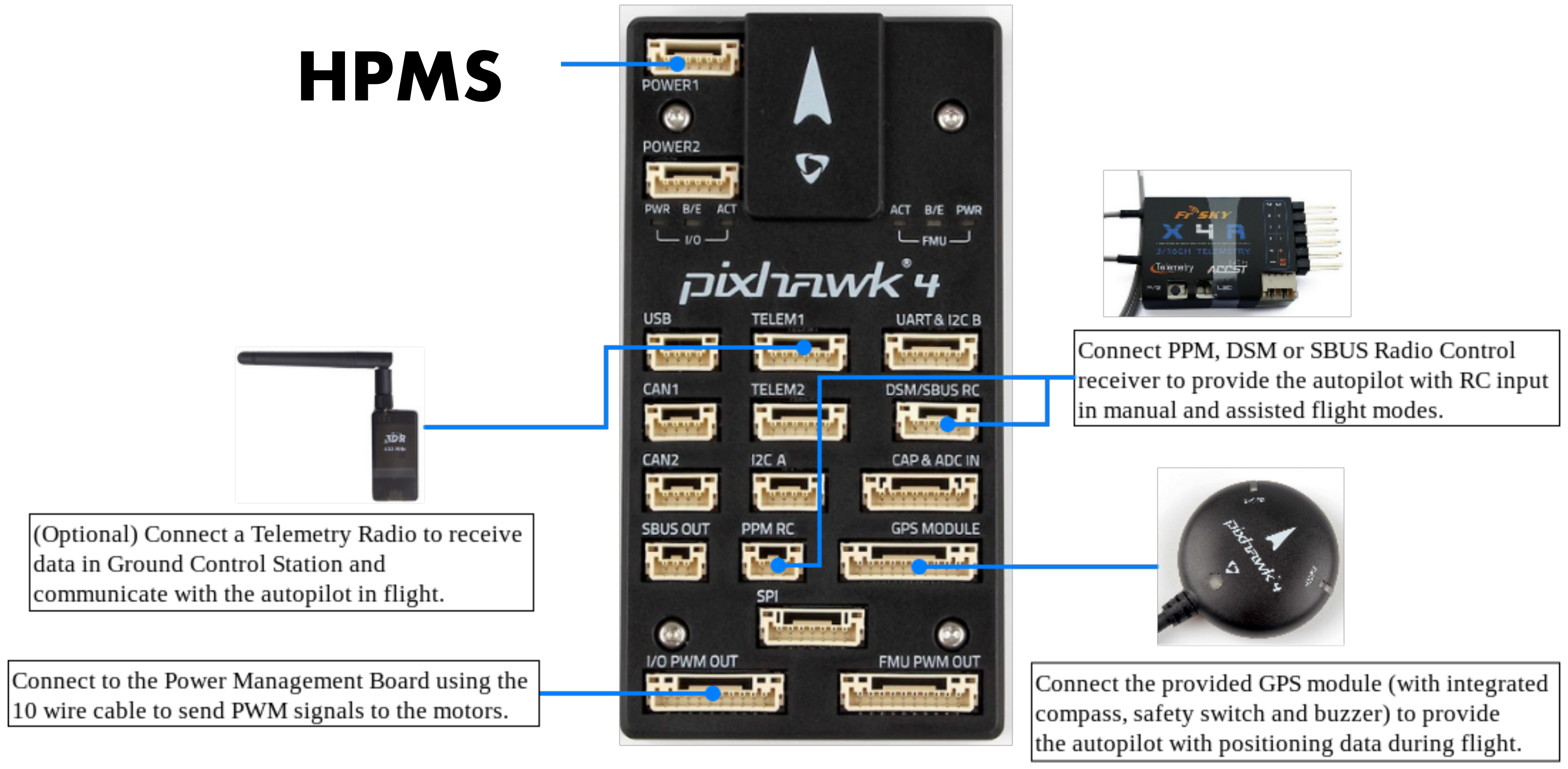
Smartly use redundant energy storage devices to enable in-flight charging with solar power from OPV

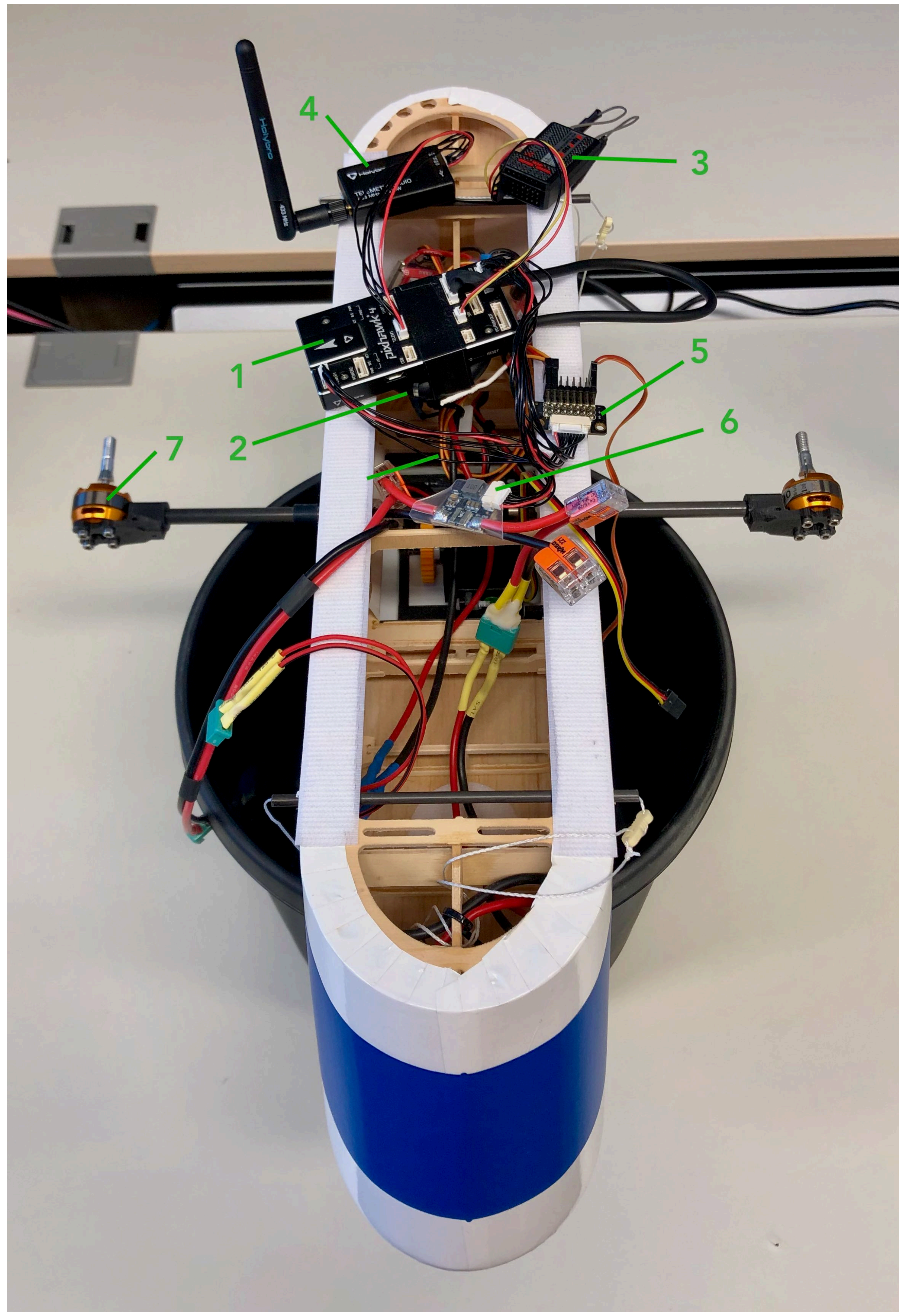
3. Airship

The Airship Prototype for the Project



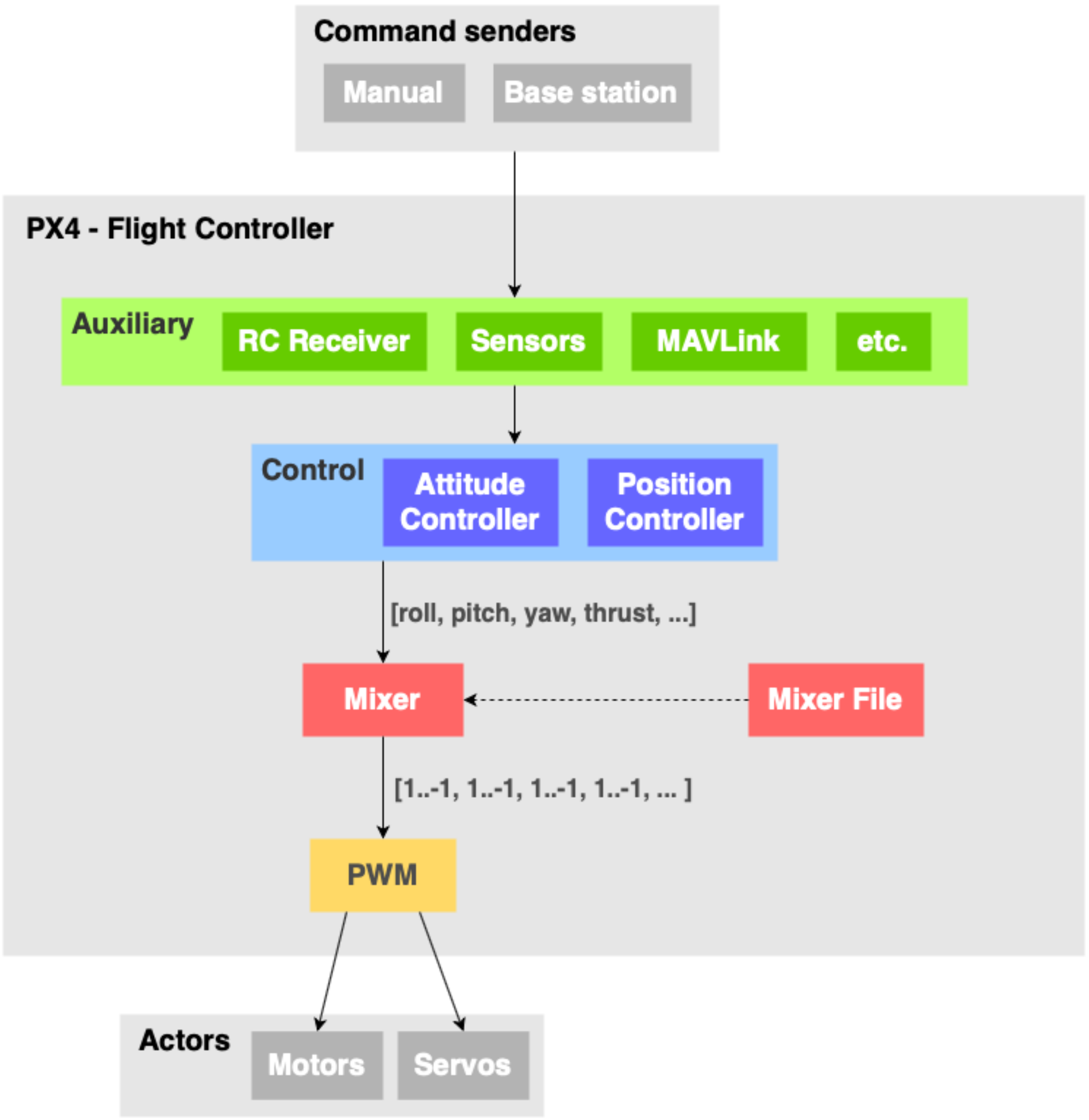
Integrating PX4 Flight Stack into Airship Prototype





PX4 Flight Controller Software

Can flexibly be used for multiple different airframes and and vehicle types



Available Payload

Airship Prototype equipped with HPMS

Available payload	1000g
- Second battery	130g
- Pixhawk	96g
- GPS	32g
- HPMS	≥130g
- OPV	500g
Free	**≤112g**

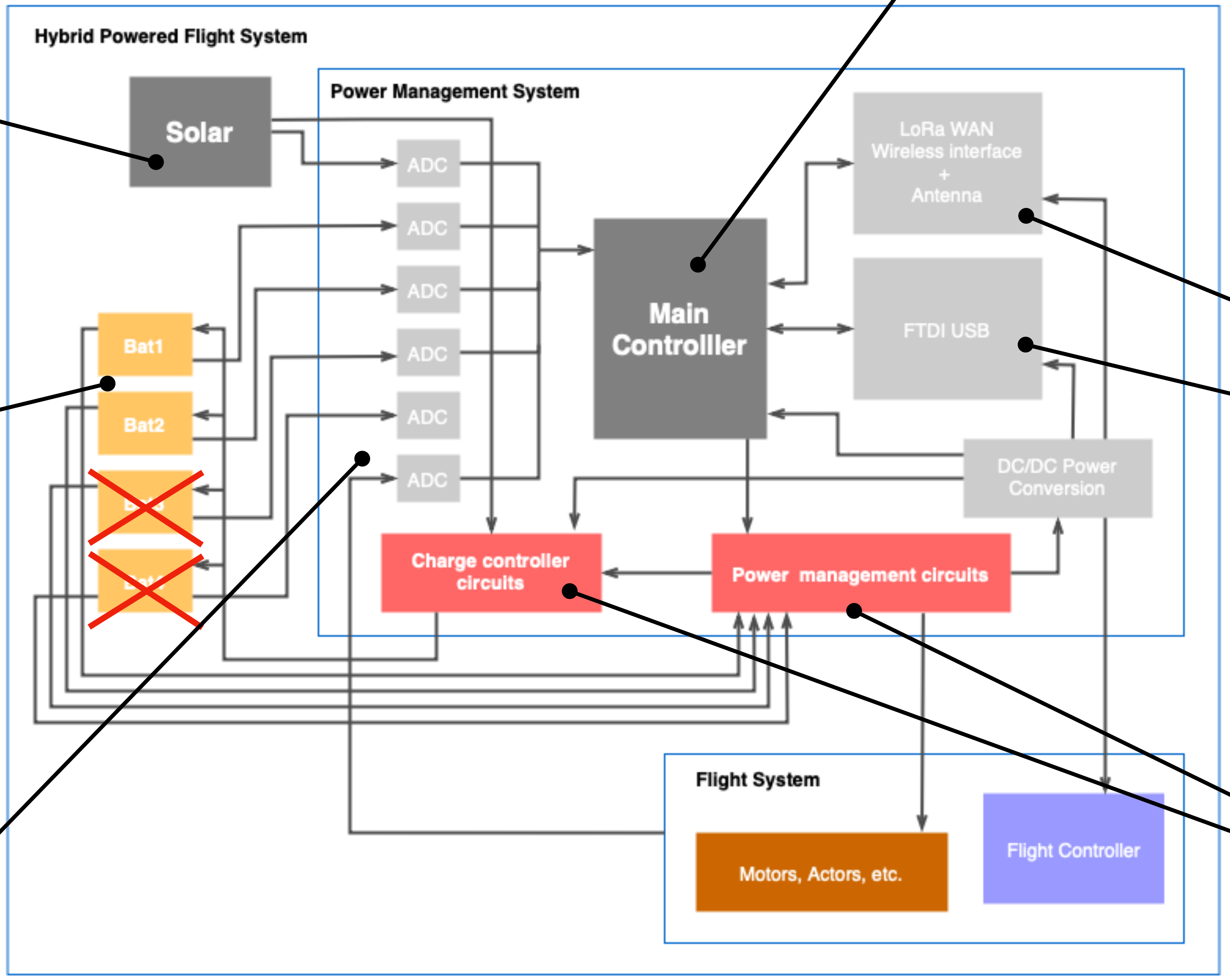
Buffer
(Not much space for additional equipment)

