Harvesting energy from high up

Midterm report

Group 1

Technische Universiteit Delft

TU Delft

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by

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Delft (the Netherlands)

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TU Delft

Executive overview

Project objectives

The discussion concerning the world-wide energy transition has been surrounded by a continuously recurring problem in the Netherlands: the lack of available area due to a high population density. This project contributes to this transition by designing a system which can provide Delft University of Technology with all its electricity demands by harvesting energy from renewable sources, all while operating above the clouds – limiting the impact of the system on ground activities – and placing a focus on the application of sustainable materials (Garcia 2019). Harvesting energy above the clouds also brings advantages regarding the amount of energy that can be captured, as wind speeds and solar intensity are higher above the lower-layer clouds.

The goal of the project, the mission need statement (MNS) and the goal of the project team, the project need statement (POS) are:

- **MNS:** To provide TU Delft with its energy demands by using an environmentally-sustainable flying energy-harvesting station operating above the low-level clouds.
- **POS:** To win the symposium by designing an environmentally-sustainable flying energy-harvesting station that operates above the low-lever clouds and feeds the TU Delft's energy demands, with 11 students in 10 weeks.

Establishing design options

Three different design options were defined. The first is a free-floating solar balloon with wireless energy transfer to the ground. The second design option is a tethered kite with a generator on the ground. The third option is a tethered floating wind-harvesting system which transfers the energy to the ground via a cable.

For the first design, three different design options were considered. All these designs use multi-junction solar cells which are used in space applications, microwave energy transfer, and control altitude through differential expansion of the balloon. The first option is composed of an inflatable ring, upon which a large solar panel platform rests. Option two has one large solar panel that is suspended by at least four balloons, which can tilt the platform towards the Sun by changing altitude independent of each other. The third option is a fleet of smaller solar panels suspended by one balloon, with retractable cables to each of the corners to tilt the platform towards the Sun. After a trade-off, the fleet of smaller solar platforms each suspended by one balloon appeared to be the best option.

For the second design, three different options are considered as well. These designs produce energy on the ground by the mechanical work the kite does, which is transferred through one or more tethers. The first option is a kite controlled by bridles connected to a control pod. The second option is a kite controlled by bridles connected to the ground station. The third option is a glider or flying wing controlled by on-board actuators. After a trade-off it was concluded that the glider controlled by on-board actuators is the best option.

The third design considers two options in a trade-off. The first option is a quad-copter which produces energy by its rotors generating lift and electricity simultaneously, while the second option is a tethered floating wind turbine. Both designs transfer energy to the ground using a conductive cable. Through a trade-off, the wind turbine was judged to be the best option.

Technical risk assessment

Many risks were identified, assessed, and mitigated. This is important in the selection of the optimal design, as well as for the general well-being of the project. The assessment was performed on two parameters: the likelihood of the risk and the impact it could have. Both are measured on a four-point scale. Likelihood ranges from remote (1), improbable (2), and possible (3), to probable (4). Impact ranges from acceptable (1), tolerable (2), and critical (3), to catastrophic (4). Different types of risks have been identified generally and for each specific design, like design, manufacturing, operational, end-of-life, and sustainability and legal risks. The highly-problematic risk – those with a score of seven or above, so (3,4), (4,3), or (4,4) – are mitigated.

N2 chart

For the trade-off it is useful to look at the interfaces between separate sub-systems and external components. The N2 chart gives an overview of all the interfaces between components, such as mechanical, communication, energy, and human interfaces. Some of the interfaces contain an asterisk, meaning these are only applicable for some of the concepts.

To compare the systems, communication and electrical interfaces will be taken into account in operations and energy trade-offs. The remaining interfaces are the mechanical and human interfaces. The only human interface is communication between TU Delft and the ground station about energy demands. These are the same for all concept, not returning as a deciding factor between the two. Mechanical interfaces are only the interactions between sensors and movements and possible interaction between ground and sustained flight component; these criteria are fairly similar across all design options. Therefore, N2 did not enter the trade-off as a separate criterion.

Aerodynamics and flight performance overview

The three system concepts differ a lot in their aerodynamic design and flight performance.

The free-floating solar balloon gets its lift from the lighter-than-air gas. The gas was assumed to be hydrogen due to its renewability and favourable characteristics compared to helium. Differential expansion (DE) is used for altitude control. DE consists of having a super-pressure balloon (SPB) inside a zero-pressure balloon (ZPB), connected via a gas-transfer device. To descend, the ZPB would let air flow through the vessel to the SPB. This decrease in volume would lead to the balloon descending. The ZPB can be fully deflated around the SPB, while inverse process would lead to the balloon ascending. The volumes for the ZPB and the SPB are the volumes to stay in the air at maximum altitude and at minimum altitude, respectively. Additionally, an optimal altitude range for the balloons, considering harvesting enough energy, is 2-16 km. The duration of the flight is dependent on the permeability of the hydrogen through the film of the balloon envelope but based on literature it is estimated to be 100 days.

The tethered flying glider generates power from its lift force driving a ground-based generator converting the mechanical power into electricity. By flying figure eights in the cross-wind direction, the glider generates lift parallel to the tether. When it reaches its maximum altitude, lift is reduced and the glider flies back to its initial altitude, starting the loop over. A 2D analytical model is made that optimises the wing loading, operating altitude, wing surface area, and reel speed of the generator via an iterative process. Based on primary calculations and literature study, the ranges for the four input values are determined. A wing surface area of 40 m^2 and an operational empty weight of 1,066 kg is found. By multiplying the wing loading by the surface area, the lift is calculated resulting in a reel speed that is directly related to a power output of 469 kW. The glider is determined to fly at an inclination with respect to ground of 22°. Due to tether drag and operational constraints, the altitude is set at 2 km. Rudders or ailerons are used for control, but further stability and control calculations are not yet performed.

The tethered floating wind turbine generates its lift from an airfoil which exploits the high wind speed. As a starting point, the blow down angle, i.e. the angle between the turbine and the vertical axis above the ground station, is set to 45°resulting in an L/D of 1. Lift is defined as excess lift: $L_e = -(m_{cable} + m_{turbine})g + L_{airfoil}$ where mass of the airfoil is counteracted by a buoyant gas inside the wing. Drag consists of thrust of the wind turbine and drag of the airfoil, while tether drag is neglected. The L/D ratio of the airfoil must be really high to compensate for the thrust of the turbine. An optimisation of the wing surface area at a certain altitude is made for existing turbines with rated power output of 200 kW for various rated wind speeds and different airfoil characteristics. Taking losses into account, 75 wind turbines flying at an altitude of 5 km are needed to reach the energy demand resulting in a total wing surface area of 220,000 m^2. As the wind speed at ground level is 5.0582 m/s and the power output of a turbine scales cubically with it, 21 times as many turbines would be needed on the ground. By using a tail plane, the floating turbine is stabilised, facing the wind.

Considering weather, the balloon scores a bit lower than the other two designs due a thin film of the balloon. Weather, take-off and landing, and the control system are the criteria for the trade-off. Considering the above, the tethered flying glider scores the best, followed in order by the floating wind turbine and the solar balloon.

Operational overview

Operations are important for different reasons, such as safety, availability, and communication. In terms of logistics, all projects are similar. They all need storage, transfer, production, and operations for which the same sites are options. In terms of communication, the free-floating balloons are difficult to manage; they fly away quite far, and only have the option of transferring information wirelessly. The tethered designs can communicate both wirelessly and via a tether. The advantage in communication of the solar balloon and the floating wind turbine is that they already have energy available on-board by generating it. The kite will require an additional energy harvesting method or carry charged batteries to power its communication systems.

An ideal location for all designs would be at the North Sea, which is close to Delft and offers options for safe crashing without too much damage. A big issue is the airspace; almost the entirety of the Netherlands is crowded with no-fly zones where the systems cannot function. Additionally, maintainability is qualitatively investigated. The balloon has good maintainability, closely followed by the tethered flying glider. For maintainability, the tethered floating wind turbine turns out to be the worst. The availability of the tethered kite is best, followed by the balloon, and finally the floating wind turbine. On safety the tethered kite is quite good. The other two design options are definitely worse, but it is hard to tell which of the two is the worst.

Above considerations result in the tethered kite scoring best, followed by the other two designs.

Energy harvesting, storage, and transfer overview

The free floating solar balloon harvests solar energy. Assumptions that are made are maximum efficiency, clear blue skies, and an average night time of 8 hours per day. For solar panels with an efficiency of 31.6%, a graph is made plotting the total solar panel area for different altitudes. In the isotherm layer, the solar panel efficiency does not increase significantly. Therefore, 11 km is the maximum altitude in which the balloon shall operate. By an iterative process, an optimum of 75 solar panels of 300 m^2 is found resulting in a power output with respect to ground of 0.5 W/m^2 and an area of the receiving antenna of 5,000 m^2, roughly the size of a football field.

The tethered flying glider generates power due to the lift of the glider $P = F_{tether} V_{reel} \eta_{generator}$. From the harvested power per kite, the total amount of kites could be determined from the design power of 10 MW (85% transfer efficiency), resulting in 22 kites which leads to a total ground area of 14.2 km^2. The power output per glider is 469 kW leading to a power output with respect to ground of 0.72 W/m^2.

For the tethered floating wind turbine, a turbine with a rated power output of 200 kW was chosen at a rated wind speed of 15 m/s. A decrease in air density at an altitude of 5 km also decreases the power output of the turbine. 75 wind turbines are needed for the design power of 11 MW (80% transfer efficiency) leading to a total ground area of 95 km^2 and a power output with respect to ground of 0.09 W/m^2.

For the trade-off, power output with respect to air and ground area were considered as well as feasibility of the energy harvesting and transfer. The results of this trade-off favour the tethered flying glider.

Structural overview

A critical structural part of the free floating solar balloon are the balloons required for differential expansion. It needs a strong super-pressure balloon, and a flexible expendable zero-pressure balloon. Pressure inside the SPB will be 6 bar for a volume of 3,160 m^3. With a balloon thickness of 3 mm, this results in hoop stresses of maximally 1 GPa. Polyethylene is a well-known material for ZPBs, which will be used in the design. Spider silk is a bio-based alternative, but cannot withstand the weather conditions with the current state of technology. The SPB can be made with zylon, which has a maximum stress of 5.6 GPa, easily sustaining the 1 GPa requirement. Material from limpet teeth could be even better, but is not developed far enough yet.

The tethered glider will have a maximum bending moment of 165 kNm, which is a reasonable value to design for. A suitable material for the tether is Dyneema, amongst other high-modulus polyethylenes. The glider can be made from light-weight composites, which can resist the weather conditions perfectly as well. Natural fiber-polymer composites are being developed and might in the future be placed in the design. Availability of all materials – even bio-based alternatives – is good, so it should not be a problem to produce the tethered glider.

The tethered wind turbine has an electrically conductive cable. As cables conduct better the larger they are, they tend to get quite heavy. This could be mitigated by adding a transformer. However, high-power transformers are heavy. Copper and aluminium are suitable metals to conduct the current. Mass estimations of these cables vary from about 500 kg for 2 km altitude, to 10,000 kg for 5 km altitude. Although extremely driving for the design, this is not infeasible. The glider previously designed is estimated to weigh $7.8 \cdot 10^4$ kg, which is huge. This delivers maximum bending moments in normal operations of about 2,000 kNm, making it very difficult to withstand with a light-weight structure. In terms of material and structural feasibility, this concepts is difficult to realise. Bio-based composites might be used in the future, but the amount of conductive material required is troublesome.

Manufacturability of all designs is important to make an informed trade-off. The balloon was assumed to be easily manufacturable, as off-the-shelf solar panels and trusses can be used to form the designs. The balloons have been produced all over the world, so they are deemed feasible. The kite needs custom-built gliders, cables, and propellers, which are harder to produce. The same holds for the tethered wind turbine, but it adds a new pylon, gigantic wing and conductive cables, making it the most difficult to manufacture.

Sustainable development strategy

As this project is fundamentally concerned with sustainability, a robust sustainable development strategy is required. The project most significantly contributes to sustainability by offering a measure to lower the emission of greenhouse gasses to meet energy demands. As was established in the *Baseline Report* (Arblaster et al. 2019), the sustainability of the airborne energy-harvesting system will be evaluated in two ways: its environmental footprint (EF) and its direct impact on its surroundings.

All three design options are examined in terms of the environmental footprint of their production, from which it becomes clear that the solar panels and receiving antenna of design option 1 are unsustainable when compared to airborne wind-energy systems. Design option 3 requires many kilometers of conductive cable and is therefore considerably less sustainable than design option 2.

The impact the design options have on their environment is assessed from a wildlife point of view: bird collision risk and disturbance (which is partially based on noise and visual disturbance). Collision risk is related to the movement of the tether and inversely related to tether thickness, implying design option 1 has the fewest collisions and design 2 the most. However, the receiving antenna of design option 1 is expected to have a profound disturbing effect. The disturbance of design options 2 and 3 are based on the movement of their tether, which is expected to have both a visual impact as creating some noise – more so for design option 2 than 3. These noise-related findings also influence the impact of the system on the nearby human population, although they are also – to a lesser degree – impacted by the visual pollution the system could cause. Once again, design option 1 is considered to have a large impact here, while the other designs are fairly similar: design 2 has a less-visible tether, although it moves; while design 3 has a thicker, but stationary, tether.

Comparing all these influences, design option 2 is considered to be the most favourable – mostly due to its comparatively good environmental footprint – followed by design 3, and finally design 1.

Design & development logic

The design and development logic comprises the steps which need to be taken to bring the product to the market. It gives a good indication of the specialisms and resources needed for the follow-up steps. The project design & development logic is given in figure 1.

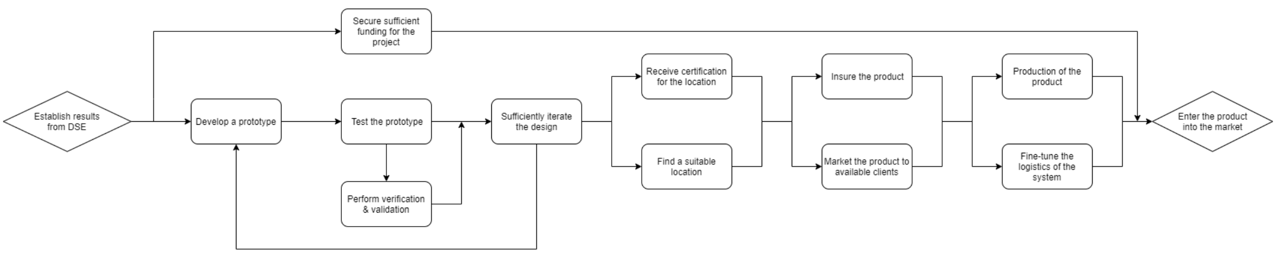


Figure 1: Project design & development logic

Design option trade-off

To determine which of the designs will be chosen, a trade-off is performed. To perform a proper trade-off, weights have been assigned to the different criteria. In this case, these add up to 100. The success of the system is heavily linked to the amount of energy the system can generate. Therefore, the energy performance was granted a weight of 30%. As an important requirement of the client is to be sustainable, the sustainability (sust.) was granted a weight of

20%. The availability and safety of the designs are of utter importance, so operations (ops) was also granted a weight of 20%. Another important aspect of the system involves the many risks which were assessed, so risk was given a weight og 15%. All systems are designed for their energy harvesting sub-system, not for their flight performance (FP), but this is still an important aspect to consider. Because of this, FP was given a weight of 5%. A lot depends on the structures and materials (S&M) required for a system, which also affects aspects such as cost and sustainability. Therefore, structures and materials were given a weight of 10%.

Table 1 displays the scores given during the analysis of each the trade-off criterion, including the weights as prescribed. Columns are scaled to this weight factor to give a visual overview of the trade-off.

Table 1: Trade summary table

Concept	FP, 5	Ops, 20	Energy, 30	S&M, 10	Risk, 15	Sust., 20	Total
Design 1	3.0	2.6	3.1	2.1	3.0	2.1	2.7
Design 2	3.8	3.6	3.5	2.6	3.8	3.9	3.6
Design 3	2.3	3.1	2.9	2.1	1.2	3.3	2.7

The sensitivity analysis of this trade-off only took the weights into account, as the sensitivity of the scores within each criterion had been previously analysed in the relevant chapters. However, design 2 scores highest for all criteria, thus changing the weight factors will not affect the outcome. Design 2 will always be the best design option.

Alternative designs

From the trade-off it can be concluded that design option 2 is by far the most feasible option. Extra attempts to get closer to design option 2 in terms of criteria were made in the form of two extra designs. These are a tethered floating balloon and the flying wind turbine.

When limiting the power output per ground area to 0.71 W/m^2 or higher for the tethered floating solar panel balloon, the results yielded a balloon volume of 411,059 m^3 when using two balloons at 20 km altitude. This is considered to be infeasible, due to the fact that solar rays would get blocked by this size of balloon. Also, because only 2 balloons were used, the solar panel area and weight per balloon would be disproportionately large and thus cannot be achieved structurally-wise.

The crosswind-flying tethered turbine generates lift due to drag force and can generate a power of 86.6 kW at an altitude of 2 km. 112 Units would be required and this would lead to a power output per area on ground of 0.13 W/m^2. This is still much lower than the 0.71 W/m^2 of design option 2. Thus, this design can be discarded as well.

Finally, calculations for the stationary flight turbines were revised, with aluminum as cable material instead of copper. However, the number of devices would need to be increased by 25%, because another turbine would need to be selected. The new characteristics would still be inferior to those of design option 2.

Verification and validation procedures

Verification and validation will be vital for the final product, so a plan had to be made to ensure it was performed properly. For most of the design processes, technical verification and validation must be done for the models created to replicate the concept. These models are analytical and numerical. The analytical model could be verified using experimental data from literature and analytical solutions from research papers. The numerical model could use inputs from the analytical model. This could be verified by the analytical model and potentially experimental data. The accuracy of the analytical model should be in the order of magnitude of 90%, while the accuracy of the residuals for the iterative convergence process of the numerical model should be in the order of magnitude of 10^{-5}.

The tools that will be used for engineering calculations will predominantly come from the simulation platform Ansys. Inherently, simulation software systems have their biases and errors. These errors come from assumptions the solver makes and the nature of the solver itself. The former can be verified using literature studies to corroborate it.

The three mission requirements, as well as four stakeholder requirements of TU Delft, have to be met. Review and inspection will be used to validate this.

Contents

Lists of abbreviations & symbols

Abbreviation	Definition
Aa	Achieved availability
ACM	Authority for Consumers & Markets
Ai	Inherent availability
Ao	Operational availability
AWES	Airborne wind energy system
CAES	Compressed-air energy storage
CO_2	Carbon dioxide
DC	Direct current
D&D	Design and development
DE	Differential expansion
DO1	Design option 1
DO2	Design option 2
DO3	Design option 3
DSE	Design Synthesis Exercise
DSO	Distribution system operators
EASA	European Union Aviation Safety Agency
EC	European Commission
EF	Environmental footprint
EHAC	Energy harvesting above the clouds
EIB	European Investment Bank
ERO	Emergency response officer
EU	European Union
EVA	Ethylene vinyl acetate
EWICON	Electrostatic Wind Energy Convertor
FBD	Free body diagram
FBS	Functional breakdown structure
FFD	Functional flow diagram
FMEA	Failure mode and effect analysis
FP	Flight performance
GG	Ground generator
GNSS	Global navigation satellite system
HAP	High-altitude platforms
HMPE	high-modulus polyethylene
IEA	International Energy Agency

Abbreviation	Definition
ILT	Human Environment and Transport Inspectorate
ISO	International Organisation for Standardization
LCA	Life-cycle assessment
LVNL	Air Traffic Control the Netherlands
MAI plan	Maintenance, assembly, integration plan
MDT	Mean downtime for maintenance
MNS	Mission need statement
MPMT	Mean preventive maintenance time
MTTM	Mean time to maintain
MTTR	Mean time to repair
NECP	National Energy & Climate Plans
Ops	Operations
PBL	Netherlands Environmental Assessment Agency
PEF	Product environmental footprint
POS	Project objective statement
PSH	Pumped-storage hydroelectricity
PVF	Polyvinyl fluoride
RAMS	Reliability, availability, maintainability, and safety
RF	Radio frequency
RPAS	Remotely-piloted aircraft systems
SMES	Superconducting magnetic energy storage
SPB	Super-pressure balloon
S&M	Structures and materials
Sust	Sustainability
TRL	Technology readiness level
TSE	Energy Top Sector
TSO	Transmission system operators
TU Delft	Delft University of Technology
TU/e	Eindhoven University of Technology
USD	United States Dollars
V&V	Verification and validation
WBS	Work breakdown structure
WFD	Work flow diagram
ZPB	Zero-pressure balloon

Symbol	**Description**	**Value**	**Unit**
β_0	Mean flight position with respect to the ground		[°]
δ	Blowdown ratio		[-]
η	Efficiency		[-]
λ	Wavelength		[m]
ν	Opening angle of the operational envelope		[°]
ρ	Density		[kg/m^2]
ρ_{el}	Resistivity		[$\Omega \cdot m$]
σ	Stress		[N/m^2]
A	Area		[m^2]
b	Wing span		[m]
c	Speed of light	$3.0 \cdot 10^8$	[m/s]
C_d	Drag-coefficient in 2D		[-]
C_l	Lift-coefficient in 2D		[-]
C_p	Pressure coefficient		[-]
C_t	Thrust coefficient		[-]
d	Diameter		[m]
d_{tether}	Tether diameter		[m]
d_u	Ground distance between units		[m]
D	Drag		[m]
E	Energy		[Wh]
f	Frequency		[Hz]
F	Force		[N]
F_b	Buoyancy force		[N]
g	Gravitational acceleration	9.80665	[m/s^2]
h	Altitude		[m]
I	Current		[A]
l	Length		[m]
L	Lift		[N]
L/D	Lift-over-drag ratio		[-]
m	Mass		[kg]
M	Moment		[Nm]
OEW	Operational empty weight		[N]
P	Power		[W]
S	surface		[m^2]
SF	Safety factor		[-]
t	Thickness		[m]
T	Thrust		[N]
U	Voltage		[V]
v	Volume		[m^3]
V	Velocity		[m/s]
V_a	Apparent velocity		[m/s]
V_{TO}	Apparent take-off speed		[m/s]
V_w	Wind velocity		[m/s]
W	Weight		[N]
W/S	Wing loading		[N/m^2]

1
Introduction and project objectives

According to common consensus amongst scientists, the dramatic increase of atmospheric greenhouse gasses compared to pre-industrial levels forms a growing threat to life on Earth. This threat ranges from global warming and the rise of sea levels, to the collapse of ecosystems on a global scale. The city of Delft (the Netherlands), where the Delft University of Technology (TU Delft) operates, is located at sea level. As the world faces turbulent economic-political times, sustainable and independent energy solutions are required.

The discussion concerning this world-wide problem has been surrounded by a continuously recurring problem in the Netherlands: the lack of available area due to a high population density. This project contributes to this transition by designing a system which can provide TU Delft with all its electricity demands by harvesting energy from renewable sources, all while operating above the clouds – limiting the impact of the system on ground activities – and placing a focus on the application of sustainable materials (Garcia 2019). Harvesting energy above the clouds also brings advantages regarding the amount of energy that can be captured, as wind speeds and solar intensity are higher above the lower-layer clouds.

The goal of the project in the form of a mission need statement (MNS) and the and the goal of the project team, the project need statement (POS) are:

- **MNS:** To provide TU Delft with its energy demands by using an environmentally-sustainable flying energy-harvesting station operating above the low-level clouds.
- **POS:** To win the symposium by designing an environmentally-sustainable flying energy-harvesting station that operates above the low-lever clouds and feeds the TU Delft's energy demands, with 11 students in 10 weeks.

This report presents the progress of the project since the *Baseline Report* (Arblaster et al. 2019). By establishing the baseline of the project, three broad design options were selected, which are further established in this report. These design options vary in many ways, from their method of energy harvesting, to how they maintain flight, to how the energy they harvest is transferred down to Earth.

Each of these designs is examined to such a degree that they may be fairly compared in a trade-off. The design that is shown to be superior through this trade-off will be developed further in the next phase of this project.

This report is roughly divided into four parts. First, the project set-up is reiterated by providing the organisational structure of the team in chapter 2.

Next, the three design options are established. The rationale for this process is presented in chapter 3, while chapters 4, 5, and 6 discuss how each design option should be defined. These are a free-floating solar platform, a tethered glider, and a tethered wind turbine. Finally, an overview of these designs is given in chapter 7, including the configurations and sub-systems.

The possible systems are examined in many ways. An N2 chart is presented in chapter 8, which indicates the complexity of the systems. The main engineering aspects are examined in chapters 9, 10, 11, and 12, which respectively deal with the flight performance, operations, energy harvesting, and structures of the designs. Risks are assessed in chapter 13, while chapter 14 is concerned with sustainability. The design & development logic is presented in chapter 15.

Finally, the trade-off is performed in chapter 16. Some alternative designs are briefly discussed in chapter 17 to further investigate the robustness of results of the trade-off. The verification and validation procedures are presented in chapter 18, with the updated project logic diagrams – which dictate the flow of the project – presented in chapter 19.

2
Organisational structure

This chapter contains a full overview of all team members and what functions they have been given within the team structure. Section 2.1 identifies where the functions are located in the organisational structure, while section 2.2 lists the functions with their descriptions and assigned team members.

2.1. Organisational structure

The structure of the team is illustrated in figure 2.1. There are two branches: technical (bottom, red) and managerial (top, blue), with the system engineers (purple) as the common factor.