3.1 Implementation: Hardware

Concept of the HPMS Hardware

Processing of data and
interaction with client

Supply charge power



Redundant batteries supplying
the system

Communication with
desktop client software
(HCI) via USB or wireless

Measure and monitor
system data and transmit to
microcontroller

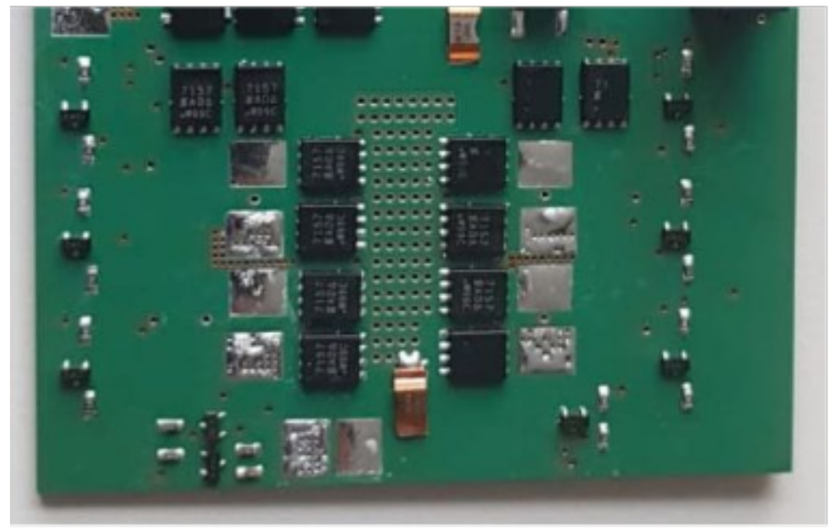
Charge demultiplexing and supply
multiplexing

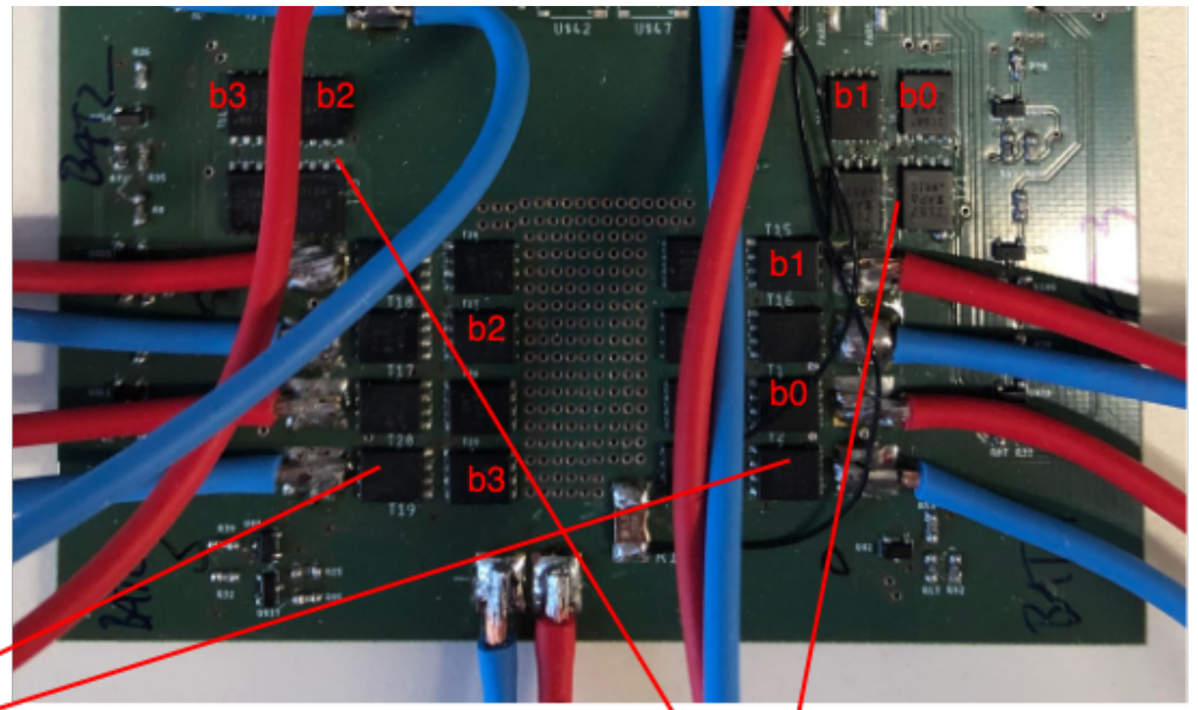
(Dis)Charging in alternating manner
(while one battery supplies an empty
battery is charged)