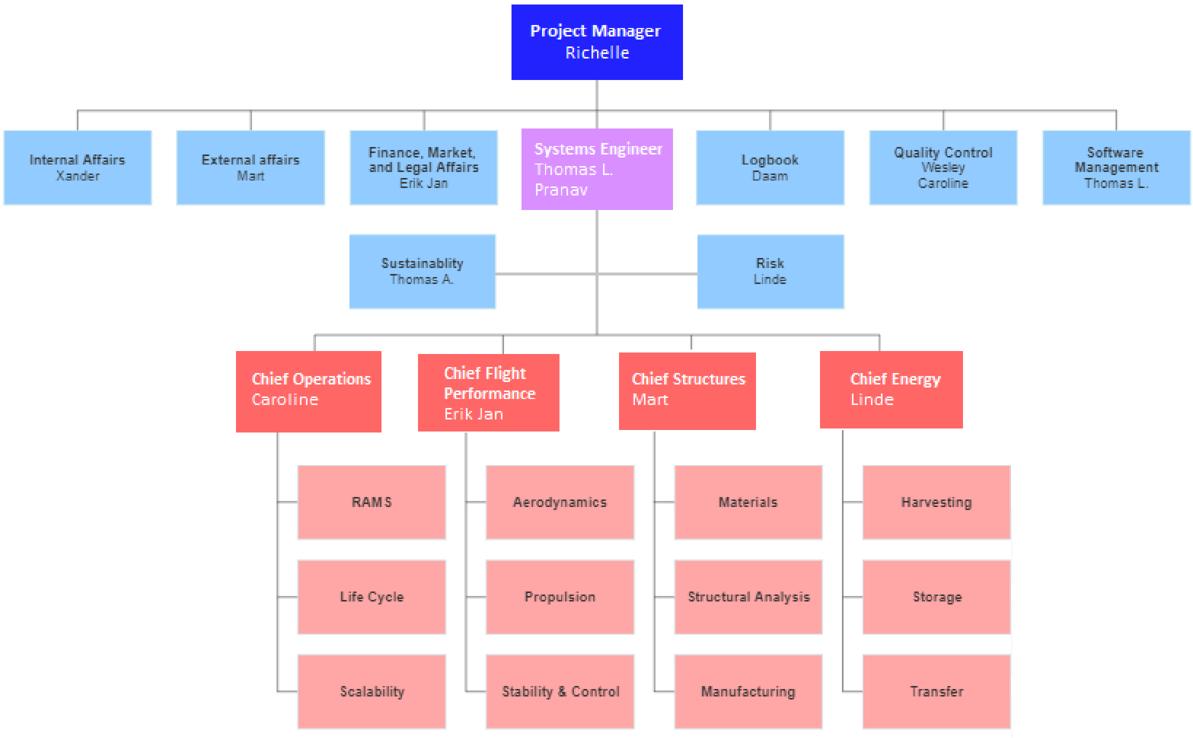


Figure 2.1: Organisational structure, illustrated as organogram

2.2. Task division

To create a clear division of responsibilities, every group member was assigned both a technical function and managerial function. These managerial functions, followed by the technical ones, are:

- **Project manager (Richelle):** Responsible for chairing all meetings, keeps an overview of the overall planning and progress, while making sure that deadlines are met. The project manager is also the point of contact for personal issues and potential absence regulations.
- **Internal affairs (Xander):** Responsible for all organisational aspects of meetings, including the shared calendar, reserving meeting rooms and taking minutes. Internal affairs is also responsible for keeping the shared drive organised.
- **External affairs (Mart):** Responsible for all communications outside of the team, including the experts in

the field, the tutor and coaches, and the OSSA. External affairs collects all questions for these parties and performs quality control on these questions.

- **Quality control (Wesley, Caroline):** Responsible that the lay-out and styles used throughout reports and presentations are consistent and that there are no contradictions within the text. Quality control also guides the spelling and grammar checks before handing in reports.
- **Logbook (Daam):** Responsible for the project logbook, including archiving the minutes of meetings and action points and justifying key decisions made during the project.
- **Risk management (Linde):** Responsible for identifying and mitigating the potential risks to the functioning of the team, such as illness, use of public transport, personal circumstances, hard- and software failure, etcetera.
- **Software management (Thomas L.):** Responsible for the use of software within the team, including integration of MATLAB scripts and git. The software manager is also the point of contact for the team in case of problems with software.
- **Sustainability officer (Thomas A.):** Responsible for the overall sustainability of the project, including regular checks and/or meetings with the rest of the team on the sustainability of their (sub-)systems. The sustainability officer is also responsible for developing methods and tools for verifying sustainability.
- **Finance, market, and legal analyst (Erik Jan and Linde):** Responsible for the business side of the project; keeping an eye on the requirements (return on investment) and combining the financial budgets of individual sub-systems. Also responsible for the legal feasibility of the project, regarding government regulations.
- **System engineer (Thomas L. and Pranav):** The system engineers are the link between the managerial and technical side of the project. They are responsible for the integration between the different departments and provide guidance with the planning of the sub-systems. Any delays within departments must be reported to the system engineers, so that the planning can be adjusted accordingly. The system engineers also provide the final verification that all technical requirements are met.
- **Department chief (Mart, Erik Jan, Linde, Caroline):** The technical side of the organisation is divided into four key departments: structures, flight performance, energy, and operations. Each department has a chief, who is responsible for communication within the department, as well as communication with the system engineers.
- **Structures department (Mart, Thomas A., Caroline, Thomas L., and Richelle):** Mart is the chief of this department, which is focused on the trinity concept of structural design: the balance between structural analysis, material selection, and production methods.
- **Flight performance department (Erik Jan, Pranav, Daam, Linde, Wesley, and Xander):** Erik Jan is the chief of this department, which is focused on the in-flight performance of the product. This includes the aerodynamics, potential propulsion, and the stability and control of the product.
- **Energy department (Linde, Pranav, Erik Jan, Daam, Wesley, and Xander):** Linde is chief of this department. This department is focused around the harvesting, storage, and transfer of energy, including the power grid analysis.
- **Operations department (Caroline, Thomas L., Richelle, Mart, and Thomas A.):** Caroline is the chief of this department, which is focused on the reliability, availability, maintenance, and safety of the product, as well as performing life-cycle analysis and scalability analysis of the product.

3
Sub-system trade-off method

There are generally three possible top-level concepts: balloon, kite and turbine. These concepts do still have quite some sub-system options for energy harvesting, which cannot all be analysed for the system trade-off due to time constraints. Therefore, it is paramount that the most important sub-systems are narrowed down to one energy harvesting method per design; these are determined based on a sub-system trade-off per concept. These trade-offs are performed in chapters 4 to 6, though the rationale and citeria are given here. The trade rationale and organisation can be found in section 3.1 and the trade criteria are determined in section 3.2.

3.1. Trade rationale & organisation

The trade-off of the sub-systems within each of the three top-level concepts is performed based on engineering insights and initial calculations. Every top-level concept is assessed on the trade-off criteria. The used criteria are the same for each sub-system trade-off, but the weights of the criteria differ per trade-off. This is due to the fact that for different systems, different parameters are driving.

3.2. Trade criteria

The trade criteria are divided into: power density (with respect to ground area and with respect to airborne area), energy transfer method, scalability, feasibility, controllability, reliability, availability, maintainability, safety, sustainability, and cost. The reasons for choosing these criteria and their meaning can be found below.

- **Power density**: The power density is the amount of power per square meter, this is not only dependent on the operational altitude but also on which flying subs-ystem is used. The power density gives a measure on how efficient the energy-generating sub-system is, measured in W/m^2. The power density is measured with respect to ground area as well as with respect to airborne area.
- **Energy transfer**: Energy transfer determines how feasible and efficient the energy transfer method for that design option is.
- **Scalability**: Scalability determines how easily the system could be expanded if more (or less energy) were to be demanded.
- **Feasibility**: Feasibility relates to the technology readiness level (TRL) of the system and therefore its complexity. Also the need for new technologies for a system is taken into account.
- **Controllability**: The controllability criteria indicates how much input is needed to be able to control the system, for example, an altitude control system.
- **Reliability**: Reliability relates to the probability of failure of the system and the impact of those failures.
- **Availability**: Availability relates to the amount of up-time of the system. Bad weather, for example, could cause the system to be grounded, impacting the energy harvested on that day.
- **Maintainability**: The maintainability criteria indicates how the system is going to be maintained and how difficult this is going to be.
- **Safety**: Safety relates to the impact the system could have on human and wild-life health, both during operation and in cases of failure.
- **Sustainability**: Sustainability relates to the impact the design has on the environment. It also concerns the materials needed in the design.
- **Cost**: The cost criterion indicates how much money is needed to be able to produce the design and release it to the market.

4
Establishing design option 1: free-floating solar platform

The first design considered is a free-floating solar balloon, with wireless energy transfer to the ground, as determined in the *Baseline Report* (Arblaster et al. 2019). In section 4.1 the different design options within design option 1 are discussed. Next, in section 4.2 the trade-off on these design options is done. A sensitivity analysis on the trade-off can be seen in subsection 4.2.1.

4.1. Design options within design option 1

Before anything can be designed, some of the driving sub-systems must be taken into account. For this design option, the solar cells, wireless power transfer method and the altitude alteration (balloons) method are determined before a specific design is made. From these decisions, three designs are created and traded off.

4.1.1. Solar cells

To determine which solar cells to use in the design, different type of cells were considered. For example, silicon cells, III-V cells, and amorphous cells, but also single- or multi-junction cells. The efficiencies are measured at 25 degrees Celsius for a 1,000 W/m^2 solar intensity (Green et al. 2019). It was decided that concentrated cells are not used since these require extra material in the form of mirrors, to concentrate the light. This will add too much extra weight compared to the gained efficiency. The organic cells are excluded since they do not reach the efficiencies of non-organic cells for now, maybe in the future these cells can be used when further developed.

The final decision between the solar cells is between single junction cells or multiple junction cells. The efficiency limit for a single-junction solar cell is 33.16% (Ruhle 2016). Multiple junction cells can reach higher efficiencies, for this reason a multiple junction solar cell will be used. There is however a constraint on the type of solar cells used. Due to the high altitude the cells have to be able to withstand temperatures of around -60°Celsius. Since triple junction solar cells are used in space applications (Takamoto et al. 2006), these are the most suitable solar cells to use in this design since they can function in low temperatures.

4.1.2. Wireless power transfer method

The two possible far-field wireless power transfer methods are both using electromagnetic radiation: lasers and microwaves. For further development of the system, one of these options must be chosen.

Laser beams have the advantage of smaller sized aperture and more concentrated power transfer. However, safety concerns remain, with the possibility of using the lasers for weaponisation and the effects on eyes and skin (Gavan et al. 2010). Additionally, current laser technologies only have infrared-to-dc conversion efficiencies of less than 20%. Another major disadvantage is the high atmospheric losses due to clouds and rain (Gavan et al. 2010).

Microwave power transfer has been researched to a further extent, having achieved incident microwave power to dc output efficiencies of up to 84% at distances of 1.6 km (Brown 1996). Lower frequency microwaves (such as the often suggested 2.45 GHz) are hardly influenced by weather conditions (Brown 1983), but do require larger aperture than higher frequency microwaves (Gavan et al. 2010). Those frequencies are safe for humans and wild-life. However, most research for microwave power transfer is conducted for high altitude platforms (HAPs) as a replacement for communications satellites, meaning the energy would be transferred up, instead of down. Other applications include space-based solar power satellites, which operate in geostationary orbit.

With the current technologies and research available, microwave power transfer is considered to be the better option, as efficiencies are higher and the technology poses a lower health risk. However, in the future, this microwave power transfer may be challenged by laser beaming.

4.1.3. Altitude control

The balloon needs to be able to use the different wind speeds and directions to move to different locations. These wind directions vary for different altitudes. Therefore, the altitude of the balloons must be controlled.

There are two types of high-altitude balloons; zero-pressure balloons (ZPB), and super-pressure balloons (SPB). The former uses ducts to let out air when the volume of the balloon gets too large while ascending, causing the balloon to descend. Ballast from the balloon is then dropped to decrease the weight and gain altitude. It maintains altitude by compensation maneuvers. The balloon requires less strong materials than SPBs.

SPBs are sealed and do not alter their volume to maintain altitude. They maintain altitude by keeping their volume and mass (and thus density) constant. They require very strong materials since the pressure in the balloon rises to a considerate level, especially during the day when the gas inside the balloon expands. Also, they have no problems with icy air entering the balloon, which might be a problem for ZPBs which have direct contact with the atmospheric air.

The possibilities for changing altitudes for high-altitude balloons are air ballast, mechanical compression, differential expansion, ballast-and-bleed systems (mentioned above), hot-air systems and propulsion systems (Voss et al. 2005). The last three are not considered because hot-air and propulsion systems are not energy efficient and ballast is limited and therefore not durable.

Air ballast consists of an SPB with a bladder inside which fills with atmospheric air. Since icing can occur inside the bladder and an unreasonably high pressure is present inside the SPB due to the added bladder, air-ballast will not be used further.

Mechanical compression makes use of mechanically compressing the balloon. Since compressing the balloon until 50% of its original volume will only result in a few kilometers in altitude change and a large force is required to compress the balloon, mechanical compression is not considered a good altitude control possibility.

Differential expansion consists of having a SPB inside a ZPB, connected via a gas-transfer device. To descend (or during daytime to prevent increasing altitude) the ZPB would let air flow through the vessel to the SPB. This decrease in volume would lead to the balloon descending. The ZPB can be fully deflated around the SPB. Again, the inverse process would lead to the balloon ascending. This manner of changing altitude is being used at this moment by, for example, the Google Loon project [1]. Thus, for this design the best option chosen is differential expansion.

Hydrogen was determined to be the favourable lift gas, due to its low density (0.0838 kg/m^3) and its renewability (when generated using electrolysis). However, safety measures will have to be taken due to its flammability.

4.1.4. Design option tree

A design option tree has been made and can be seen in figure 4.1. Combinations of two grey boxes are discarded, as well as the black boxes. The outcome of the design option tree is a free floating ZPB in combination with a SPB using differential expansion for altitude control, multi-junction solar cells for energy harvesting and microwave energy transfer.

[1] `https://loon.com/`

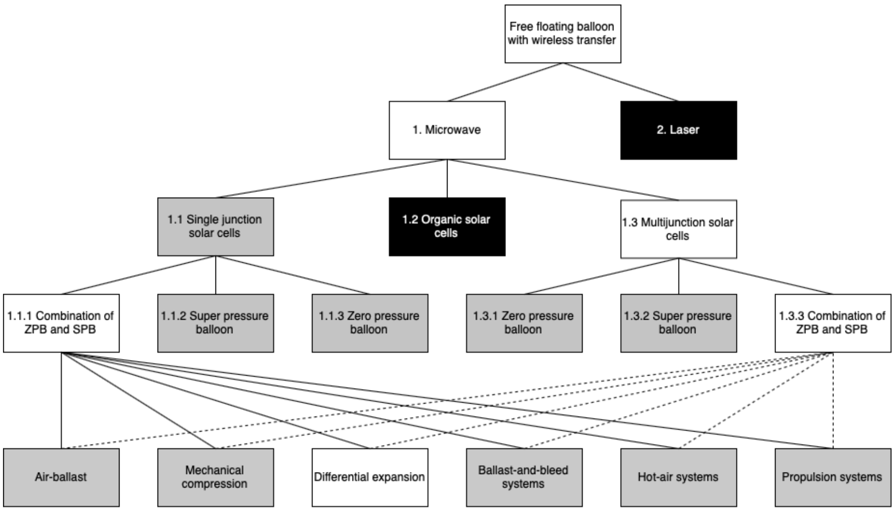
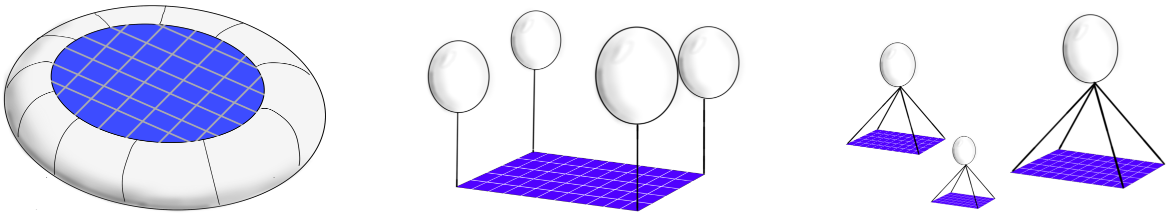


Figure 4.1: Design option tree for design 1

4.2. System trade-off within design option 1

With the decisions on the driving sub-systems made, more ideas on the size and shape of the overall system can be thought of. The three design options are illustrated in figures 4.2a to 4.2c. Design option 1 is composed of an inflatable DE ring, upon which a large solar panel platform rests. Design option 2 has a large solar panel that is suspended by at least four balloons using differential expansion (DE), that can tilt the platform towards the sun by changing altitude. Design option 3 is a fleet of smaller solar panels suspended by one balloon, with retractable cables to each of the corners to tilt the platforms towards the sun. All designs will have the microwave power transfer aperture attached to the bottom.



(a) Design option 1: Inflatable ring (b) Design option 2: Multiple balloons (c) Design option 3: Single balloon

Figure 4.2: The three chosen designs options

Table 4.1: Trade-off of the three design concepts within design option 1.

Trade-off criteria, weights	**Design 1**	**Design 2**	**Design 3**
Power density, 3	1	4	5
Airspace use, 2	5	4	2
Energy transfer, 4	3	4	2
Scalability, 3	2	3	5
Feasability, 3	1	2	4
Controllability, 2	1	5	4
Reliability, 2	2	4	3
Availability, 5	2	3	5
Maintainability, 4	1	2	4
Cost, 1	4	3	2
Total score	**58**	**95**	**111**

Power density: Since design 1 cannot face the sun but can only lie horizontally, it will produce the least power per square meter. Design 2 and 3 will produce more energy due to the ability of making the platform face the sun. However, design 2 will likely have more shadow on the platform due to the balloons blocking the sun rays.

Airspace use: Design 3 has multiple platforms that move and need to be coordinated by the operators and other airspace users. Design 2 still changes in altitude, which is why it will still take up more space than the "stationary" design 1.

Energy transfer: Energy is transferred more easily and more efficiently using designs 1 and 2 than using design 3. This is due to the fact that designs 1 and 2 have bigger areas, thus more efficient antennas can be placed underneath the platforms. Design 2 is flatter and more rigid underneath the surface than design 1. This would lead to more opportunity for installment of one or multiple antennas.

Scalability: Design 3 is the easiest to scale, since it has multiple small systems instead of one big system. One can easily put a few more balloons up in the air, whenever a small increase in power output is desired. Design 1 and 2 require another big platform to be lifted up, though design 2 can be extended by an extra row of cells without major alterations.

Feasability: Design 1 is considered to have the lowest TRL, because there are no comparable designs known. The other two designs make use of a ZPB and an SPB to change altitude, which are known concepts. Design 3 would furthermore score higher than design 2 in TRL, as the retractable cables are less complex than the DE. Additionally, design 2 scores low on the feasibility of such a large and heavy structure hanging (stable) in the air.

Controllability: Design 3 is the most controllable, as the cables connected to the corners of the balloon provide the stability necessary in case of winds. Design 2 performs worse in this, as the size of the platform makes is more difficult to manoeuvre or withstand wind gusts. As design 1 does not have a control method, it scores the worst.

Reliability: Balloons will most likely be the major point of catastrophic failure, should there be a failure. This means that design 1 has low reliability. Design 3 has slightly better reliability, as the impact of failure is lower (only one of multiple platforms will fail). In design 2, multiple balloons support the structure, which means that if a balloon fails, there are other balloons that could support the structure and guide it back to the ground for maintenance.

Availability: Design 3 scored highest in availability, since there are multiple energy harvesting platforms. This leads to at least one platform being available at all times, whereas in case of absence of the platforms of design 1 and 2 the energy supply is stopped.

Maintainability: Design 3 was considered to be the easiest to maintain. This due to the fact that the individual balloons can be descended to the earth and maintained on the ground. The platform of design 2 is less easy to lower down to earth since it has a large size. Design 1 is even harder to maintain since it has even more difficulty in changing altitude, having the balloon below the solar panels.

Safety: As well as sustainability, safety was not included in the trade off table. This is because the safety is similar for all the designs, if one of the hydrogen balloon pops the platform will fall down. A parachute can be installed in all of the designs to minimise the damage.

Sustainability: Sustainability was left out of the trade off table since all the designs score the same for this criterion. The same type of solar cells as well as hydrogen balloons are used in each of the designs.

Cost: Design 3 would be the most expensive since there are a large number of platforms which have to be launched and monitored. Design 1 would be the least expensive because it is merely one balloon with a platform on top of it. Material costs are therefore reduced.

4.2.1. Sensitivity analysis

The trade-off reveals design 3 as the winner, as can be seen in table 4.1. During the sensitivity analysis the uncertainty of the trade-off is critically looked at. The weights that are assigned to all the different parameters can be changed. The influence these changes has on the outcome of the trade-off is analysed. Especially the highest and lowest weights, being one for cost and feasibility and a five for availability, are taken into account.

When increasing the weight of the cost parameter the first design gains points, however this change is not sufficient to change position. The same goes for the feasibility parameter. The availability parameter can be changed to a lower weight, but since the third design scores highest it will only decrease the gap between the designs and not the final positions. When changing the weights of the other parameters the outcome of the trade-off is not changed either.

Furthermore, the points given to the different designs for a certain parameter can be changed in case the points lay close together. For example, the points for the energy transfer and the reliability can be redistributed among the three designs. This however does not influence the final results of the trade off either. When changing scores, design three remains the best result in all cases.

5
Establishing design option 2: tethered glider

The second design option considered was conceptualised as a tethered kite with a generator on the ground. In the field of airborne wind energy, this is classified as an airborne wind energy system (AWES); more specifically a ground-generator AWES (GG-AWES). In a GG-AWES, electricity is produced on the ground by the mechanical work the kite does, which is transferred through one or more tethers (Cherubini et al. 2015).

The current state of airborne wind energy is limited by many technical and legal challenges, resulting in systems which operate at a few hundred meters altitude. However, the enticing wind velocities of higher altitudes – starting around 1 km, but even more so in the jet streams around 10 km – are an earnest goal (Schmehl 2018). This situation means that the designs discussed in section 5.2 will almost exclusively be versions of existing systems, but imagined at a higher altitude. The advancement of AWESs to the altitudes required for this project is a considerable one, but is already being investigated (Schmehl et al. 2013; Schmehl 2018).

What the scope of possibility is with regard to GG-AWESs is explored in section 5.1. Subsequently, the specific design within this field that will be further explored is selected in section 5.2.

5.1. Design options within design option 2

GG-AWES exploit their advantageous aerodynamic characteristics to harvest energy. Aerodynamic forces are transferred to the ground through tethers, where the movement is converted to electricity. Within these systems, there is still a wide range of possible design options. Options that have already been explored vary in many ways, including whether the ground station is fixed or moving, what the type and shape of the airborne sub-system is, how it is controlled, and what altitude(s) the system operates at (Cherubini et al. 2015).

To determine a preliminary design to consider for the trade-off, a design option tree of existing GG-AWES designs is created, as seen in figure 5.1. Some options are discarded based on feasibility, while others enter a trade-off, as will be discussed in section 5.2.

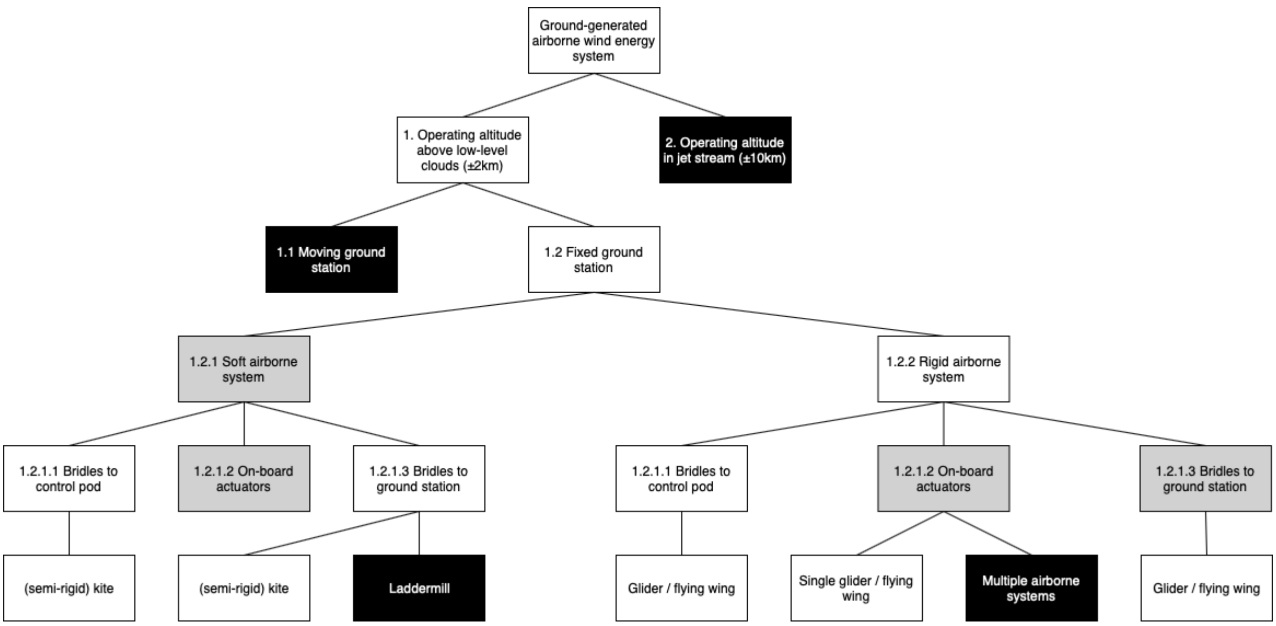


Figure 5.1: Design option tree displaying options for GG-AWESs within design option 2.

5.2. System trade-off within design option 2

For the trade-off in chapter 16, a complete GG-AWES must be obtained, which will be a design from the design option tree presented in figure 5.1. Many of these options are coloured either grey or black to indicate the degree of their feasibility; this relates either to how developed the concept is, or how applicable it is expected to be at the aimed operational height. Black options and systems that combine two grey options are not considered for the trade-off.

5.2.1. Reasoning behind preliminary categorisation

The operational height of the energy-harvesting system shall be above the low-level clouds at a minimum, as dictated by requirement EHAC-MIS-03. This is beyond the scope of existing airborne wind energy technologies (Schmehl 2018; Schmehl et al. 2013). It is true that the ambition to someday reach the jet steam winds of high altitudes is present, but due to the state of current technologies, only operations above a few kilometers (branch 1) will be considered.