In-flight charging with solar power from
OPV

Dedicated Switching Circuits

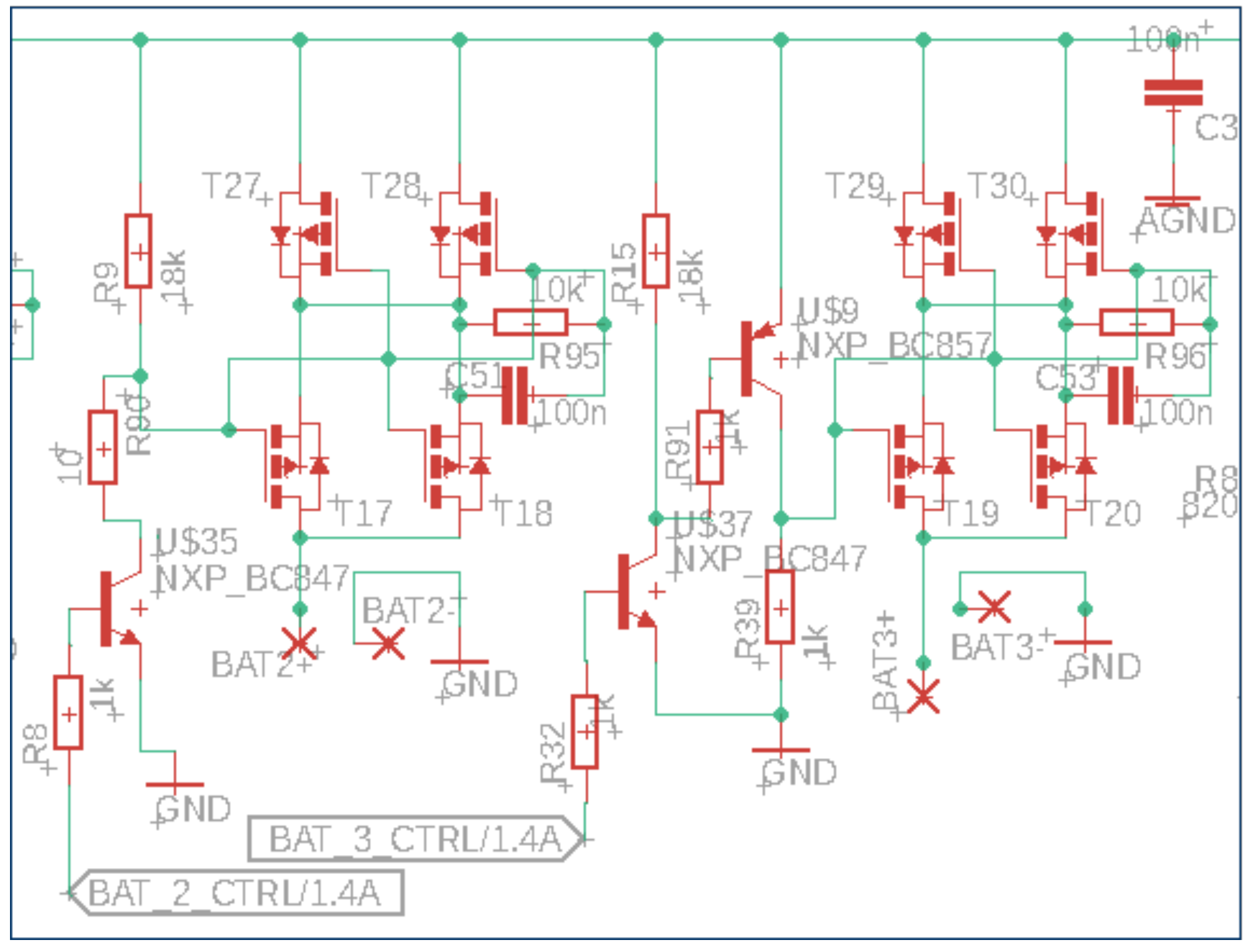
Based on redundant power sources

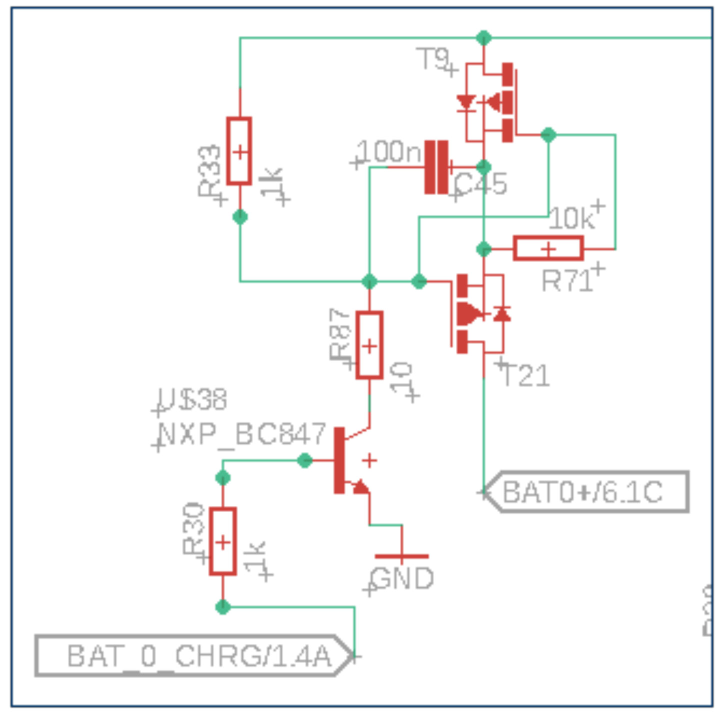




- Bidirectional Power Switches (BPS)
- Paralleling power MOSFETs

Supply Multiplexing
Switching power source in flight





Charge Demultiplexing
Switching between batteries to be charged in flight

MPP charging possible during operation

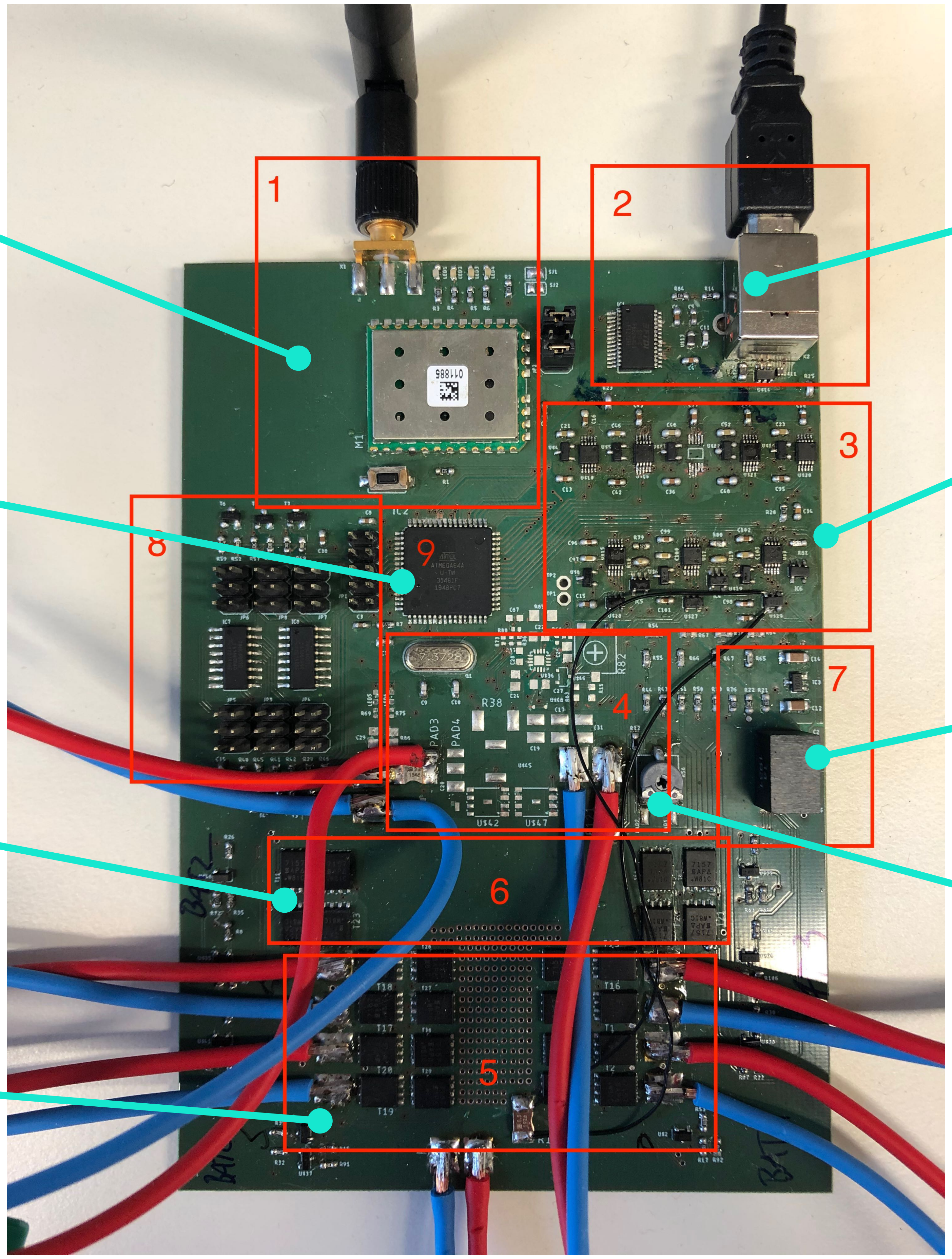
HPMS Prototype

1. WiMOD LR Base radio module and antenna

2. FT232R USB UART interface and connector

9. ATmega64, Microcontroller

3. Measurement Circuits and Analogue Digital Conversion (ADC)



7. DC/DC Converter to supply the board with 3.3V

5. Supply multiplexing

4. Charge controller for solar power input with MPPT

6. Charge demultiplexing

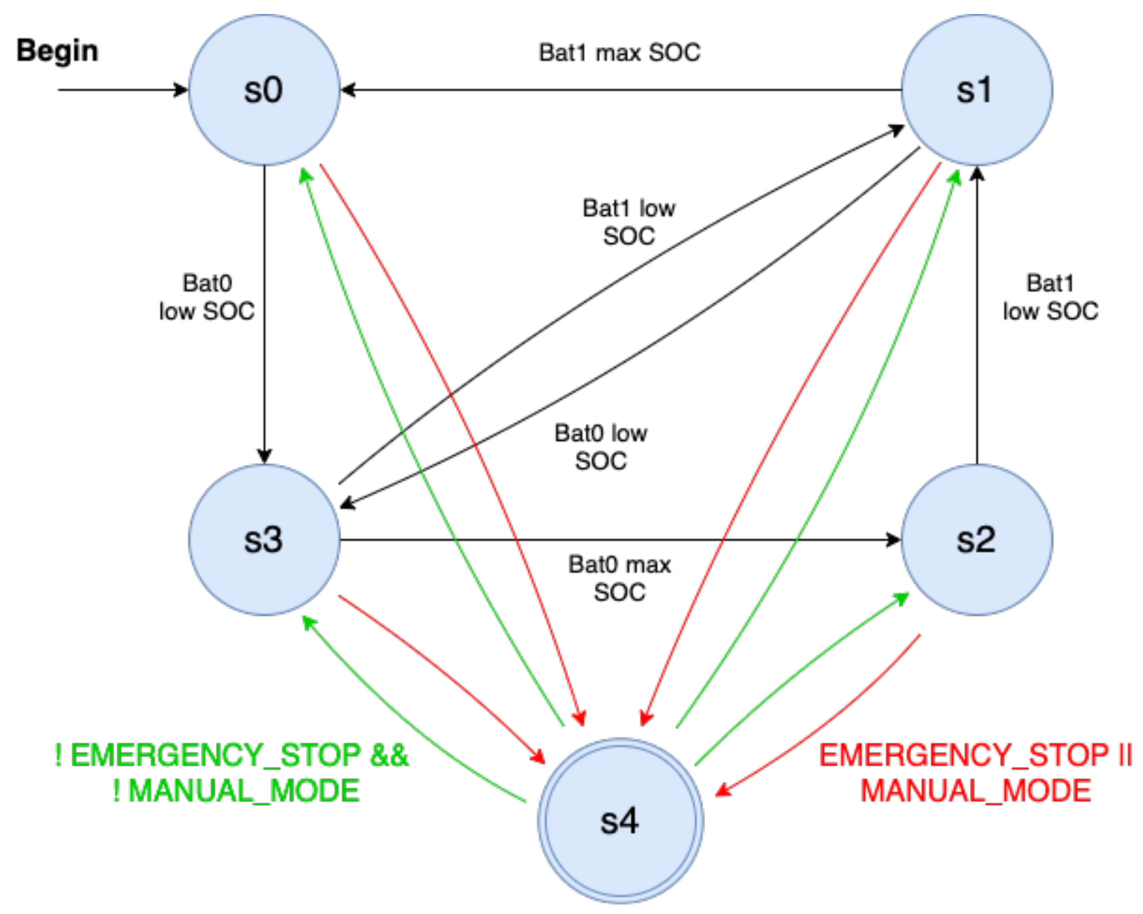
3.2 Implementation: Firmware

The firmware controls power management (automatic or manual) and interacts with communication client

A static schedule is applied to charge and discharge two batteries in alternating manner

Bat	Start		1	2	3	4	5	6	7	8	9	10
0	D	C	D	C	D	C	D	C	D	C	D	C
1	F	D	C	D	C	D	C	D	C	D	C	D

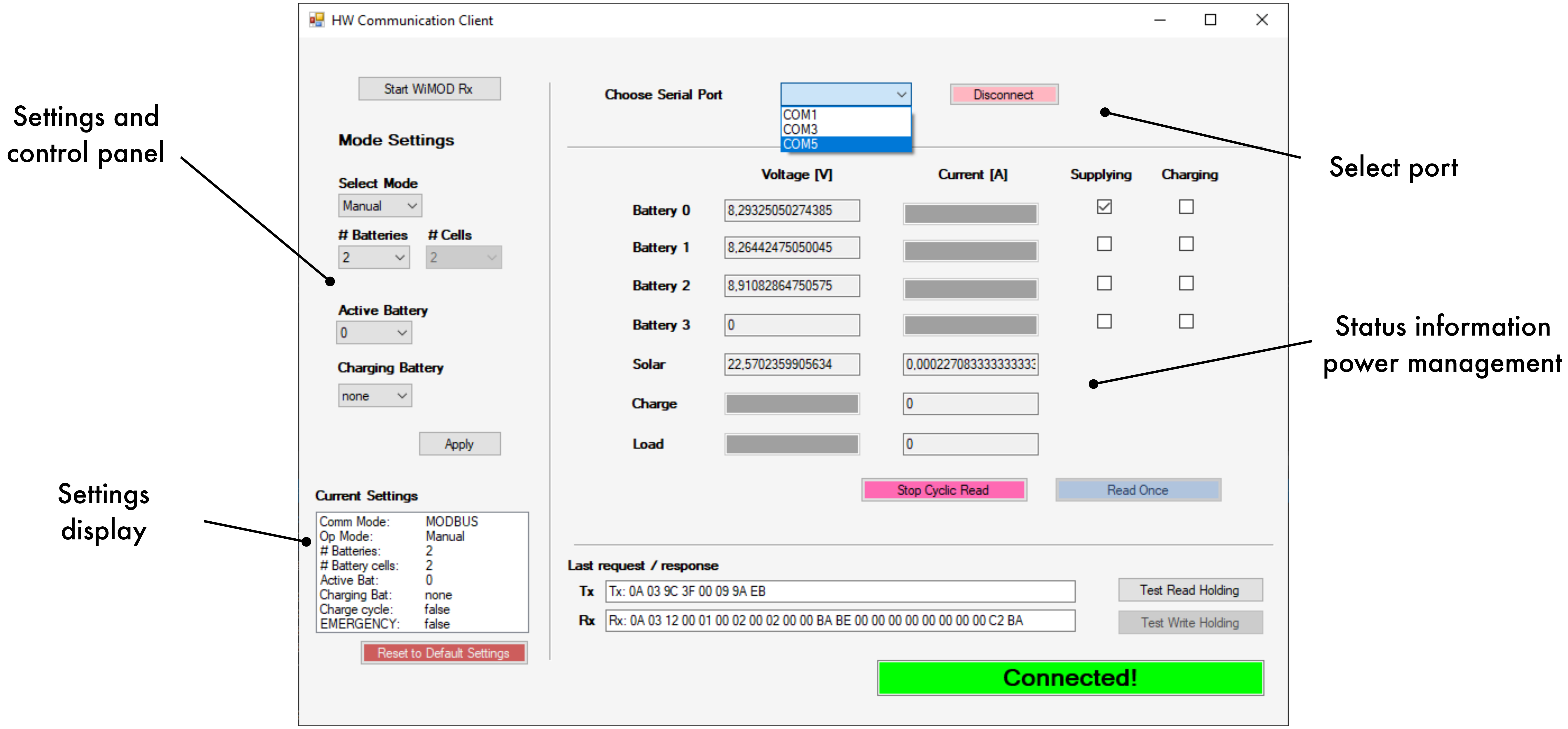
Routine illustrated as finite state automaton (FSA)..



3.2 Implementation: Software

Hardware Communication Client (HWComClient) - GUI

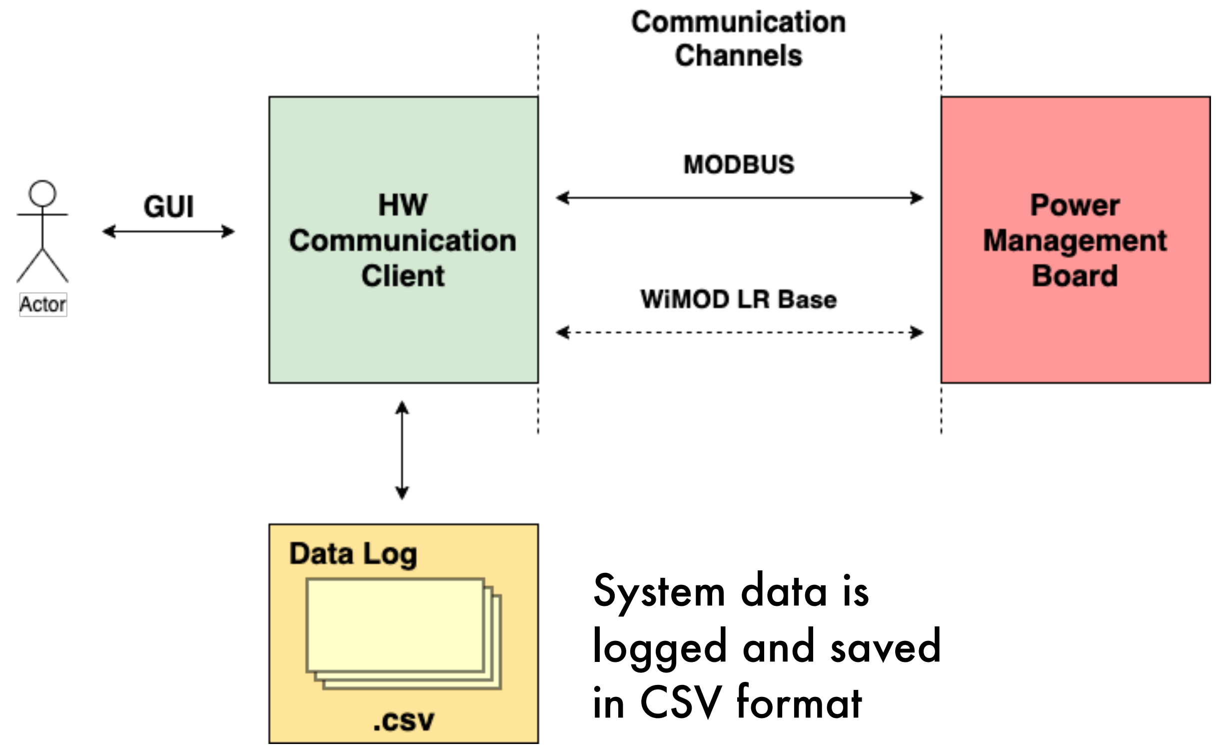
Desktop software to help user to interact with HPMS



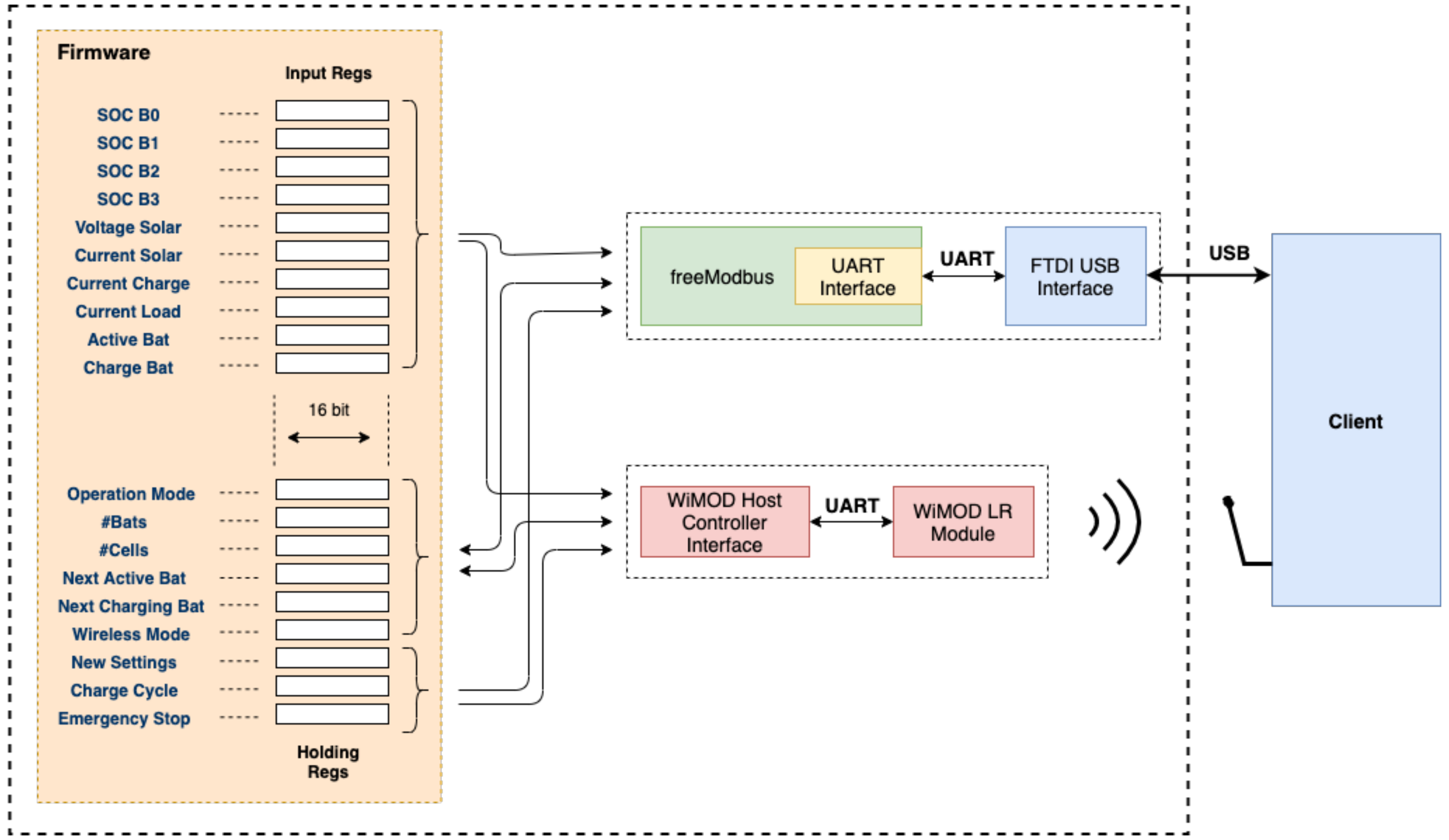
- Receives and displays cyclic status information sent by the firmware
- User can..
  - adjust settings of the firmware
  - switch off power management routine to have manual control

Communication and Data Exchange

User interacts with HPMS firmware through HWComClient GUI



System data is logged and saved in CSV format



Communication Protocols:

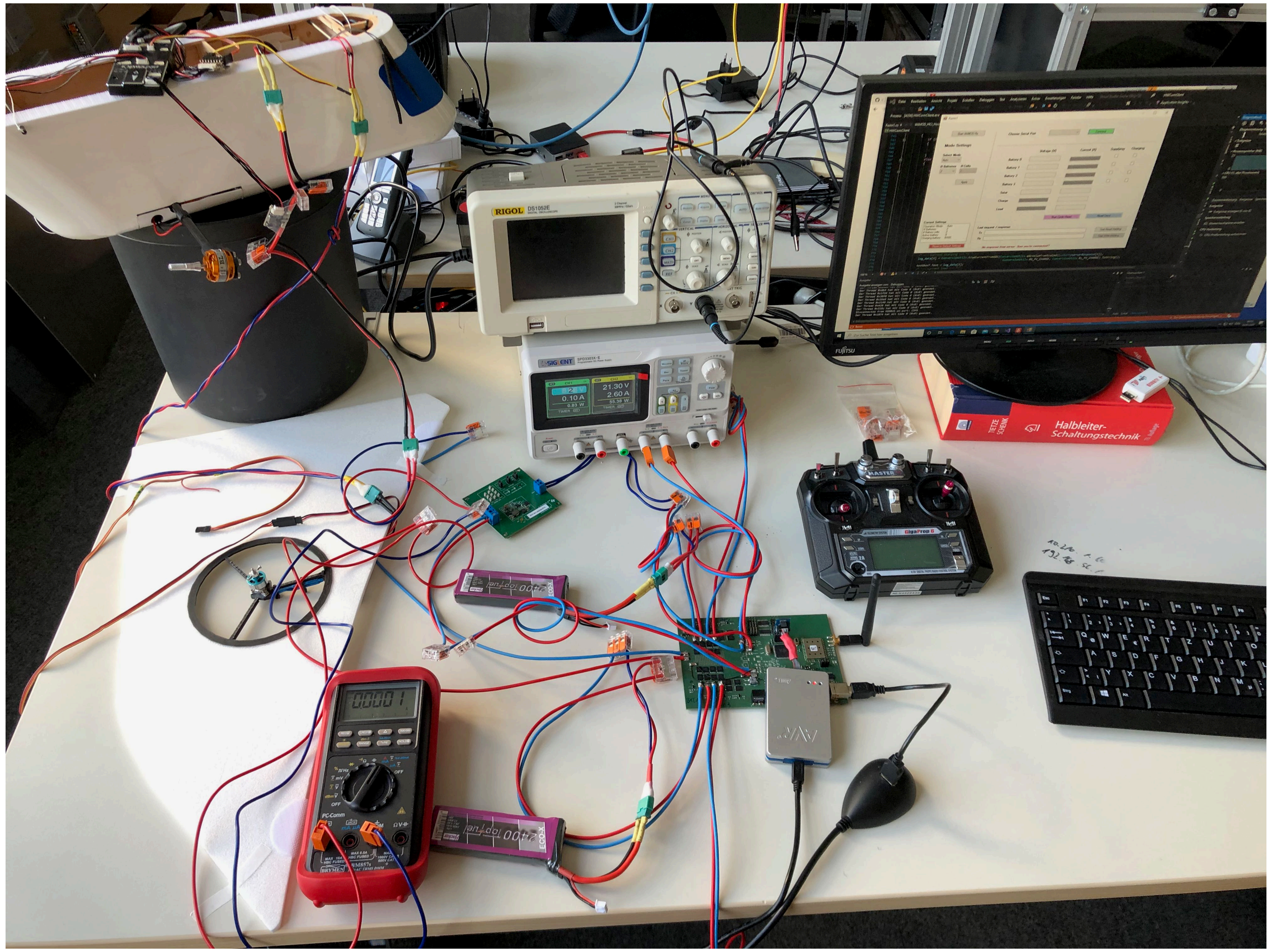
- Serial: Modbus
- Wireless: WiMOD LR Base

Benefits of the protocols:

- Software structure to interface the chosen communication channels
- Data integrity (using CRC16)

4. Performance Evaluation

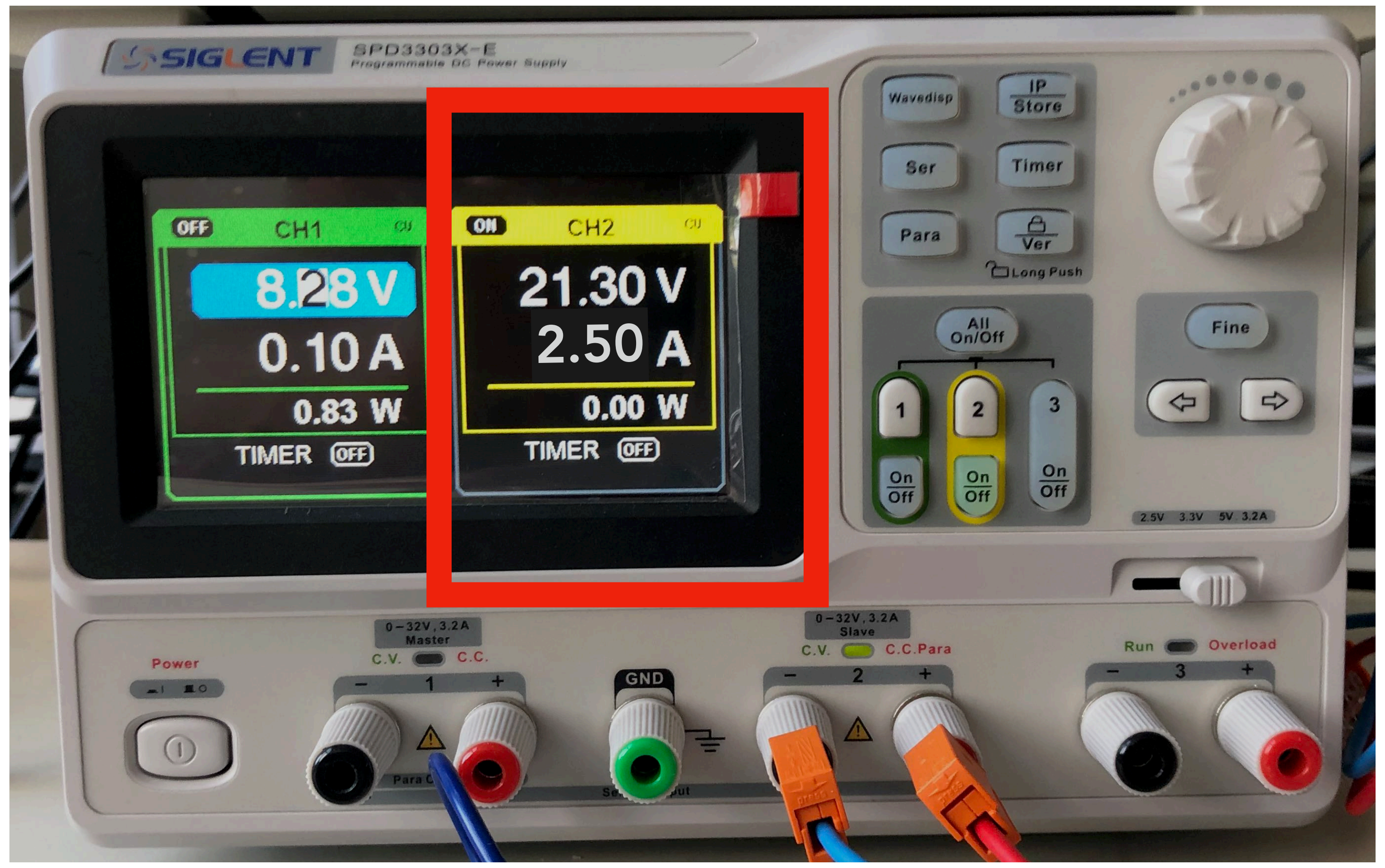
Evaluation of the developed HPMS in the lab



Batteries

- LiPo 2400mAh 2S
- Defines max. state-of-charge: $SOC_{max} = 2400mAh$
- *Charge circuits and HPMS designed for this battery. (max charge current of 6Amps which is 2,5C)*

Charge Power Supply



- DC source from the lab
- Charge power: $P_C \approx 52{,}5W$
  (minimum charge power to supply desired charge rate of 2,5C)

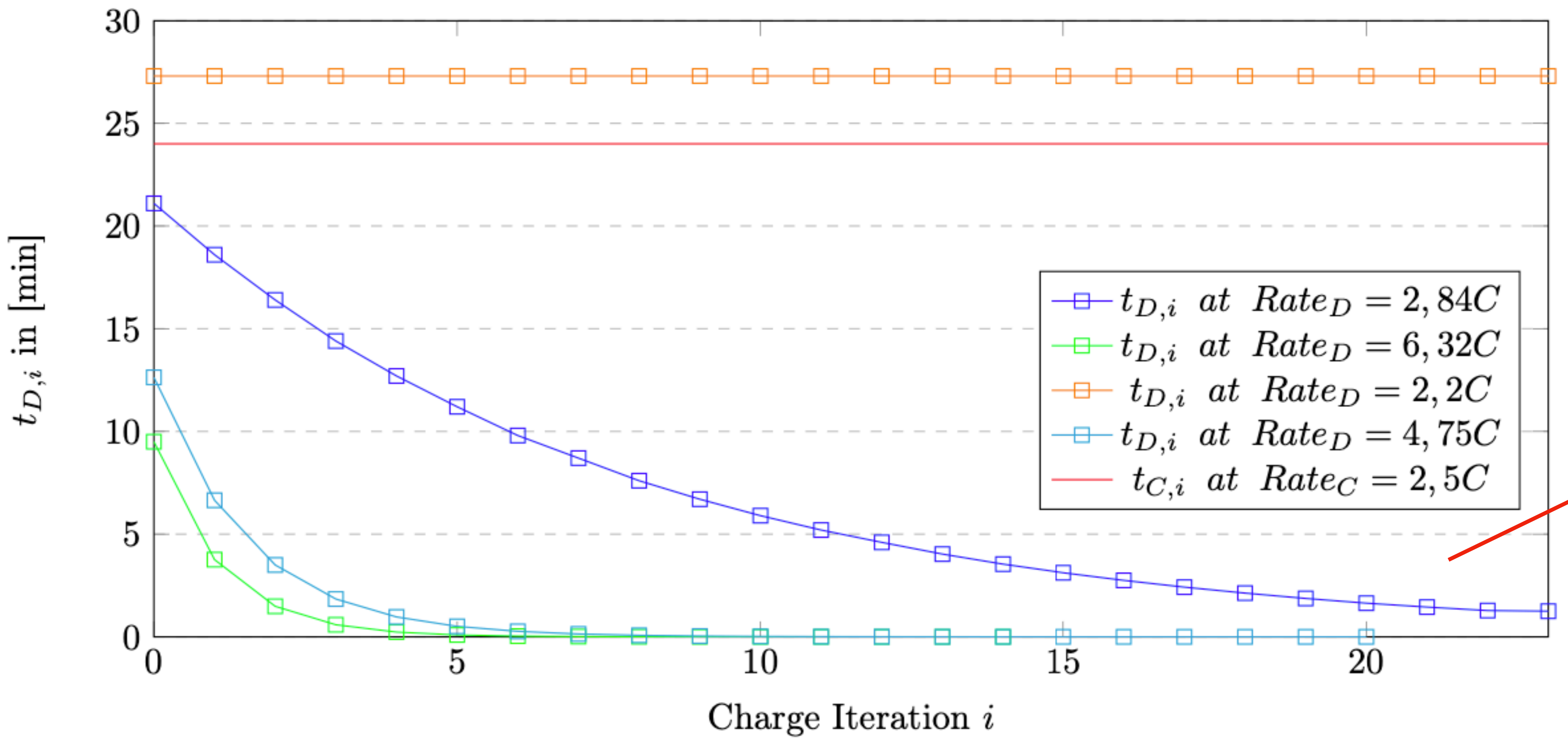
How does HPMS influence the flight time of the airship?

Index i	$Rate_D$	I_D	$t_{D,1}$	$t_{D,total}$	$Rate_C$	I_C	t_C	SOC_{max}	$\frac{Rate_C}{Rate_D}$	$D_{FTE,rel}$	Color
		mA	min	min		mA	min				
1	2,2	5280	27,27	∞	2,5	6000	24	2400	1,14	∞	
2	2,84	6825	21,13	189,33	2,5	6000	24	2400	0,9	8,96	
3	4,75	11400	12,63	39,3	2,5	6000	24	2400	0,53	3,11	
4	6,32	15160	9,5	25,22	2,5	6000	24	2400	0,4	2,65	

$D_{FTE,rel} = \frac{t_{D,total}}{\Theta_{D,total}}$: relative flight time enhancement.

$\Theta_{D,total}$: total flight time without HPMS.