Moving-ground-station GG-AWESs (branch 1.1) produce electrical energy by converting mechanical energy in a fundamentally different way from fixed-ground-station GG-AWESs (branch 1.2): rather than the tether unwinding generating electricity, electricity is generated by the translation/rotation of the ground station itself. This should allow for continuous generation of electricity, which would simplify the connection to the grid (Cherubini et al. 2015). However, as of 2015, no working prototypes of such a system have been developed (Cherubini et al. 2015). Because the concept of a fixed-ground-station GG-AWES is considerably more developed than the moving-ground-station alternative, moving ground stations will not be considered any further for the purpose of this project.

Within the development of fixed-ground-station GG-AWESs, a general divide can be seen between soft wings (branch 1.2.1) and rigid wings (branch 1.2.2). Soft wings have many inherent advantages due to their tensile structure, allowing for a low weight – a factor beneficial to power generation – and crash-free tests. However, hard wings are a lot more durable than soft wings, as well as having a higher aerodynamic efficiency – which is beneficial to power generation. It is a fact that both types of wing are heavily investigated, however more and more companies are switching from soft to rigid wings in their AWES (Cherubini et al. 2015).

Although a global choice between a rigid wing and a soft wing is not obvious (Schmehl et al. 2013, p. 235), for the purpose of this project, the maintenance and short lifespan of soft kites is considerably detrimental. The scale at which the energy-harvesting system at large will have to operate will involve many kites, meaning a lower-maintenance system is preferred. Kites are not discarded entirely, but are labeled grey to indicate them to be less feasible.

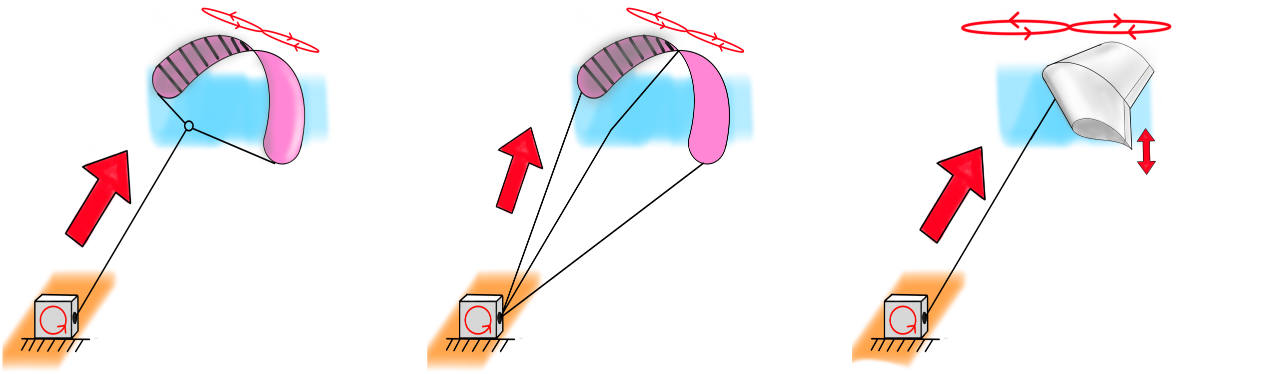
Some novel GG-AWESs are included in the design option tree too. The Laddermill, first developed by Wubbo Ockels (Ockels 2001), is considered to be unfeasible for the scale and altitude necessary for this project.

Attaching several kites with shorter tethers to one main tether is very promising, but at this stage very conceptual. This increases the efficiency of the kites per square meter of kite area, as there is less tether drag involved than the alternative of two separate kites (Zanon et al. 2013). Additionally, making such a system to exploit pulleys could result in an extremely cost-efficient system (Schmehl et al. 2013, p. 235). However, the way the airflow around the kites interacts, as well as the delicate launch procedure required, results in such a system not yet having been implemented (Schmehl et al. 2013, p. 11). Such a system could be an ideal solution to harvest wind energy at high altitudes, but will not be investigated in depth at this stage.

5.2.2. Trade-off between viable concepts

Five system options remain:

- **1.2.1.1:** A (semi-rigid) kite controlled by bridles connected to a control pod
- **1.2.1.3:** A (semi-rigid) kite controlled by bridles connected to the ground station
- **1.2.2.1:** A glider or flying wing controlled by bridles connected to a control pod
- **1.2.2.2:** A glider or flying wing controlled by on-board actuators
- **1.2.2.3:** A glider or flying wing controlled by bridles connected to the ground station



(a) Design option 1.2.1.1: A (semi-rigid) kite controlled by bridles connected to a control pod

(b) Design option 1.2.1.3: A (semi-rigid) kite controlled by bridles connected to the ground

(c) Design option 1.2.2.2: A glider or flying wing controlled by on-board actuators

Figure 5.2: The three chosen design options

These five basic systems can be summarised by comparing them to existing GG-AWESs being developed. Option 1.2.1.1 is evaluated based on the work of Kitepower at TU Delft[1], while option 1.2.1.3 is evaluated based on Kitegen[2]. For the options including a glider or flying wing, the most successful system appears to be developed by the startup Ampyx Power[3]. The Ampyx glider is a rigid glider which has a propeller system for launch and control, with on-board control surfaces and actuators. This results in three distinct systems, each with its own control method, while also including variety in the type of airborne sub-system. These three systems will be put in a trade-off with multiple trade-off criteria. For each design option a schematic drawing can be seen in figure 5.2.

Power density was split into two forms of parameters; power density with respect to to ground area, and power density with respect to air space needed. The units for power density are kW/m^2. For power density with respect to ground area, the grading is assigned depending on the order of magnitude. For an order of magnitude of 10^{-2}, a weight of four was assigned. Similarly, weights of three and two were assigned to orders of magnitude 10^{-3} and 10^{-4}, respectively.

The results of this trade-off can be found in table 5.1. The reasoning behind the scores each concept was given, are as follows:

Power density with respect to the air: The larger the system, the greater the costs and risks. Hence it would be beneficial to choose a system that generates the same power for a smaller system size. The rigid glider had an ideal value between 17 kW/m^2, the semi-rigid kite gave a value of 1.67 kW/m^2, while the flexible kite gave a value of 20 W/m^2. These orders of magnitude resulted in the grades 4, 2, 4 for the respective kite types.

Power density with respect to the ground: The ground area includes the area of the ground equipment and the clearance area needed. This number often comes from a set of multiple systems, called a farm, and finding the power density of it. For example, a 2 MW three-tether kite farm requires a ground clearance radius of approximately 773m between each kite. Hence, the power density with respect to the ground is approximately 10^{-3} kW/m^2 (Schmehl 2018).

Feasibility: The feasibility of both the rigid glider and flexible wing with one tether are scored 5, as versions of this concept are close to being commercially available. The third option is under development, but not yet flight proven.

Controllability: The controllability of the rigid glider is considered to be a marginal improvement compared to a kite, as it can more effectively deploy control surfaces.

Reliability: For a glider the reliability is quite high, as the materials it is made of will most likely be of higher quality than for a kite.

Availability: One of the main factors influencing availability was considered to be how well the system fairs under varying weather conditions. For this reason, the rigid glider comes out on top.

Maintainability: A rigid glider is a relatively complex system compared to a soft kite. Additionally, the control pod of a single-tethered kite is estimated to require more maintenance than a three-tethered kite.

[1] `https://kitepower.nl/tech/` [cited 29 November 2019]
[2] `http://www.kitegen.com/en/technology/details/` [cited 29 November 2019]
[3] `https://www.ampyxpower.com/technology/demonstrator-ap3/` [cited 29 November 2019]

Safety: The soft material of kites is a well-documented advantage over rigid systems (Cherubini et al. 2015; Schmehl et al. 2013). This difference means impacts of kites are safer to wildlife and humans – both in the sky and on the ground.

Cost: Given the potential to produce kites cheaply due to the little material needed, they could be considerably better than a rigid glider, even taking into account the difference in lifespan. Well-maintained gliders are estimated to have a lifespan upwards of 20 years, while for a kite this could be as little as a few weeks (Cherubini et al. 2015).

Table 5.1: Trade-off table tethered kite flying energy harvesting

Trade-off criteria, weight factor	**Rigid glider**	**(Semi-rigid) kite, 1 tether**	**(Semi-rigid) kite, 3 tethers**
Power density (ground), 5	4	2	3
Power density (air), 2	4	2	4
Feasibility, 3	5	5	3
Controllability, 3	4	3	3
Reliability, 3	4	2	3
Availability, 4	4	2	2
Maintainability, 3	2	4	5
Safety, 4	2	3	3
Cost, 2	2	4	4
Total score	**101**	**84**	**93**

As can be seen in table 5.1, the ideal option appears to be a rigid glider with an on-board control system. As mentioned before, the advantages a rigid system has over a soft system seem to be particularly impact full given the intended application.

5.2.3. Sensitivity analysis

A sensitivity analysis is performed to investigate what possible situations would result in a different design coming out on top. Judging from table 5.1, the main categories in which the glider does not come out on top are maintainability, cost, and safety.

The maintainability and cost of the glider are relatively poor assuming it is maintained over a long lifetime. Therefore, it can be estimated that kites become more beneficial in situations where the system as a whole has a short lifespan, such as a remote location temporarily disconnected from the main grid. Additionally, the advantage rigid gliders have in rough weather conditions disappears at locations where weather is generally clear.

The safety of rigid systems compared to soft systems could become a deciding factor in certain situations, such as if local wildlife or the human population are likely to frequent close to the ground station. However, considering the general advantages of rigid systems (also regarding controllability and reliability) should result in a system with clearly manageable risks.

Finally, it is possible that advances in soft or semi-rigid systems in the coming years improve the reliability and availability of kites, for example due to improved material qualities. This would also lead to a situation in which gliders lose the advantage they currently have.

In conclusion, situations do exist in which soft kites would outperform gliders. However, given the particular framing of this project, the advantages of a rigid glider prevail.

6
Establishing design option 3: tethered wind turbine

The third design considered is a tethered floating wind energy harvesting system, which either generates energy in the air and transfers the energy to the ground by use of the cable, or generates mechanical energy on the ground through movement in the sky.

Five different tethered floating wind energy harvesting systems are considered and are reviewed in section 6.1. In section 6.2 a trade-off table is shown together with an explanation for all the inputs. A sensitivity analysis on the trade-off is done in subsection 6.2.1.

6.1. Design options within design option 3

This section gives a brief overview of the five concepts. The different concepts are discussed and it is considered whether it enters the trade-off or whether it is already proven to be incompatible with the requirements and therefore not interesting for the trade-off.

6.1.1. Magnus effect

One way of harvesting energy is to make use of the Magnus effect. When a curved object spins in a fluid medium, like air, such that the rotational axis is at an angle to the flight path, a force perpendicular to the plane in which the flight path and rotational axis lie is generated. The magnitude of the force depends on the rotational velocity, air speed and body shape. When the upper separation point moves rearward relative to the freestream, and the lower separation point moves forward, the top surface gives a greater negative pressure, resulting in positive lift (Swanson 1961). In a Magnus effect airborne wind energy system (AWES), the wind will bring the body in a rotational motion to generate lift. However, the few experimental studies have shown that the generated net power is very low (K. van Hussen et al. 2018). A harvesting system using the Magnus effect will not enter the trade-off since it will not be able to compete with other concepts.

6.1.2. Quadcopter

The quadcopter is an AWES that produces electricity by its rotors generating lift and electricity simultaneously. It flies to the desired altitude using its rotors, once the operational altitude is reached, the device is inclined at an angle of up to 50 degrees relative to the wind. This angle causes the rotors to autorotate due to the wind, the rotors switch from motor to generator. The autorotation generates both thrust and electricity (Cherubini et al. 2015). The electricity is transferred to the ground using an electrical cable.

6.1.3. Wind turbine

Based on the design of the Altaeros Bat [1], the tethered floating wind turbine is a ring-shaped aerostat with a turbine in its center. The entire construction is lighter than air and the tether keeps the system at the operational altitude. Energy is harvested in the constant wind streams and transferred to the ground via an electrical cable. The wind turbine is stabilised and controlled by rudders to keep the generator in the optimal position relative to the wind (Cherubini et al. 2015).

6.1.4. EWICON

TU Delft developed EWICON, a system using wind to transport negatively loaded particles, such as charged water droplets. The positive remaining load is compensated by current from earth or a cable, which is used to generate electricity. Nowadays 7% efficiency has been reached and it is expected that efficiencies of 25%-30% are possible. A new prototype should reach 1 kW. Similar alternatives might produce 100 W/m^2 (Hubacz et al. 2015). A flying option could

[1] `http://news.mit.edu/2014/high-flying-turbine-produces-more-power-0515` [cited 29 November 2019]

consist of a device in a hollow, cylindrical balloon. As the power output is very low and much of the concept needs to be developed, the EWICON is not seen as a feasible option for this project and thus discarded from the trade-off.

6.1.5. Windmill

Based on the design explained in subsection 6.1.1 a fifth concept was derived. Based on the principle of watermills, a windmill could possibly turn as a whole instead of using rotor blades. Instead of using the Magnus effect to go up and down it uses the rotational energy to drive an on board dynamo to generate electricity. The idea to use a balloon as a mill transferring mechanical energy to a generator on Earth was patented in 1978 (Kushto 1978).