$Rate_C = 2{,}5C$



Decrease of $t_{D,i}$ when $Rate_D > Rate_C$

$Rate_D = 2{,}84C \longrightarrow Rate_D > Rate_C$

Bat	**Start**		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
t min	**21,13**	**21,13**	**18,6**	**16,4**	**14,4**	**12,7**	**11,2**	**9,8**	**8,6**	**7,6**	**6,7**	**5,9**	**5,2**	**4,5**	**4,0**
0	D	C	D	C	D	C	D	C	D	C	D	C	D	C	D
1	F	D	C	D	C	D	C	D	C	D	C	D	C	D	C

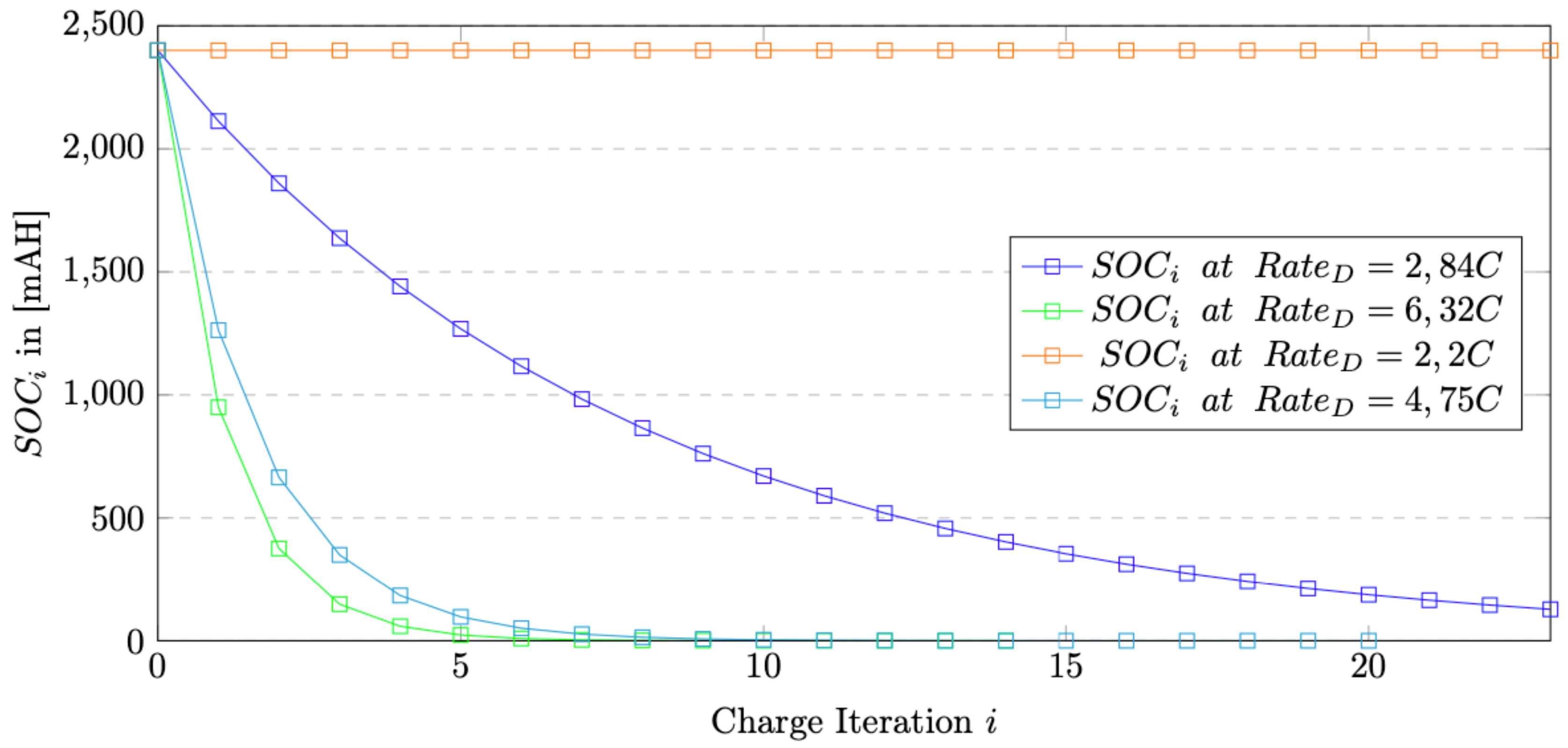
…

$Rate_D = 2{,}2C \longrightarrow Rate_D \leq Rate_C$

Bat	**Start**		**1**	**2**	**3**	**4**
t min	**27,3**	**27,3**	**27,3**	**27,3**	**27,3**	**27,3**
0	D	C	D	C	D	C
1	F	D	C	D	C	D

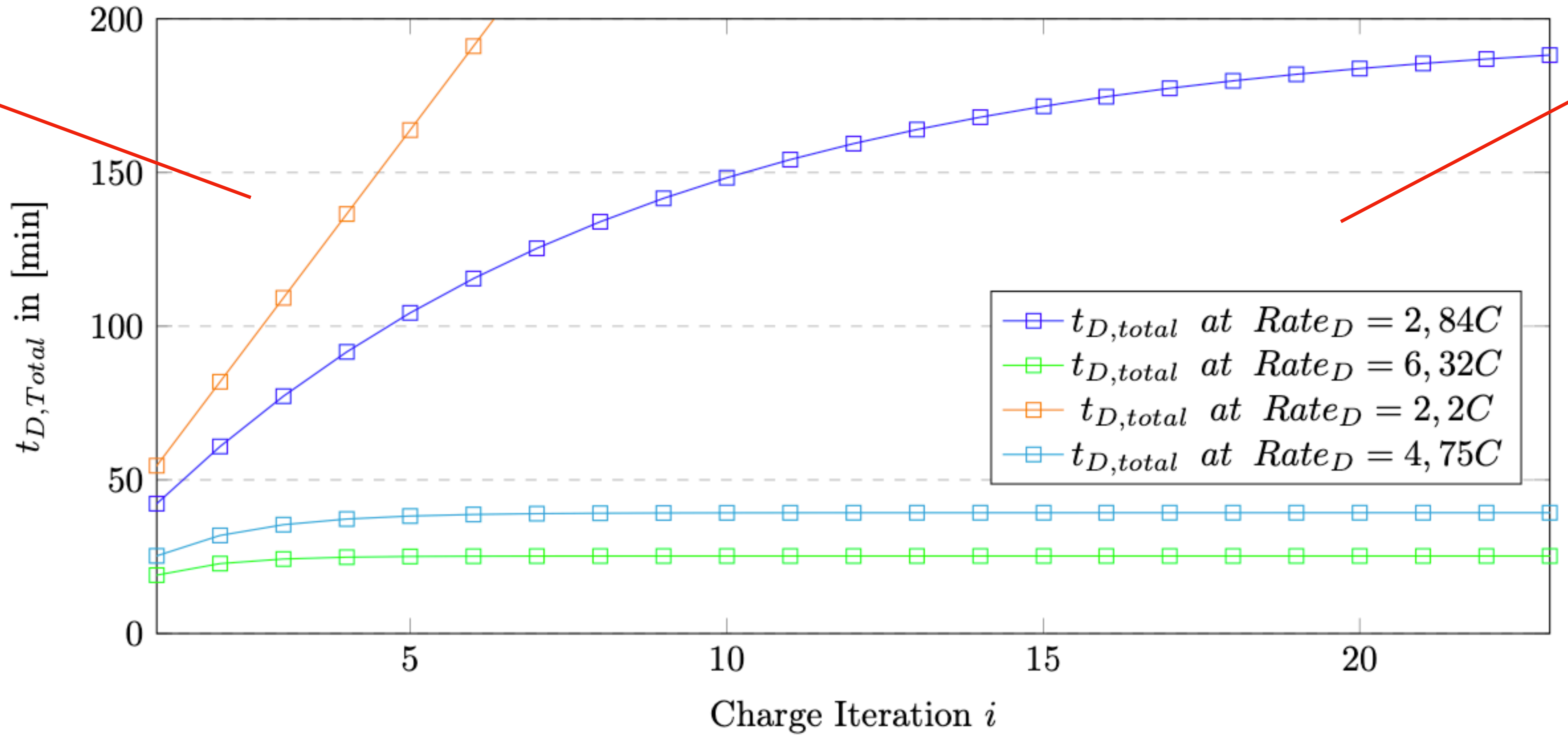
…

$Rate_C = 2{,}5C$



Linear growth $t_{D,total} \longrightarrow \infty$ when $Rate_D \leq Rate_C$

Logarithmic growth towards maximum total flight time $t_{D,total} \longrightarrow max$ when $Rate_D > Rate_C$



HPMS shows positive FTE in optimal conditions

Does HPMS increase flight time with OPV as charge power input?!

For the particular prototype the size of the OPV is limited by the available payload!

OPV surface: $A_{OPV} = 1{,}25m^2$ (straight surface)

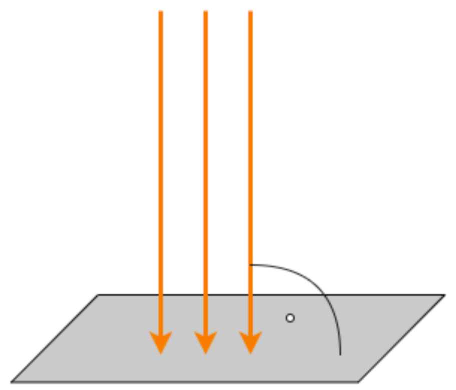
Efficiency: $\eta_{Ph} = 4{,}54\,\%$

Power output: $P_{Ph} = 56{,}7W$ For maximum sun irradiation and optimal orientation to sun. *(Dresden, Germany, 50°Lat, 21st June, 12 p.m., clear sky)*

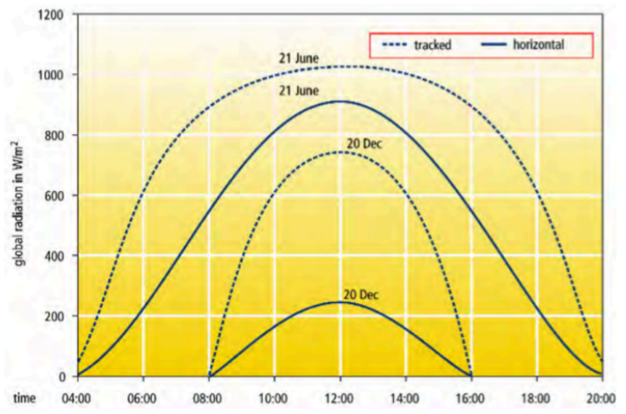
$P_{Ph} > P_{C,min}$

HPMS shows FTE with OPV as charge input
(Under optimal irradiation conditions)

Optimal Operating Conditions

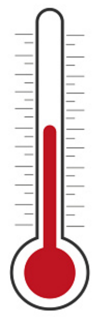


Perpendicular to
sun irradiation

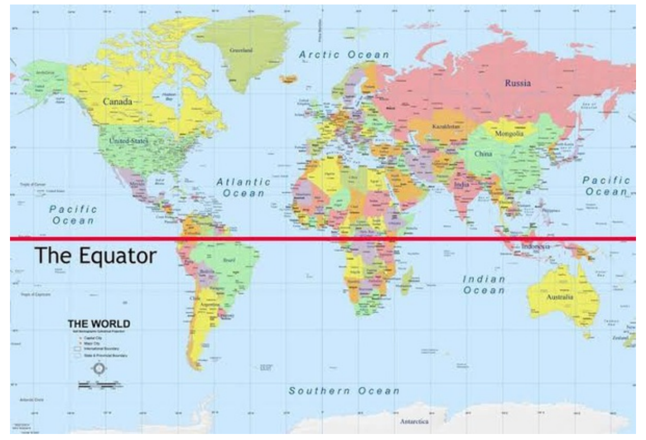


Mid summer,
daily peak irradiation

Good weather,
few clouds
(direct exposure)

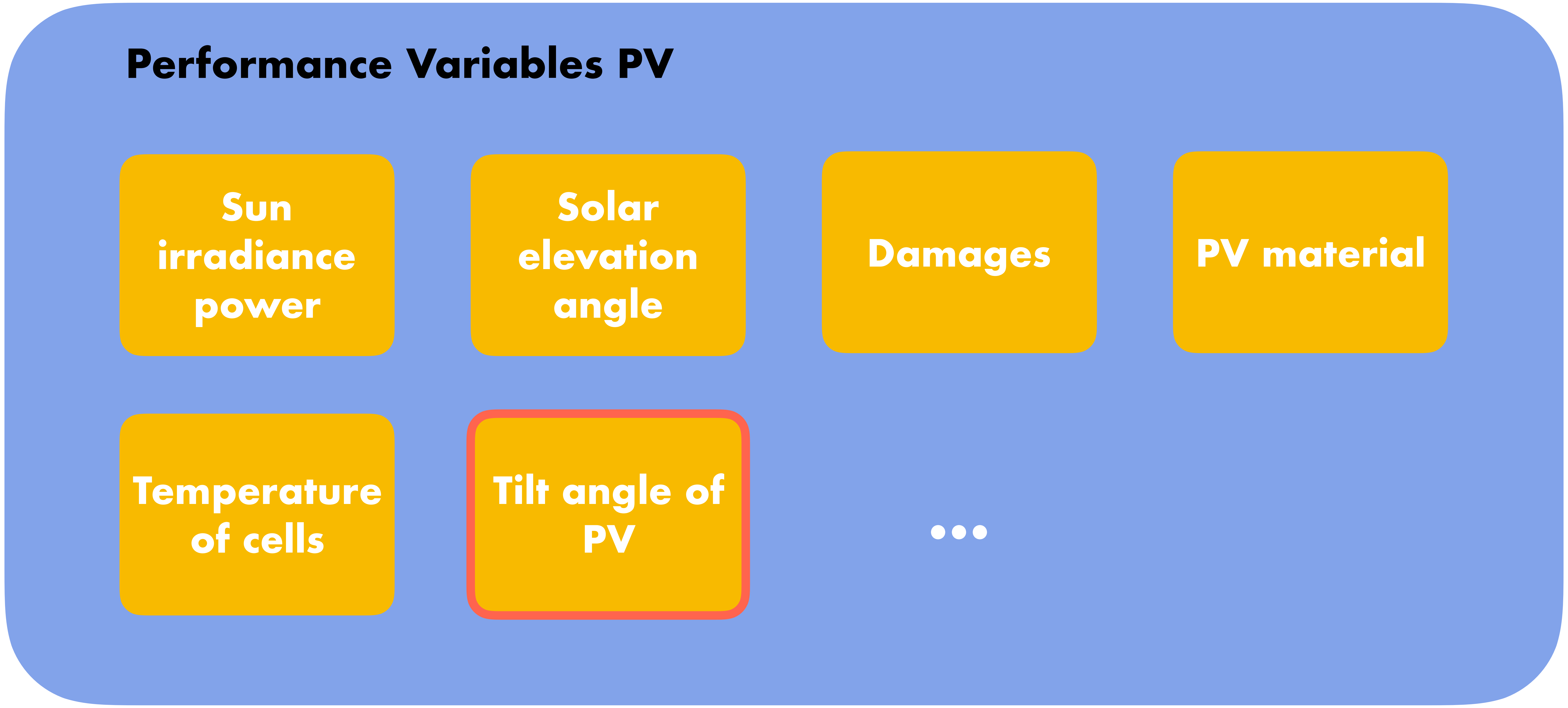


Adequate
cell
temperature



Near Equator

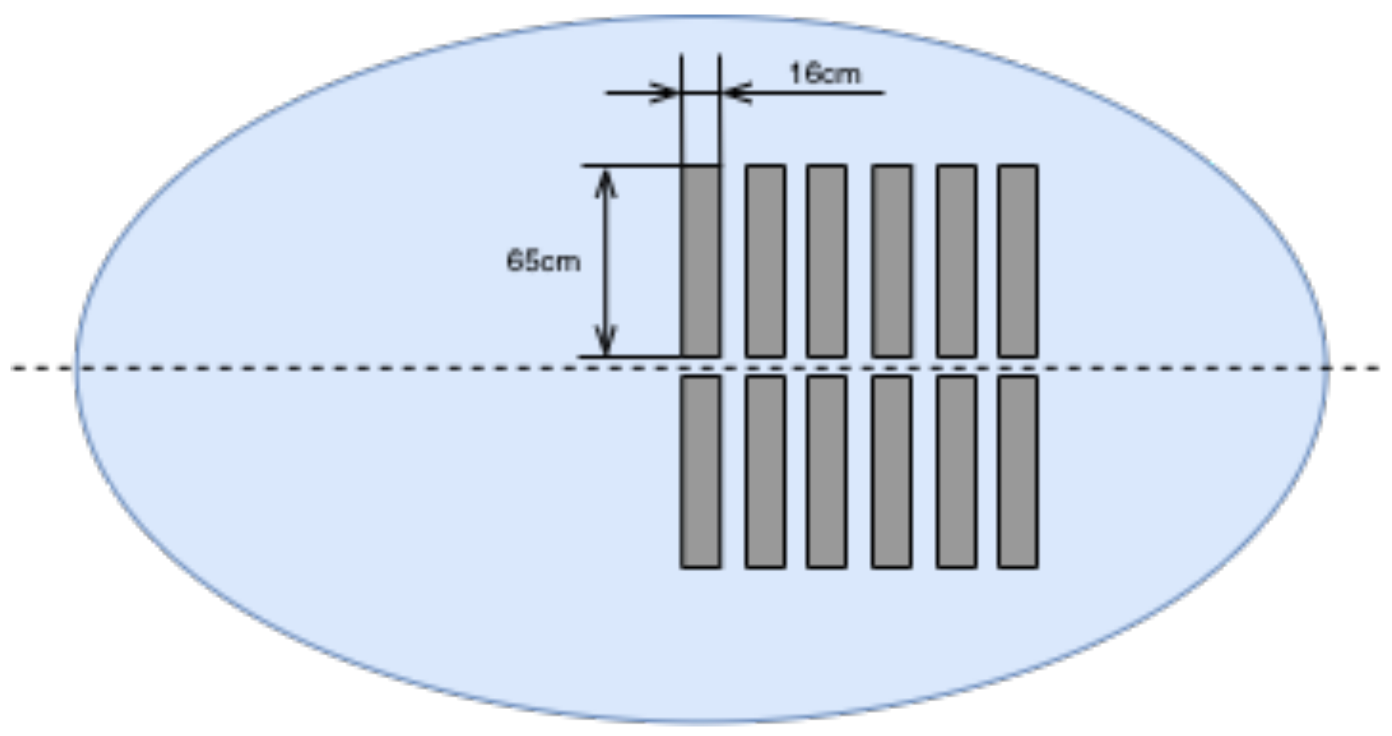
What if sun exposure is not optimal?!

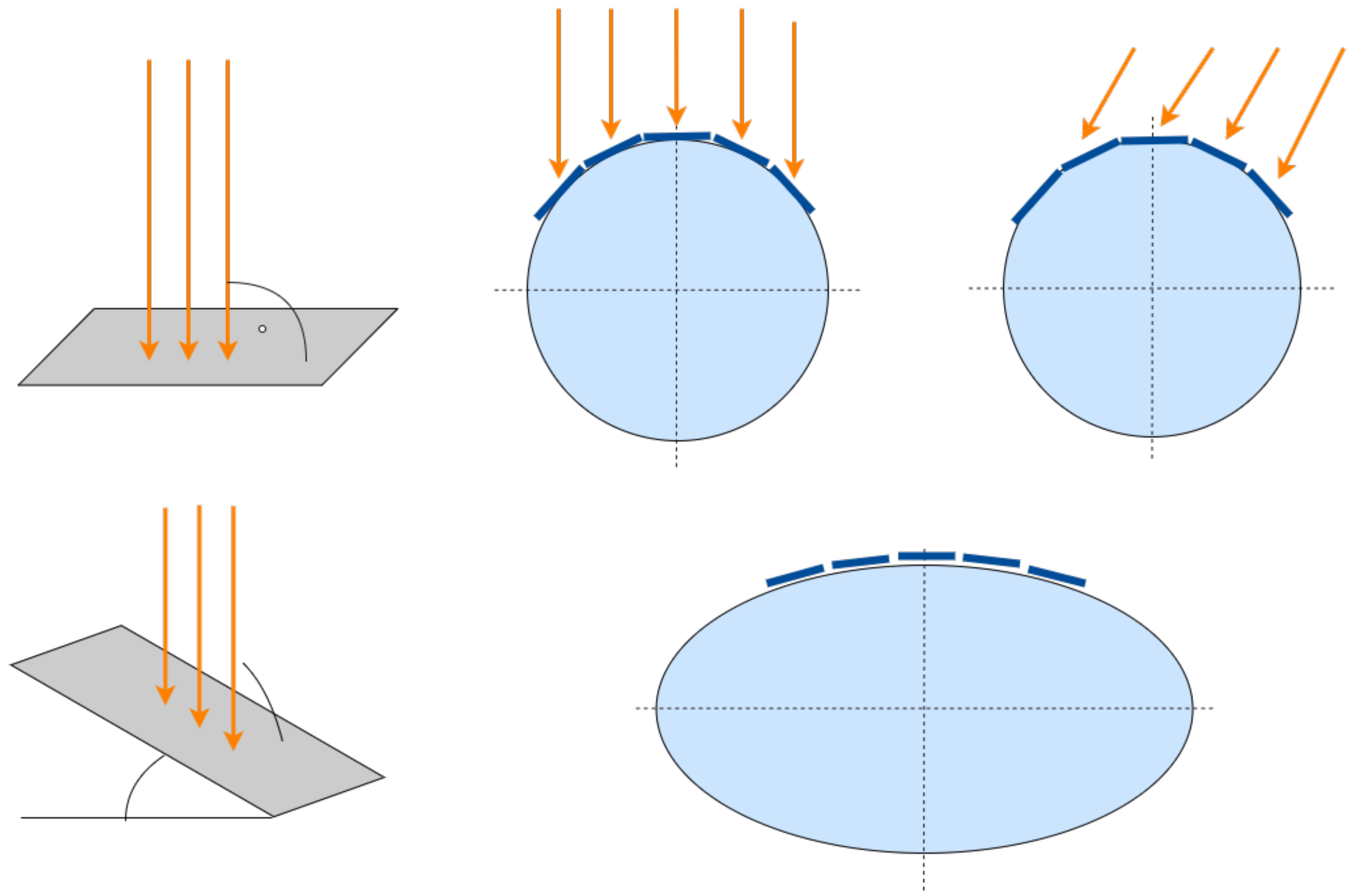


.. can cause performance issues in real application.

Curving OPV over Airship Body

Mounting OPV to the airship body curves the flexible modules.



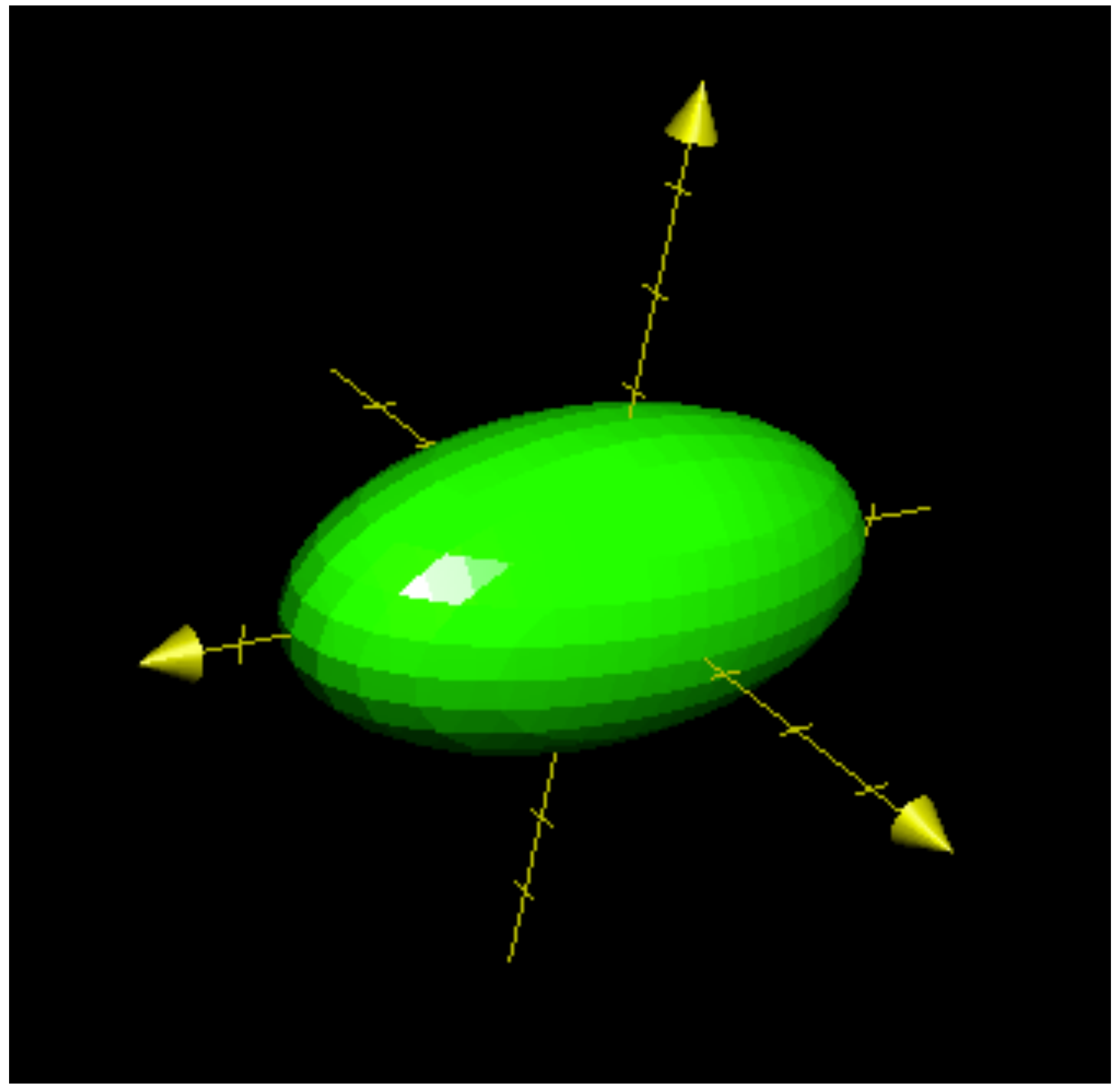


Problem: Varying, sub optimal tilt angles across the module.

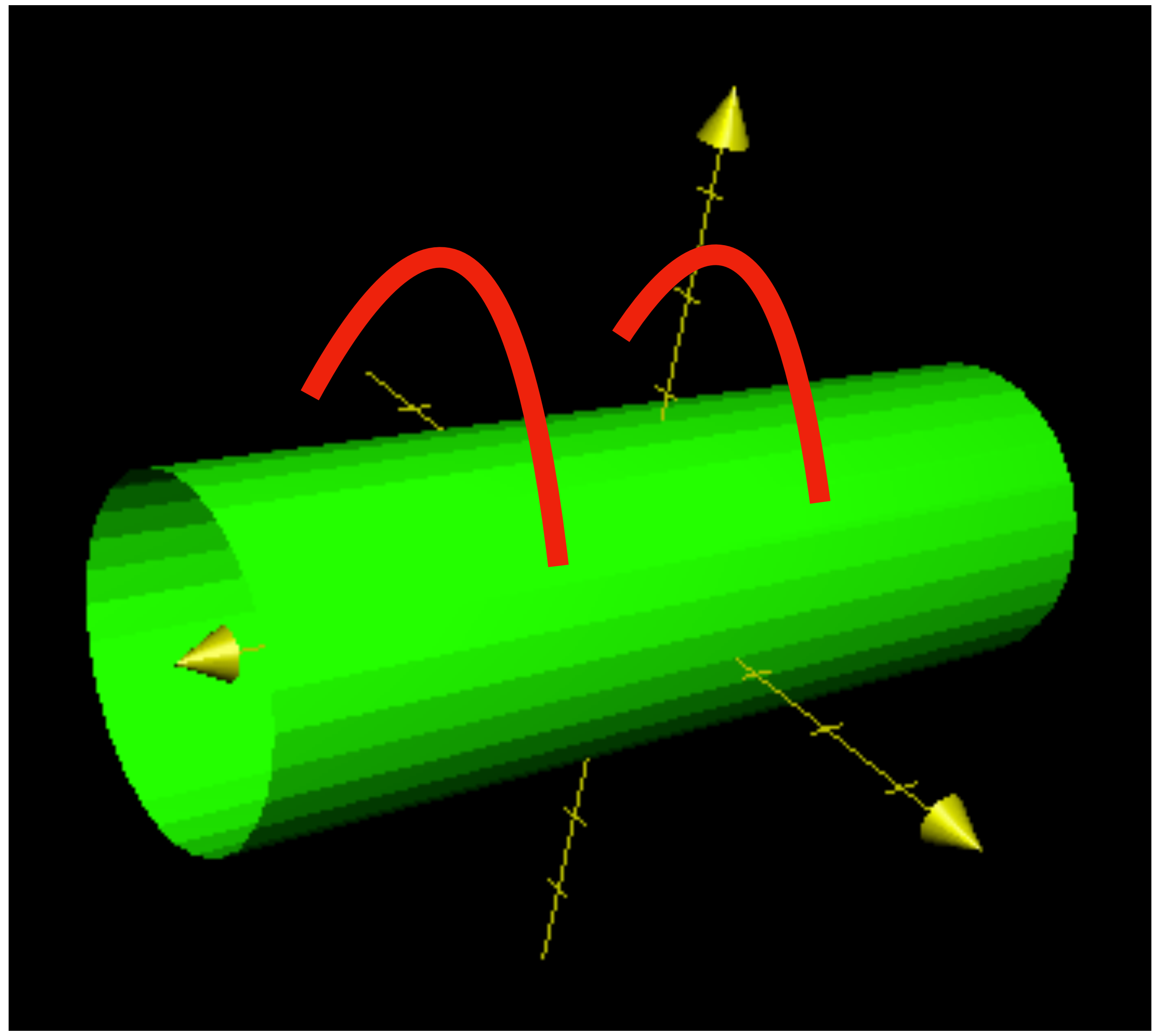
Optimal exposure of the modules is never possible.
(even at maximum irradiation power)

An approximation illustrates the performance under sub optimal sun exposure conditions, specifically tilt angles…

Airship ellipsoid simplified as cylinder (only lateral curvature of the modules)