The company Magenn in Canada planned to develop the concept. However, experimental studies on the concept indicate that the net generated power is very small (Hussen et al. 2018). Due to this, it has been chosen to leave the windmill energy harvesting system out of the trade-off.

To determine a preliminary design to consider for the trade-off, a design option tree is created, as seen in figure 6.1. Some options are discarded based on feasibility, while others enter a trade-off, as will be discussed in section 6.2.

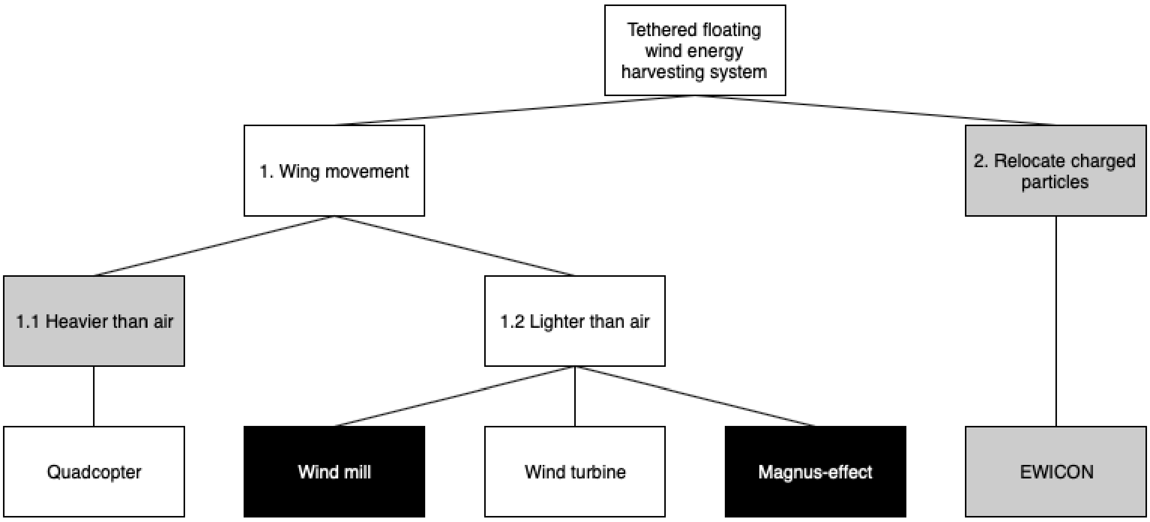


Figure 6.1: Design option tree displaying options for tethered floating wind energy harvesting systems. Some options are coded grey (impractical) or black (infeasible)

6.2. System trade-off within design option 3

As concluded in section 6.1, two system concepts enter the trade-off. These are the quadcopter and the wind turbine. A trade-off table is made in which scores are given to the different criteria elaborated on in this section. Finally, the best concept can be chosen after a sensitivity analysis proves the results are justified.

The concepts explained in subsections 6.1.2, and 6.1.3, are traded off on a relative base in table 6.1.

Scalability: Scalability is a strong point for both concepts. Since they are both easily scalable there is no difference between the concepts on this criterion. Therefore it is discarded from the trade-off.

Energy transfer: Energy transfer was discarded from the trade-off as, both concepts need a cable to transfer electricity.

Power density w.r.t ground area: Both concept require a lot of ground space for harvesting energy, as their aerial spacing can not be too small. Cables of more than 2 kilometers tangle easily. If two turbines collide, the effects are not too big, thus they require a smaller spacing than the quadcopter.

Power density w.r.t airborne area: Turbines on the sea deliver 0.3kW/m^2, as a general 1.5 MW windmill has a rotor diameter of 77 m [2]. The quadcopter is expected to harvest 0.625 kW/m^2, while the turbine is expected to harvest 1.25 kW/m^2 taking higher windspeeds and efficiencies into account. The number for the quadcopter was obtained by taking the power output of the scale model of Sky WindPower and dividing it by the area of the mechanism.

[2] `https://www.ge.com/in/wind-energy/1.5-MW-wind-turbine` [cited 29 November 2019]

Feasibility: When looking at feasibility, both concepts score normal to good. They have both been tested and proven feasible, but not at 2 km altitude nor at large scale. Windmill technology is further developed compared to the quadcopter energy harvesting technology.

Controllability: Controllability is high for the quadcopter as proven by current drones. The windmill has a high moment of inertia and frontal areas, which makes it more difficult to control. However, with high wind flows and control surfaces, there is still quite some steerability.

Reliability: As hail often occurs at 2 km, the quadcopter is expected to be very unreliable. The turbine is expected as reliable as wind turbines on the ground.

Availability: The turbine has excellent availability. Winds are very continuous and reliable at altitude and it is not dependent on wind speeds to stay airborne. The quadcopter has the advantage of reaching the reliable wind stream, but if the wind decreases, there is a point at which it will come down.

Maintainability: The wind turbine has few moving parts, which are in a far stage of development. Therefore it will not require a lot of maintenance, which will result in small downtime for maintenance. The quadcopter will require a lot of maintenance, but is rather quick in take-off and landing, making it perform sufficient on maintenance.

Safety: The quadcopter is unsafe as disintegrating turbine blades are very dangerous, they cause the entire copter to fall from the sky. The same risk applies for the turbine, but this system itself is less likely to crash, as it is a balloon with few moving parts.

Sustainability: The quadcopter needs much materials and electronics, which are mostly non-renewable. The wind turbine is in terms of materials comparable to other wind harvesting mechanisms.

Cost: The costs of the turbine are estimated to be equal to the costs of turbines on ground. A quadcopter involves a lot of sensors and complex parts, which will have to be custom-made for this application. Therefore it is more expensive than other devices.

Table 6.1: Trade-off table tethered floating wind energy harvesting system

Trade-off criteria, weight factor	**Quadcopter**	**Wind turbine**
Power density w.r.t. ground area, 5	1	2
Power density w.r.t airborne area, 3	4	5
Feasibility, 2	3	4
Controllability, 3	5	3
Reliability, 3	1	3
Availability, 4	3	5
Maintainability, 4	3	4
Safety, 4	1	2
Sustainability, 3	2	3
Cost, 1	2	3
Total score	**77**	**107**

As shown in table 6.1 the tethered floating wind turbine received the highest total score. In order to be sure this concept is the best, a sensitivity analysis is performed which can be seen in subsection 6.2.1.

6.2.1. Sensitivity analysis

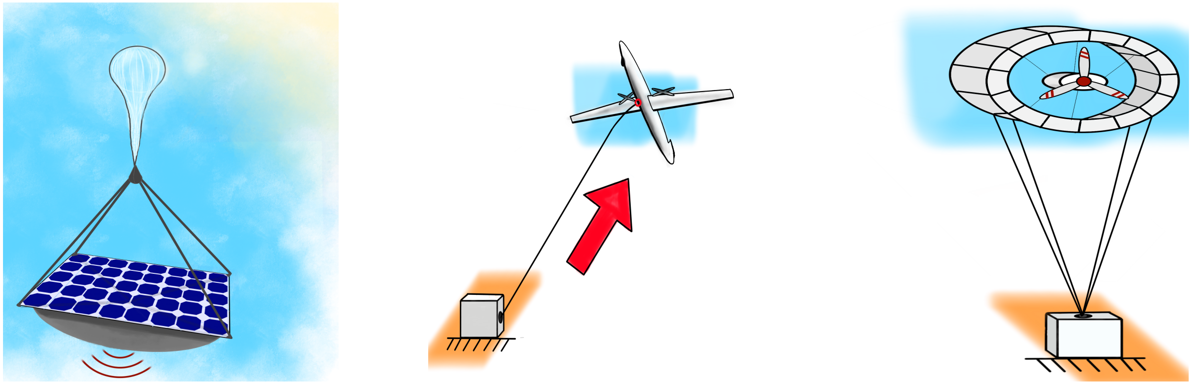
As visualised in table 6.1 the tethered floating wind turbine scores better in all trade-off criteria apart from controllability. Even when the highest trade-off weight of 5 would be granted to this criterion, the turbine would still come out of the trade-off as the better option. If all the criteria where the turbine scores only one unit higher than the quadcopter are discarded, cost, maintainability, scalability, feasibility, the power outputs, energy transfer and safety are left out. Still the turbine turns out to be the best option.

7
Configuration and sub-systems of system concepts

This chapter discusses the three final system concepts chosen in the previous chapters. Figure 7.1 shows sketches for each of the three design options. In section 7.2 the sub-systems of the three design options are shown.

7.1. Configuration of the three system concepts

Figure 12.1 gives three sketches, representing the configurations of each design option. These were established in chapters 4, 5, and 6, respectively.



(a) Design 1: Free-floating solar platform

(b) Design 2: Tethered glider

(c) Design 3: Tethered wind turbine

Figure 7.1: The designs selected to enter the trade-off

7.2. Sub-systems of the three design options

Table 7.1 shows the sub-systems for the three design options. Besides these design-specific sub-systems, all designs have the following sub-systems in common: Global Navigation Satellite System (GNSS), communication system, and internal battery. Additionally, each design must be able to supply electricity to the grid, so a transformer and high-voltage cables are necessary. Finally, for safety reasons, all the designs should have an emergency shutdown mechanism.

Table 7.1: Table showing the sub-systems for each chosen design.

Design 1	**Design 2**	**Design 3**
Super-pressure balloon	Generator	Generator
Zero-pressure balloon	Ground anchoring	Ground anchoring
Pump	Propeller(s)	Propeller
Solar panels	Tether	Tether
Solar panel attachment	Main disconnect	Main disconnect
Cable pulley system	Control surfaces	Control surfaces
Parachute	On-board computer	On-board computer
DC to RF converter	Electric motor	Ground control
Microwave transmitting antenna	Fuselage(s)	Balloon
Rectenna	Wing(s)	Internal battery
		Airfoil/wing

8 N2 chart

For the trade-off it is useful to look at the interfaces between separate sub-systems and external components. With that goal, an N2 chart is made which can be seen in figure 8.1

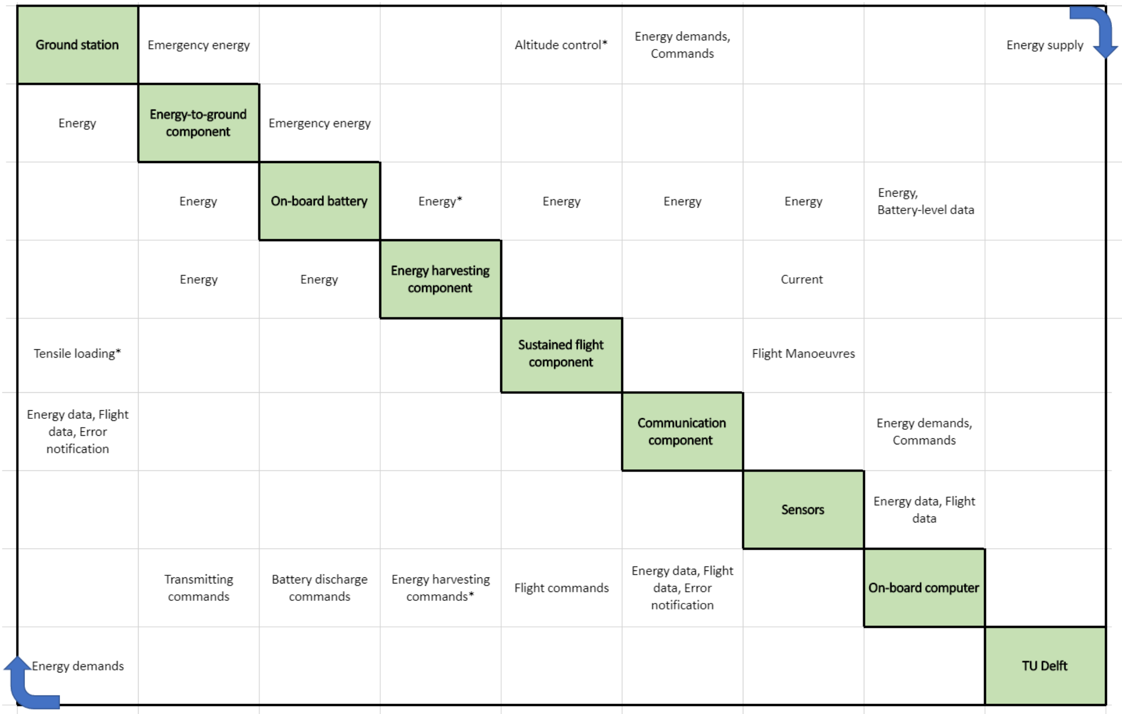


Figure 8.1: N2 chart

The N2 chart gives an overview of all the interfaces between components, such as mechanical, communicational, energy and human interfaces. The communication and energy interfaces will later on be further elaborated on in the communication flow diagram and the electrical block diagram. All blocks containing "energy" will be revisited in the electrical block diagram. The communication flow diagram will involve all the blocks containing "commands" and "data".

Some of the interfaces contain an asterisk. These are only applicable for some of the concepts. The ground station and sustained flight component for instance only have a direct interface in concept 2 and 3.