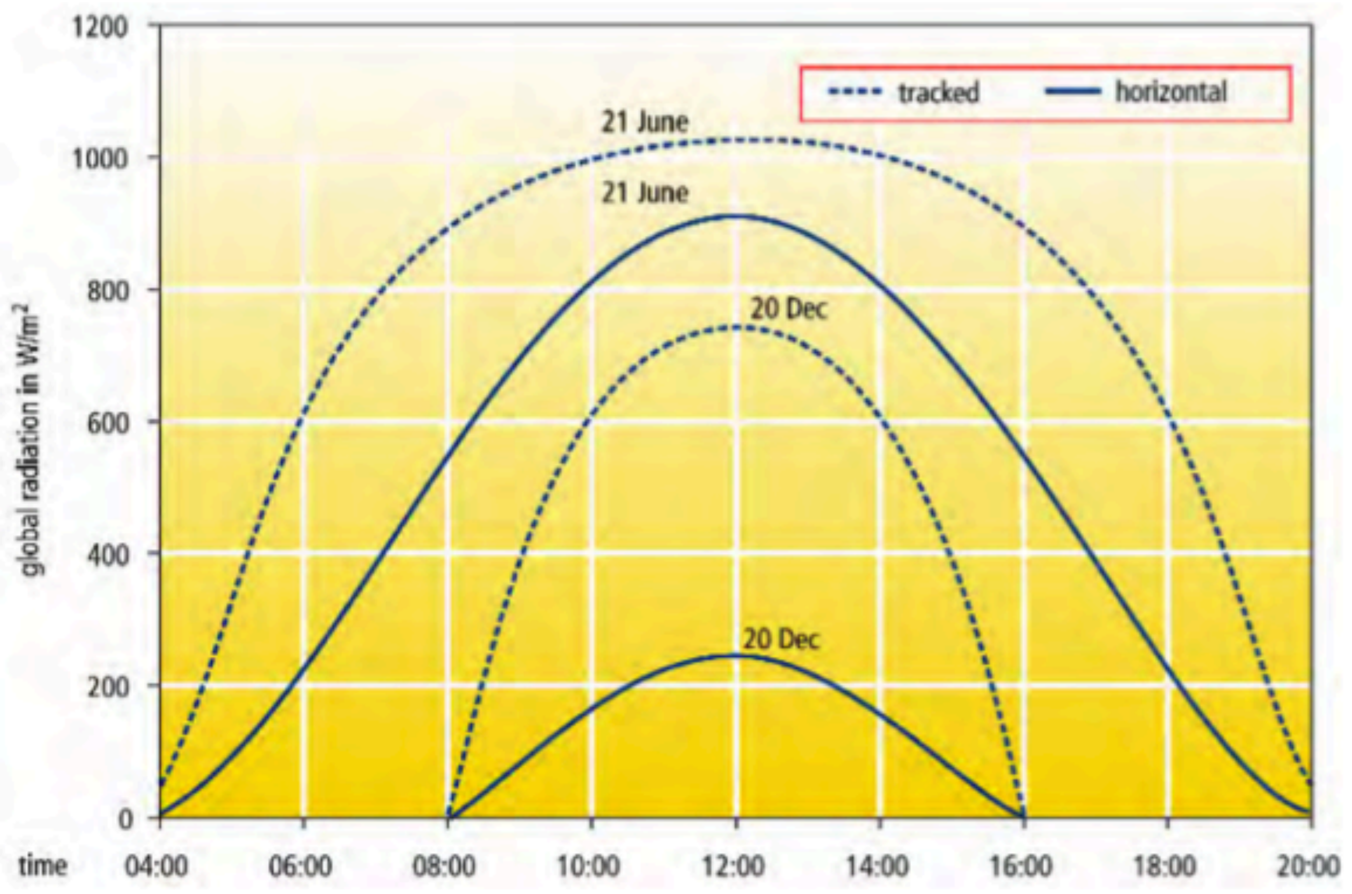
$$\frac{x^2}{3{,}5^2} + \frac{y^2}{1{,}7^2} + \frac{z^2}{1{,}7^2} = 1$$



$$\frac{x^2}{1{,}7^2} + \frac{y^2}{1{,}7^2} = 1$$

Irradiation conditions for example chosen at annual and daily peak:

21st June, 12 p.m. (noon), no wind, clear sky



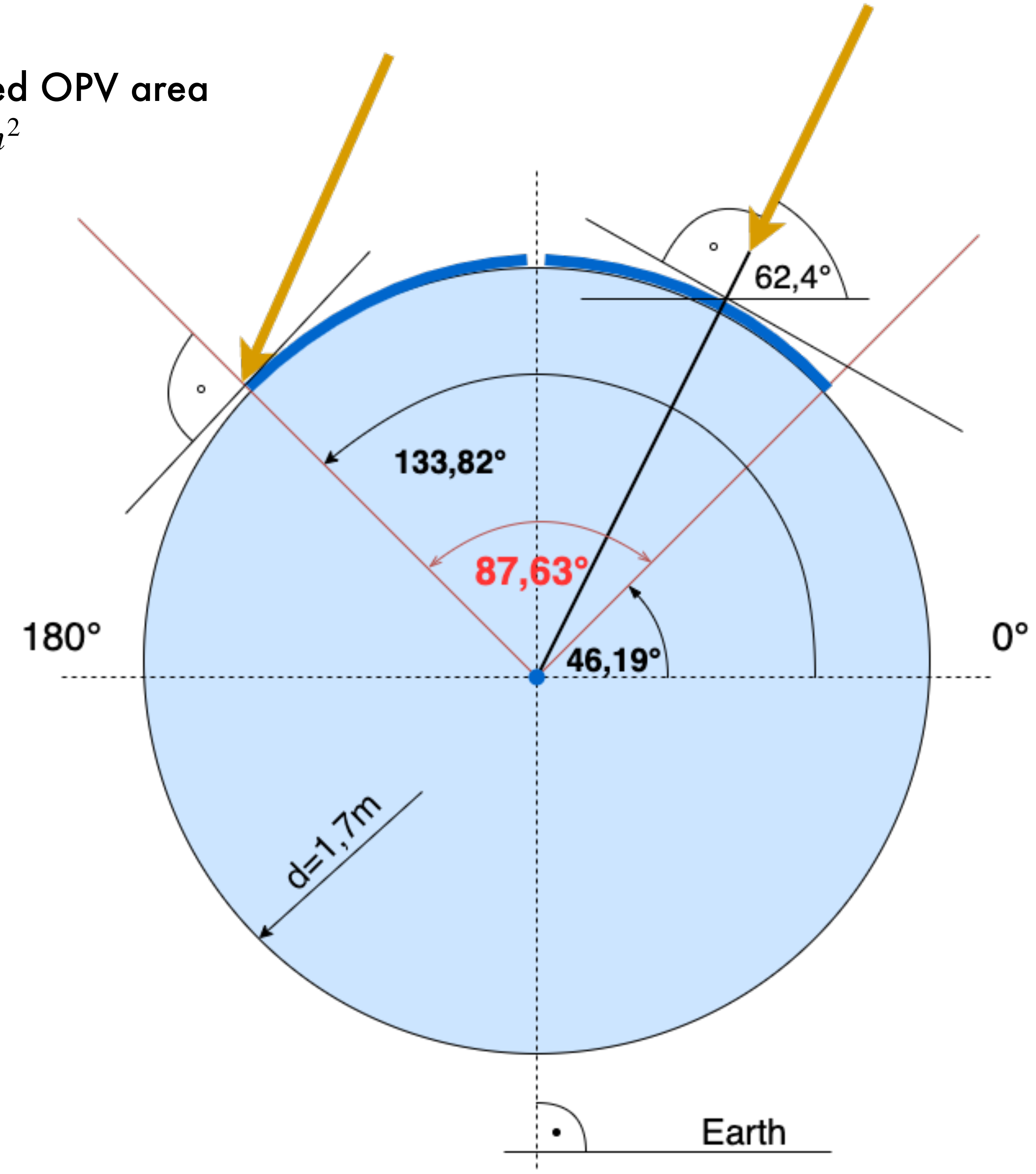
Different scenarios:

Scenario	Location	Geodetic	γ_S
1	Dresden, Germany, 50° Lat	122m	62,4°
2	Near the equator, 0° Lat	122m	90°
3	Near the equator, 0° Lat,	122m	62,4°
4	Santo Domingo, Ecuador, 0° Lat	655m	90°
5	Quito, Ecuador, 0° Lat	2850m	90°

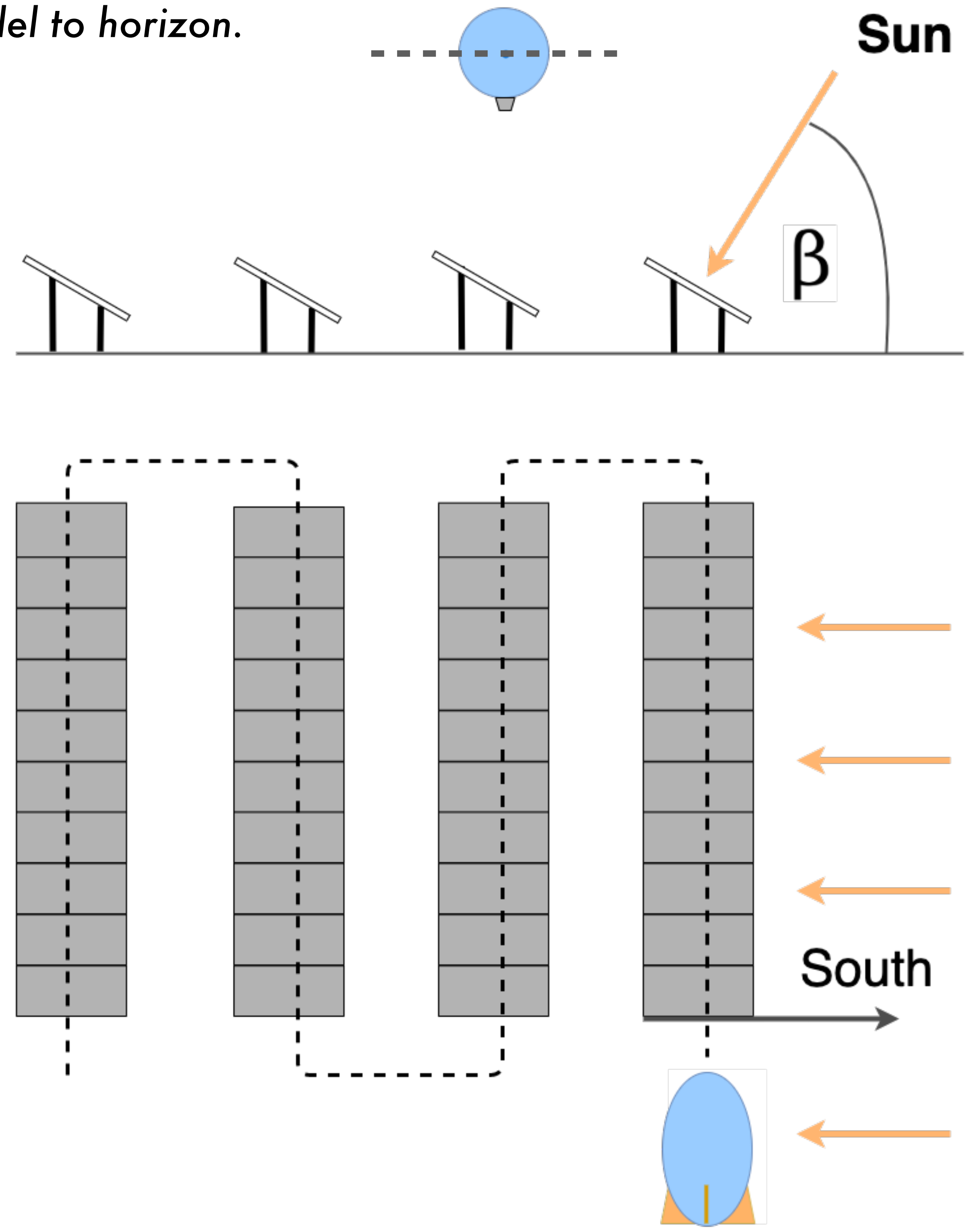
γ_S : Solar elevation angle

Definition of a Mission Model

Laterally curved OPV area
with $A = 1{,}25m^2$



Vehicle body axes parallel to horizon.



Flight course idealised. Perpendicular to sun irradiation.

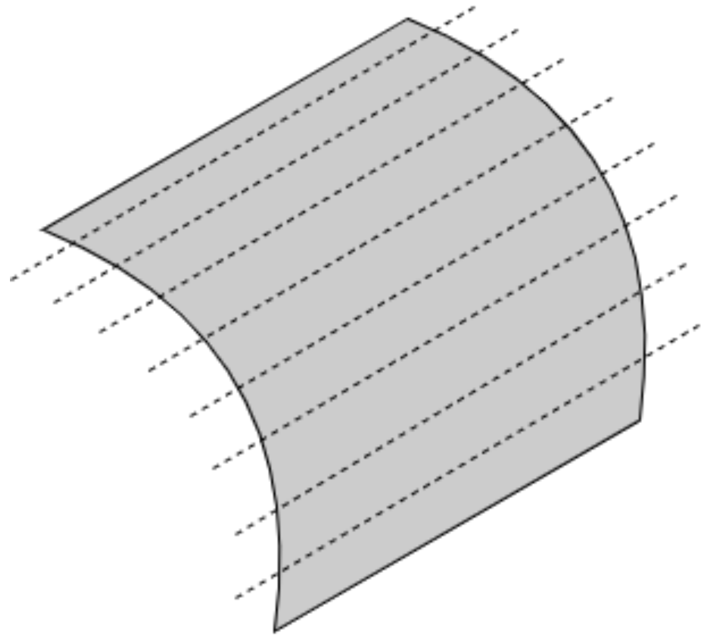
Numeric Approximation of the OPV Output Power

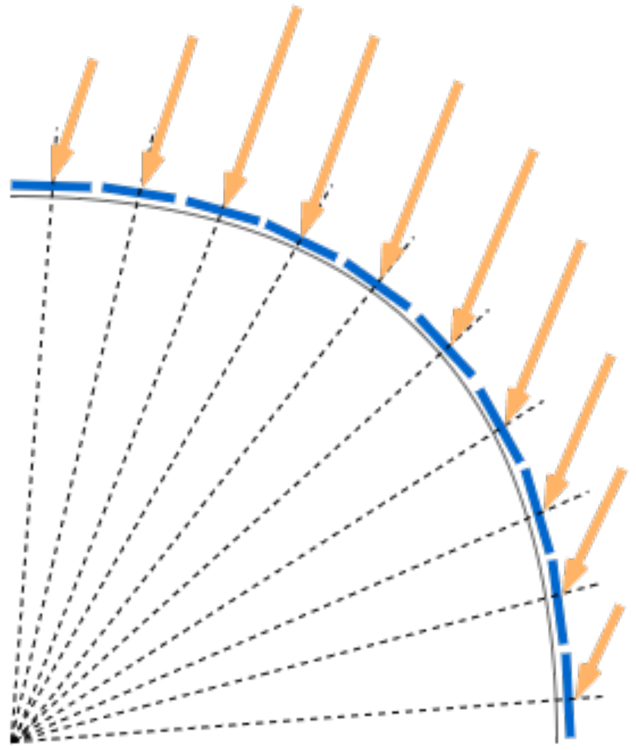
Considering lateral curving of the OPV over cylinder body

OPV area divided into PV strips

PV strips differ in the tilt angles relative to sun irradiation

Power output varies amongst strips.





$$P_{Ph,eff} = \sum_{\theta=\lceil \phi_L \rceil}^{\lfloor \phi_H \rfloor} \frac{1}{(\lfloor \phi_H \rfloor - \lceil \phi_L \rceil)} * P_{Ph,strip}(\theta)$$

Precision – Step width of the strips

$$\Delta_{step} = \frac{130cm}{87{,}64^{\circ}} = 1{,}48cm$$

Angles of arc limits based on rotation angle in airship cross section.

Computed from sun irradiation power based on tilt angle and solar elevation angle.

Location	**G.h.**	γ_S	$P_{Ph,tilt}$	$P_{Ph,eff}$	$\frac{P_{Ph,eff}}{P_{Ph,tilt}}$	$Rate_C$
	m	*deg*	W	W		C
Dresden, Germany, 50° Lat	122	62,4	56,7	46,6	0,82	2,2*
Near the equator, 0° Lat	122	90	63,3	57,2	0,91	2,72*
Near the equator, 0° Lat,	122	62,4	56,4	46,3	0,83	2,2*
Santo Domingo, Ecuador, 0° Lat	655	90	64,4	58,3	0,91	2,77*
Quito, Ecuador, 0° Lat	2850	90	69,6	62,8	0,90	3*

* Calculated with $U_C = 8{,}75V$

Minimum Charge Power for Desired Charge Rates

Premise charge voltage: $U_C \geq U_{Bat,max}$

Max. battery voltage: $U_{Bat,max} = 8{,}4V$

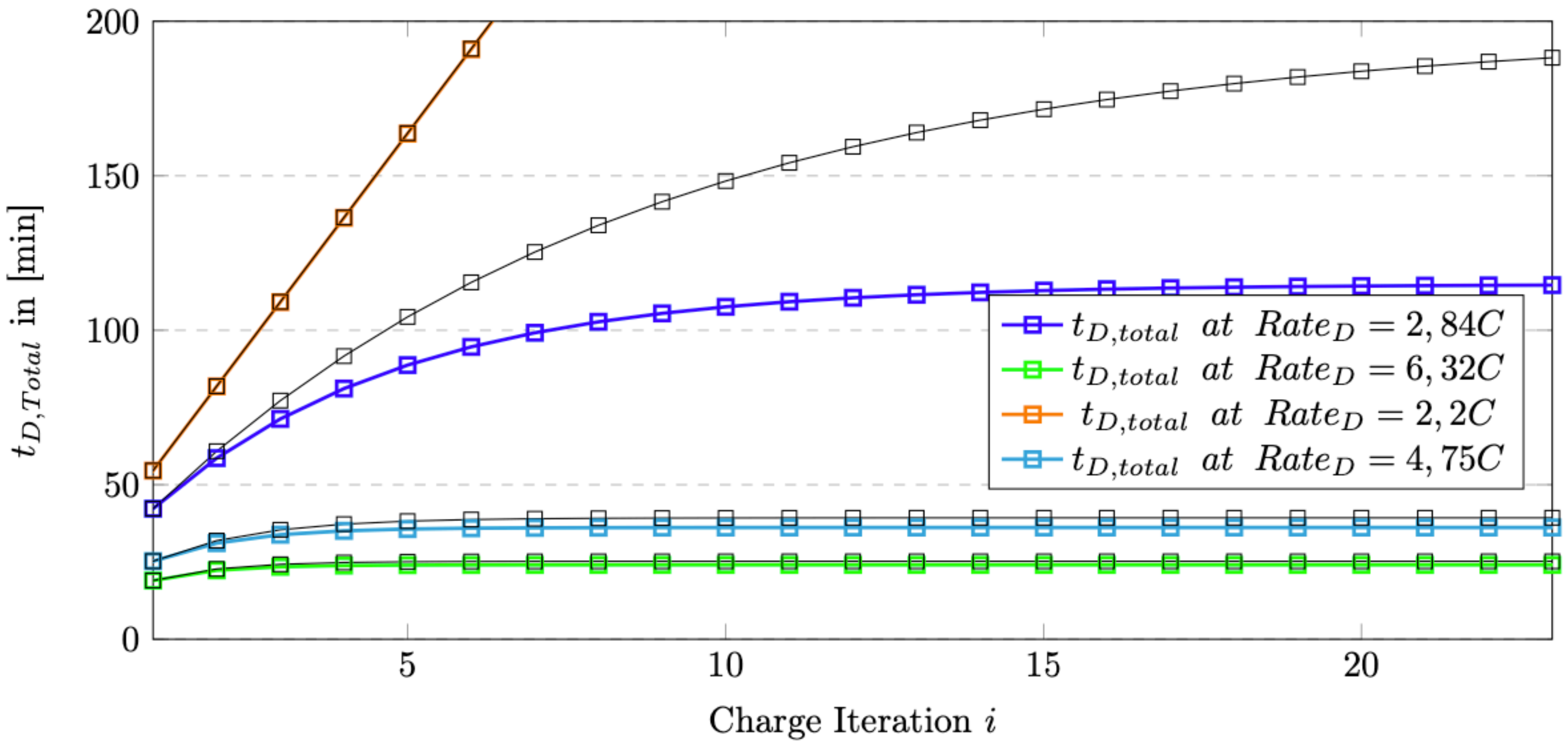
Static charge voltage: $U_C = 8{,}75V$ *(tolerance charge current:* $\Delta I_C = 0{,}25A$ *)*

$$P_C = \frac{U_C}{I_C}$$

Charge rate $Rate_C = 2{,}5C$ requires charge power $P_{C,min} = 8{,}75V * 6A \approx 52{,}5W$.

Dresden, Germany, 50° Lat , curved and non-curved (black) OPV

~~$Rate_C = 2{,}5C$~~
$Rate_C = 2{,}2C$



Curving OPV module along lateral vehicle axis decreases FTE.

Power output of OPV will decrease further in real application, due to following factors..

A. **Ellipsoid** shape of airship body introduces **additional curving** in other directions (e.g. longitudinal)

B. At other times of the day or year **solar irradiation power is less**.

C. **Weather conditions not as stable** in other scenarios.

D. **Vehicle moves constantly** relative to sun irradiation.

$$P_{Ph,real} = (D * (C * (B * (A * P_{Ph,eff}))))$$

with $0 \leq A, B, C, D \leq 1$

5. Results & Conclusion

Variables for Flight Time

Two main variables influencing flight time:

1. **Power consumption (Discharge Rate)**
2. **Charge power input (Charge Rate)**

Possible conditions during (dis)charging:

1. $Rate_D < Rate_C \iff t_D > t_C$
2. $Rate_D = Rate_C \iff t_D = t_C$
3. $Rate_D > Rate_C \iff t_D < t_C$

Flight time improves when...

$$\frac{Rate_D}{Rate_{C,max}} \longrightarrow 0 \quad \text{or} \quad \frac{t_D}{t_{C,max}} \longrightarrow \infty$$

Overall: HPMS shows positive impact on the flight time of the system

FTE is possible

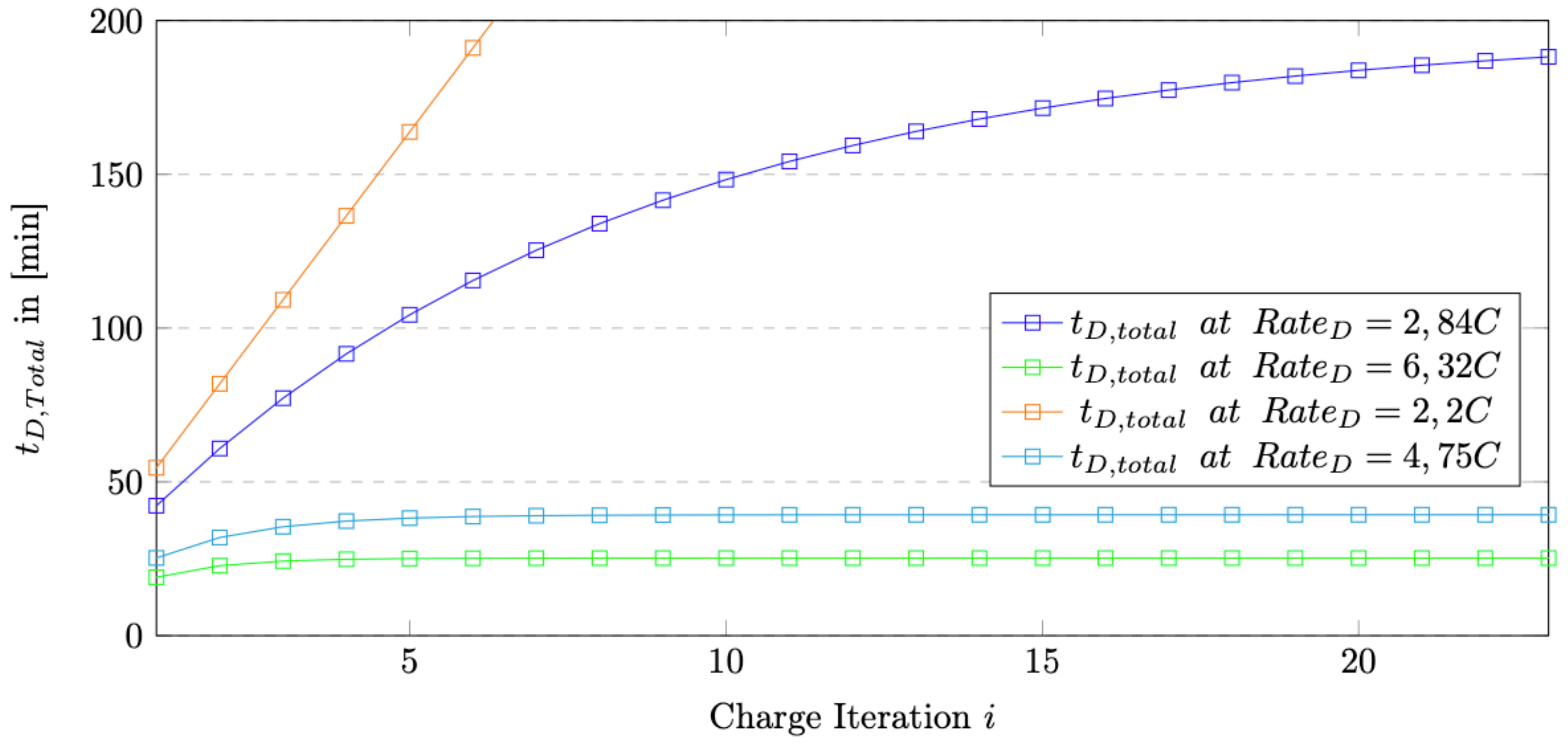
Enhancement factor dependent on power consumption and sun irradiation conditions

Performance is subject to the application scenario and its characteristics

Find the right application scenario

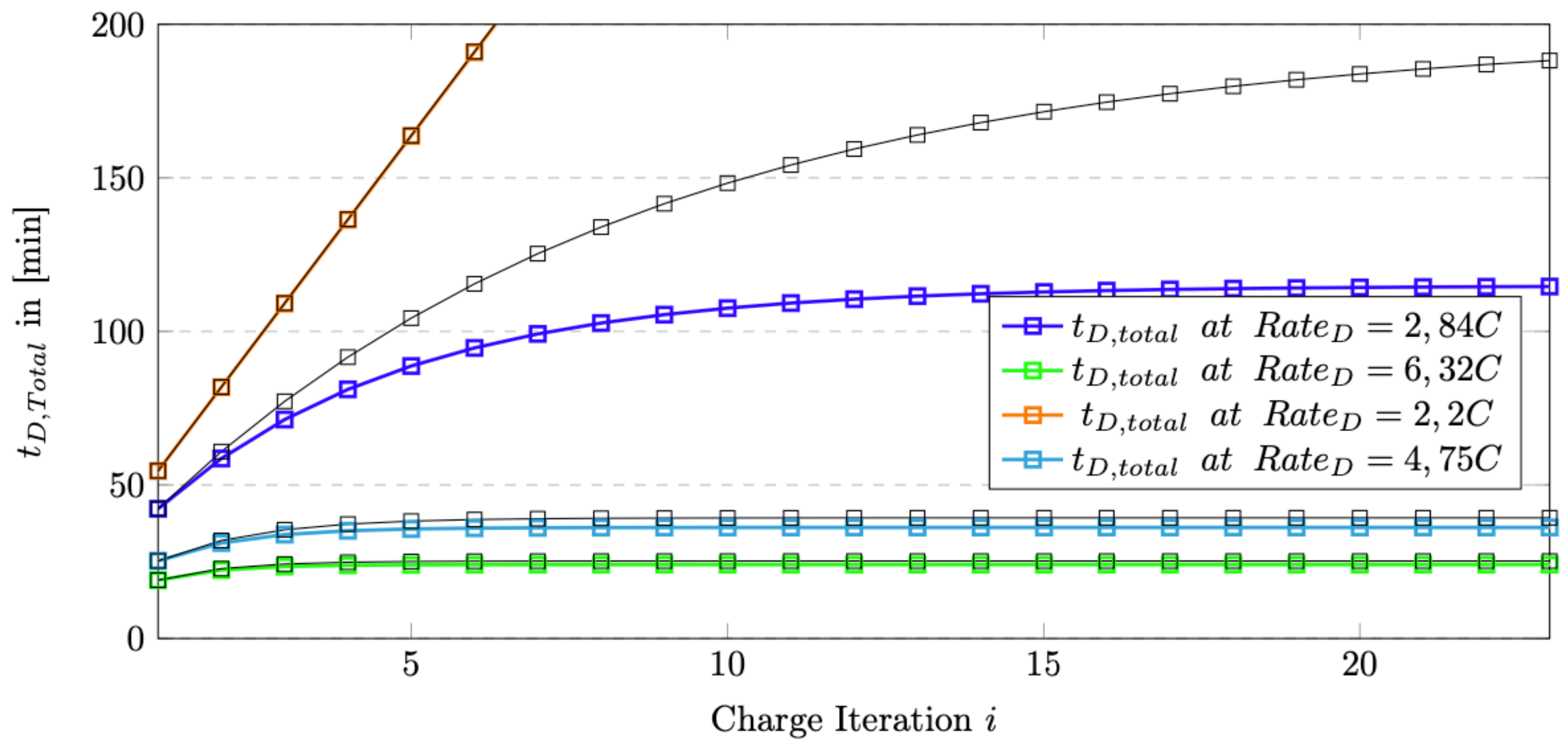
Further optimisations of the system to improve performance

$Rate_C = 2{,}5C$



- OPV modules straight (optimal orientation)
- *Location: Dresden, Germany, 50° Lat*
- *Date/Time: 21st June, 12p.m.*
- *Weather: clear sky*

$Rate_C = 2{,}2C$



- OPV modules curved on cylinder
- *Location: Dresden, Germany, 50° Lat*
- *Date/Time: 21st June, 12p.m.*
- *Weather: clear sky*

Scenarios closer to realistic application show less improvement in flight time.
(e.g. mounting the modules to the airship)

	Straight $Rate_C = 2{,}5C$	**Curved** $Rate_C = 2{,}2C$
$Rate_D = 2{,}2C$	∞	∞
$Rate_D = 2{,}84C$	189 min	114 min
$Rate_D = 4{,}75C$	39 min	36 min
$Rate_C = 6{,}32C$	25 min	24 min

Locations close to the equator offer more potential for success due to better irradiation conditions

The system has technological limitations

Improvements

Increase efficiency of OPV

Increase possible charge rates of batteries

Thank you.