To compare the systems, communication and electrical interfaces will be taken into account in the operations and energy trade-offs, thus not in the determination of the N2-trade-off-score. The interfaces left are the mechanical and human interfaces. The only human interface is communication between TU Delft and the ground station about energy demands. These are the same for all concepts, not returning as a deciding factor between the designs. As mechanical interfaces are only the reaction between sensors and movements and possible interaction between ground and sustained flight component, there are not enough criteria at which there is a significant difference or which are comparable in a reasonable matter. Therefore, N2 will not enter the trade-off as a separate entry.

9 Aerodynamics and flight performance overview

In this chapter an overview of the flight performance characteristics of the three concepts is given. In section 9.1 the aerodynamic properties of each concept are evaluated. Section 9.2 describes the stability and control of each concept. Section 9.3 analyses the performance. Finally the trade-off is done in section 9.4.

9.1. Aerodynamic characteristics

The aerodynamic characteristics of the three design options can be found in the following subsections. General equations and assumptions are given that are used for further calculations in this chapter to perform the flight performance trade-off.

9.1.1. Design option 1: free-floating solar platform

Lift and drag are the first aerodynamic characteristics of aerial vehicles that one thinks of. The drag equation for balloons is the same as for airfoils and noted in equation 9.1. The C_d is around 0.0008 for spheres. A spherical balloon is used.

$$D = \frac{1}{2}\rho V^2 S C_d \tag{9.1}$$

Lift is generated using the buoyancy equation (9.2). Typically airborne wind energy systems have an excess of 10 to 20 % lift (Schmehl et al. 2013).

$$F_b = v(\rho_{air} - \rho_g) \tag{9.2}$$

9.1.2. Design option 2: tethered glider

Design option 2 consists of a glider (sailplane) that generates lift to create mechanical power with a grounded tether. A generator would then convert the mechanical energy into electrical energy for TU Delft. First, a Class I estimation had to be made of the glider. Seven gliders in the 15, 18 and 20 m span range were used in order to estimate wingloading and weight estimations based on area [1]. As the average wind speed changed throughout the height of the atmosphere, this had to be accounted for (Schmehl et al. 2013). Therefore, this change in velocity was linearised with the following formula [2], valid between 1 and 10 kilometers altitude with an R^2 of 0.997.

$$V_w = 7 \cdot 10^{-8} \cdot h^2 + 0.0011 \cdot h + 7.5388 \tag{9.3}$$

It became clear that an analytical model, albeit rudimentary, would have to be made to correctly determine the operating range and the approximate characteristics of the system. Estimates were made based on four key variables: altitude, wing surface area of the glider, reel speed of the tether from the drum/generator, and wing loading. The model used a range of altitudes (2-10 km), wing surface areas (15-40 m^2), reel speeds (10-21 m^2), and wing loading (400-600 N/m^2). The altitudes range from the lowest cloud levels at 2 km to 10 km. The model does not calculate higher altitude values as the wind speeds above 10 km decrease and thus do not warrant flying that high. The wing surface areas were taken from existing glider literature information and extrapolated. Reel speeds are not common knowledge, but Kitepower uses a maximum reel speed of 8 m/s, while Ampyx power use a reel speed of 20 m/s. Gliders tend to have higher reel speeds than kites, but a conservative range of reel speeds was chosen for this model. Class-I estimations, validated with literature study, showed that most gliders tend to have a wing loading between 400-600 N/m^2, and was therefore chosen.

[1] `https://www.ssa.org/files/member/BR%20Sailplanes%20V3%2004.pdf` [cited 6 December 2019]

[2] `http://euanmearns.com/high-altitude-wind-power-reviewed/` [cited 6 December 2019]

Assumptions

At this stage of the concept development, no 3D-analytical models or numerical models were created. Therefore, all the calculations had to be simplified based on assumptions. After investigating the nature of wind energy, it became evident that developing 3D-analytical models was more than what was needed for the trade-off of system concepts. Hence, the analytical model was made only in a 2D plane. The axes of this 2D model are the x-axis (parallel to the wind direction) and the z-àxis (pointing down from the sky and perpendicular to the ground). After consulting the *Airborne Wind Energy* textbook and the TU Delft airborne wind energy master's course, the following assumptions were made:

- Straight tether
- The wind direction is parallel to the ground surface
- The wind velocity is constant and uniform
- The kite velocity is equal to the reel velocity
- Steady-state flight
- International standard atmosphere relations for temperature, pressure and density
- Dyneema SK75 tether with tensile strength of 3.9 GPa independent of temperature and is therefore approximately 3% conservative [3]
- A safety factor of 3 on the tether, because of drag
- The tether drag and weight are approximated to a point force and located on the aircraft.
- The tether is non-vibrating
- The total C_d is equal to 0.07
- The operating angle of the tether, with respect to the ground surface, is 22°. This is due to the fact that most airborne wind energy systems use this inclination angle.
- During take-off the rate of climb is 10°.
- During take-off the weight is equal to the operational empty weight.
- During take-off C_L is increased by 0.3 by using high-lift devices.

Implementation of 2D model

For each iteration loop of the 2D analytical model, there are four input parameters: altitude, wing surface area, reel speed of the tether, and the wing loading. The total lift needed (during energy harvesting flight) could be found by multiplying the wing loading and the surface area of the wing. This lift (L) should counteract the following forces: the weight of the tether, the weight of the glider, and the tension force of the tether in the z-direction. From the Class-I weight estimation method, the mass of the glider was found to be a function of the wing surface area, defined in equation 9.4.

$$m_{glider} = \frac{S + 0.0013}{0.0375} \tag{9.4}$$

The altitude input allowed the air density and wind speeds to be calculated using ISA calculations and equation 9.3 respectively. The apparent wind speed is usually a 3D vector with complicated cross-wind values, but this has been restricted to 2D in equation 9.5.

$$\mathbf{V}_a = \mathbf{V}_w + \mathbf{V}_k \tag{9.5}$$

The wind speed was calculated in equation 9.3, while the kite speed was directly related to the reel speed. The reel speed is a vector in the x and z-directions, so only the x-component was considered when calculating the apparent wind speed. Having assumed an operational angle of 22°, the cosine value of the reel speed was added to the wind speed to get the kite speed. A reality check was done to ensure that V_a would not be greater than 10 times the value of V_w (Schmehl et al. 2013).

At an angle of 22°, the total length of the tether could be calculated using the altitude and simple trigonometry. The tether diameter and density were presumed to be 8 mm and 970 kg/m^3. These values contributed to equation 9.6, and the weight of the cable could be determined.

$$W_{tether} = \pi\left(\frac{d_{tether}}{2}\right)^2 \cdot \rho_{cable} \cdot l_{cable} \cdot g \tag{9.6}$$

In equation 9.6, g is the gravitational acceleration constant. The weight of the glider is the product of m_{glider} and g. The tension force in the z-direction that must be carried by the tether, was found by subtracting the tether weight

[3] `https://issuu.com/eurofibers/docs/name8f0d44` [cited 2 December 2019]

and glider weight from the total lift force L (which came from wing loading). The total tension force (T_{tether}) in the tether at an angle of 22°was then found by dividing the tension force in the z-direction by sin(22°). With this tension force implemented in equation 9.7, the required ultimate breaking stress ($\sigma_{ultimate}$) was calculated (Schmehl et al. 2013). This tension, along with the reel speed, was then used to calculate the power generated by each glider unit. This calculation is elaborated in chapter 11.

$$d_{needed} = 2 \cdot \sqrt{\frac{T_{tether} \cdot SF}{\sigma_{ult} \cdot \pi}} \tag{9.7}$$

In the 2D model, this calculation was only done if the tether was in tension. If the cable was in compression, the input values were deemed infeasible. In future analytical model(s), the cable diameter would be optimised to minimise the cable weight and diameter. The required lift coefficient could be calculated using equation 9.8, which is a rearranged version of the traditional lift equation.

$$C_L = \frac{L}{\frac{1}{2} \cdot \rho \cdot V_a^2 \cdot S} \tag{9.8}$$

This C_L was one of the output parameters that was checked for feasibility. A list of glider airfoils were compiled to find the C_L values for various angles of attack. Most glider airfoils have a maximum C_L of approximately 1.4 - 1.6 (Lyon et al. 1997), so the output C_L values from the model had to be restricted to only the values in that range. The take-off conditions are also of great importance to the glider. By rearranging the lift equation into equation 9.9, the take-off speed could be calculated. The take-off speed is the apparent wing speed during take off, so during headwind the kite speed can be lower.

$$V_{TO} = \sqrt{\frac{m_{glider} \cdot g}{\frac{1}{2} \cdot \rho_{air} \cdot S \cdot C_{L,max}}} \tag{9.9}$$

During the energy harvesting phase of the glider's flight, the glider will fly in "figures-of-8". At this stage of the development, the exact nature of this flight path cannot be determined. However, rough estimates can be used to determine what the minimum ground spacing ($d_{u)}$ needs to be. This calculation can be done using equation 9.10 (Schmehl et al. 2013).

$$d_u = \frac{l_{cable}}{sin(\beta_0 - \nu_1) \cdot \left(\frac{1}{tan(\beta_0 - \nu_1)} + \frac{1}{tan(\nu_1 + \nu_2)} \right)} \tag{9.10}$$

It was decided that the operating angle is 22°, but it could go up to 45°. Anything further than 45°would result in very high cosine losses. Thus, the operational envelope was defined to be 45°while the mean flight path angle with respect to the ground is 26°. Therefore, for a cable length of approximately 6 km (glider flying at an altitude of 2 km with an operating angle of 22°), the distance between two ground units would be approximately 810 m. The ground area needed for each unit can be approximated as d_u^2. This way, the power density with respect to the ground can be calculated.

9.1.3. Design option 3: tethered wind turbine

The floating turbine gets its lift from the lighter-than-air gas inside the balloon and at this stage it is assumed that drag comes from the turbine only. Since the turbine is tethered, the L/D ratio is considered to determine the blow down angle (δ). The blowdown angle is the angle the tether makes with respect to the vertical axis above the ground station. For the design the blow down angle is set to 45 °, resulting in an L/D ratio of one for the total system conform equation 9.11 (Schmehl et al. 2013).

$$\delta = arctan\left(\frac{D}{L}\right) \tag{9.11}$$

In this equation, the lift is the excess lift caused by the buoyancy of the balloon. For the turbine, drag is considered to be negative thrust which from now on will be used in further calculations. Thrust of a wind turbine is calculated as follows:

$$T_{turbine} = \frac{1}{2} \rho_{air} V_w^2 S_{turbine} c_T \tag{9.12}$$

Where $S_{turbine}$ is the total swept area of the rotor blades and the thrust coefficient of the wind turbine (C_T) has an optimal value of 8/9 which can be rounded to 1 for this estimation [4]. By plugging in equation 9.12 into equation 9.11, one can see without filling in any numbers that the excess lift of the balloon must be very large, making the system unfeasible and blown down by the wind.

By replacing the donut-shaped aerostat by an airfoil, the L/D ratio would vastly increase causing the system

[4] Dr.ir.M.B.Zaayer,privatecommunication,5December2019

to reach an L/D ratio of 1. Besides, when the wind increases, the negative thrust force of the turbine increases but the lift also increases leading to a more consistent altitude of the system. The formula for δ then changes to equation 9.13. F_b is the buoyancy force, V_{wind} is the wind speed following from equation 9.3, m is the mass of the wind turbine, C_L is the lift coefficient, and C_D is the drag coefficient of the airfoil.

$$\delta = arctan\left(\frac{D}{L}\right) = arctan\left(\frac{T_{turbine} + \frac{1}{2}\rho_{air} V_{wind}^2 C_D S}{F_b - (m_{airfoil} + m_{cable} + m_{turbine})g + \frac{1}{2}\rho_{air} V_{wind}^2 C_L S}\right) \tag{9.13}$$

Assumptions

- The buoyancy force is equal to the weight of the airfoil (F_b = $m_{airfoil}g$).
- The thrust coefficient (C_T), related to the drag, of the turbine is constant.

As surface area is an indicator of the amount of material used, the choice of the turbine and airfoil were optimised to find the minimum surface area. The initial amount of turbines was set at 50, the order of magnitude of offshore Dutch wind farms [5], leading to 0.2 MW wind turbines to reach TU Delft's energy demand. A list of available 0.2 MW turbines[6] was compared as well as airfoils for low speed applications (Lyon et al. 1997). An optimisation is performed leading to an ideal combination of airfoil characteristics, altitude and type of wind turbine.

9.2. Stability and control characteristics

The stability and control characteristics determine the stability of the system in different circumstances. Especially for devices which harvest energy from lift, these require special attention. The stability of the different system concepts is shown in the following subsections.

9.2.1. Design option 1: free-floating solar platform

Stability for the balloon is easy to maintain due to the spherical shape. The center of gravity is always going to be in the center (horizontally). The one thing that could make the system unstable is if the solar panels are placed at a large distance underneath the balloon. Wind can then cause this payload to swing. The length of the cable attaching the payload to the balloon should therefore be carefully taken into consideration.

Trajectory control for free floating balloons is still very difficult. Using different wind directions at different altitudes is the only way of controlling the trajectory. NASA used the different wind speeds and directions between a balloon at 35 km and an airfoil tethered to it at 20 km altitude (Aaron et al. 2002). The system is not further developed and likely to be unfeasible.

A more feasible option would be changing altitude of the balloon in order to make use of the wind directions at different altitudes. This principle has been proven to work to an extent (Du et al. 2019). The balloon was able to stay within 25 km radius of the point where the balloon was designed to stay. This low accuracy is given a 1 in the trade-off table. This balloon used the AB concept described in chapter 4, which is less efficient than DE. Furthermore, helium is heavier than hydrogen. Therefore, it is expected that design option 1 will show better results, due to the fact that it can reach a larger range of altitudes in less time. The software required to find and navigate to the proper wind layers could be very complex. For this reason the complexity of the control system is given a 2.

9.2.2. Design option 2: tethered glider

Stability and control characteristics for the glider are very similar to conventional sailplanes and gliders. Like any conventional aircraft, the stability and control characteristics depend on the following: center of gravity, aerodynamic center, and control surfaces. The aerodynamic center came from the type of airfoil chosen (S7075). For most airfoils, the aerodynamic center is at the quarter-chord position along the mean aerodynamic chord from the leading edge. The control surfaces, like rudders/ailerons, would help keep a consistent bank angle and orient the glider in the direction that most suits the energy-harvesting mode. The tail plane will have to be sized to deal with pitching

[5] `https://nl.wikipedia.org/wiki/Lijst_van_windmolenparken_in_de_Noordzee` [cited 5 December 2019]

[6] `https://en.wind-turbine-models.com/turbines?kwrange=0%2C20000&view=table[cited5December2019]`

moments created by the wing and the fuselage. The wing gets its pitching moment from its airfoil, which can be seen below in figure 9.1[7].

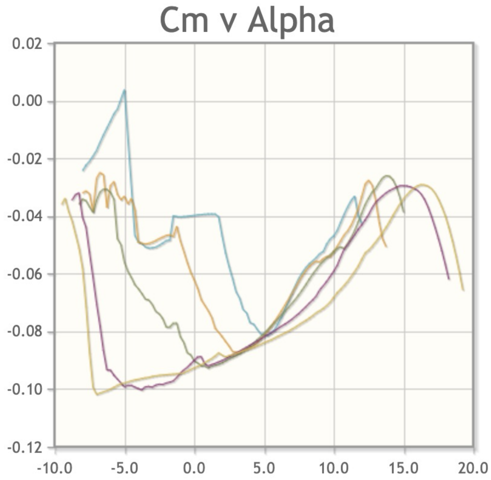


Figure 9.1: Coefficient of moment for an S7075 airfoil

Drag is going to greatly influence the glider's ease of control. At any given time during the energy harvesting phase of flight, the lift component will be providing kite speed, as well as a counteractive force for the cable weight, the glider weight, and the tether tension force. The tether drag was incorporated into the total aircraft drag as an approximation (Schmehl et al. 2013), but further development of this concept would see the cable drag as a varying distributed load. The center of gravity is simple enough to estimate, using the Class-II estimation method (Roskam 1985), but not possible to calculate at this stage of the design development. It would require an estimation of the fuselage group, which is not similar to conventional aircraft fuselages, and estimation of wing groups (which also vastly differ from conventional aircraft wing groups). Thus an operational empty weight was calculated as a total "weight budget" that the design cannot exceed. For most gliders, it is advisable to keep the center of gravity between 30-40% from the most aft center of gravity position[8]. The control mechanisms are developed and accurate for gliders, granting it a 5 in the trade-off table. Still it is complex to do it in an autonomous way, which gives it a 2 in the trade-off table.

9.2.3. Design option 3: tethered wind turbine

To maintain stability using two or four turbines in order to counteract moments could be considered.

To ensure that the turbines are facing the wind, a tail plane should be used to turn the device in the wind. Shifting buoyant gas from one side of the airfoil to the other should be used to overcome vertical forces. Flying wings use shifts in the center of gravity for control. As the generator connected to the rotors is the heaviest part, this should be movable longitudinally. Also the connection to the cable could be used as a control mechanism by reeling it, or move the connection point, or split the upper part of the cable in three or more parts to control the device in vertical direction.

As the speed is low, and inertia is high, the control accuracy of design 3 is granted a 2 in the trade-off table. As the complexity is moderate, a 3 is granted in the trade-off table.

9.3. Performance Analyses

Using the equations given in section 9.1, the performance of the three designs is presented below. Iterations are performed in order to optimise each design for optimal altitude, size and energy output.

9.3.1. Design option 1: free-floating solar platform

To fly, a buoyant gas is needed. Hydrogen and helium are the options for this. Helium is not renewable, but hydrogen is highly reactive which makes it unsafe (Schmehl et al. 2013). Nonetheless, hydrogen is chosen due to its light weight.

[7]`http://airfoiltools.com/polar/details?polar=xf-s7075-il-1000000` [10 December 2019]
[8]`https://www.dg-flugzeugbau.de/en/library/optimum-cg-sailplanes` [cited 10 December 2019]

For altitude control, differential expansion (DE) are used, as explained in subsection 4.1.3. The volumes for the ZPB and the SPB are the volumes to stay in the air at maximum altitude and at minimum altitude, respectively. For 2 km this equals a SPB volume of 3,160 m^3. For maximum altitude, it is observed that the required volume increases exponentially-like with altitude as can be seen in figure 9.2 where the volume per balloon is shown per altitude if seventy-five balloons are used.

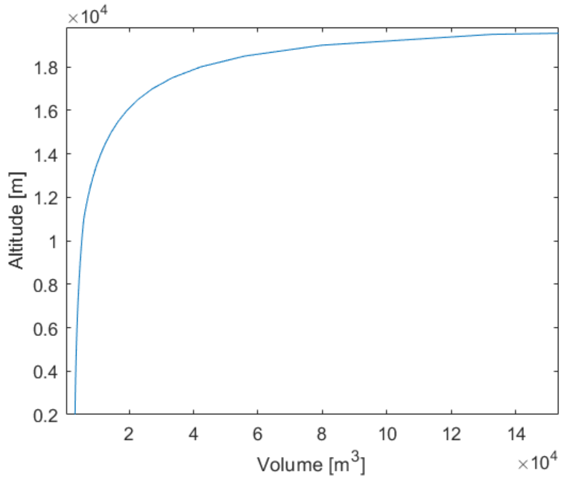


Figure 9.2: Volume of one balloon needed to keep the system in the air plotted against altitude

Considering extra material costs and increase of spacing if the volume is large, maximum ZPB volume was set at an altitude of 16 km, which equals 19,290 m^3.

Mission duration of the balloons is partially dependent on the balloons being able to sustain flight for a certain time. SPBs are shown to be able to fly for a little over 100 days (Cathey 2007). This will depend on the permeability of hydrogen through the film of the balloon envelope, on the mission altitude and on the payload weight.

9.3.2. Design option 2: tethered glider

The performance analysis is an analysis of the output generated by the method as described in section 9.1.2. From this it was clear that after restricting several outputs to feasible magnitudes, an optimum could be found. As lower altitudes are preferable because of operational constraints and tether drag, a system at 2 km altitude was found. This system has a maximum power of 469 kW with an OEW of 1,066 kg, V_a of 28.56 m/s and a surface area of 40 m^2, resulting in a C_L of 1.46. The optimum can be seen from the structural and operational plots in figure 9.3. For this C_L, a matching airfoil could be found from a list of common airfoils for gliders. (Lyon et al. 1997) An example of such an airfoil is known as S7075 (Selig S7075 low Reynolds number airfoil) and has a maximum thickness of 9%[9].

9.3.3. Design option 3: tethered wind turbine

The performance of the floating wind turbine is subject to the choice of wind turbine, the operational altitude, and the surface area of the airfoil. As explained in subsection 9.1.3, a wind turbine with a rated power output of 0.2 MW is chosen. The optimisation led to the selection of the NEPC SRC 29.8-200 turbine and the E387 airfoil. The operational altitude was determined by matching the average wind speed at different altitudes to the rated wind speed of the selected wind turbine. This leads to an altitude of 5 km. To meet the energy requirement a total of 75 devices would be needed, leading to a total surface area, S, of 220,000 m^2 and a total cable mass of 760,000 kg, calculated conform the formulas in section 12.3.

As the wind speed at ground level is around 5.1 m/s on average and the power output of a turbine scales to the power of three with it, 21 times more turbines would be needed on the ground. The rated wind speed used by the selected turbine is namely 15 m/s.

Due to the tail plane, alternating wind directions and wind speeds will not cause problems and weather conditions like rain and hail will not affect its flight performance. Lightning will be something that needs to be further

[9] `http://airfoiltools.com/airfoil/details?airfoil=s7075-il` [cited 8 December 2019]

investigated. Besides, landing and take-off is looked at. Due to the large number of devices, this causes difficulties, since flight is restricted by the tethers of the other devices and the performance is therefore moderate.

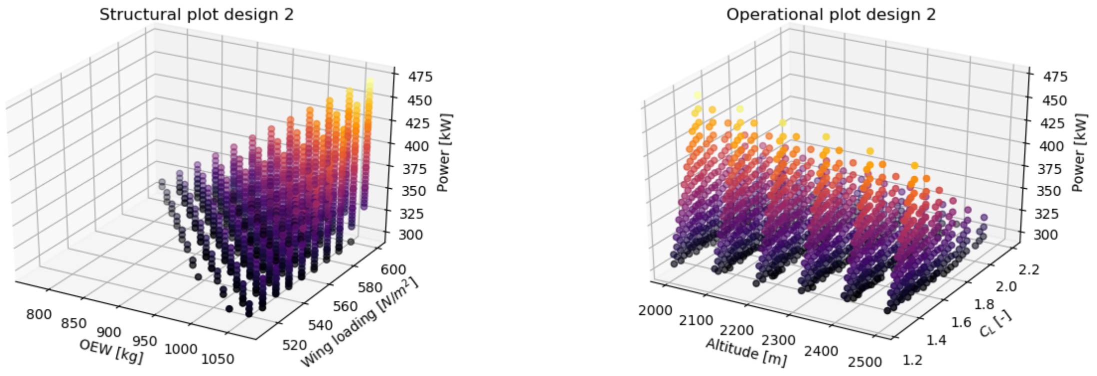


Figure 9.3: Structural parameters and operational parameters versus power for design 2; the colour is related to the vertical power axis, where black is low and yellow is high.

9.4. Trade-off table and sensitivity analysis

The different criteria were each given a weight factor. The weather was considered to be most important, and therefore it has a weight factor of four. There are five important weather conditions considered; hail, rain, freezing, lightning, unpredictable winds. Design option 1 can withstand rain, hail and freezing, thus it got a grade of 3. Design option 2 can only not withstand lightning, thus it got a grade of 4. Design option 3 can only not withstand lightning, thus it got a grade of 4. Landing and take-off is easy for design option 1, as the balloons merely have to be inflated and deflated to lift up and land, respectively. Design option 2 and 3 need actual take-off and landing procedures similar to aircraft, thus making it more difficult.

The complexity of the control system and the control accuracy both have a weight factor of three. The first is important since a complex system has a higher sensitivity for failure than a less complex system. The control accuracy determines how precise the system can be moved in the air. Finally, the landing and take-off performance of the systems was given a weight factor of two. This criterion is not as important as the other three since it does not greatly influence the overall performance of the systems. The result of the trade-off can be found in table 11.1. Design option 2 has the highest total score and thus is considered to be the favourable design when looking at the flight performance.

Table 9.1: Flight performance trade-off table

Flight performance trade-off	**Weather, 4**	**Landing and take-off, 2**	**Complexity of control system, 3**	**Control accuracy, 3**	**Total**
Design 1	3	5	2	1	2.6
Design 2	4	3	2	5	3.6
Design 3	4	3	3	2	3.1

In the sensitivity analysis the weight factors of the criteria where design option 2 did not score highest, were changed to see the impact this would have on the total score. When changing the weight factor for weather to five, design option 2 still scores highest. The same goes for the landing and take-off criteria, changing the weight to either one or three does not change the position of design option 2, however the gap with design 1 decreases. Changing the weight of the complexity of the control system positively influences the score of design option 3, but design option 2 still scores the highest. The sensitivity analysis therefore shows that the outcome of the trade-off is reliable.

10
Operational overview

In section 10.1 the operations and logistics of the system are discussed. Next, the communication flow diagram is shown in section 10.2. The horizontal positioning of the system is discussed in section 10.3. In section 10.4 all aspects of RAMS are discussed. Finally, a trade-off on the operations is done in section 10.5.

10.1. Operations and logistics

In order to not miss any system requirements, one should consider the operations and the logistics of the system. The operations and logistics might be such substantial aspects, that system characteristics may be derived from it. The method used for approaching this is evaluating the functional flow diagram, which can be found in the *Baseline Report* (Arblaster et al. 2019), determining from this diagram the main functional block from which support blocks could be derived. The operations and logistics diagram is presented in appendix A in figure A.1.

The orange blocks represent the functional main blocks and the light blue main blocks represent the operations required to support the main functions. The functional orange blocks are vertically placed based on position in the life-cycle. The light blue blocks do not accurately represent time flow. The numbering of the blocks is based on what phase they are the most relevant. Some blocks are linked back to from a later phase.

10.2. Communication flow diagram

In order to design and trade-off a system, it is vital to know the communication flow running through it. To be able to evaluate this, a communication flow diagram for the mission is set-up which can be seen in figure 10.1.

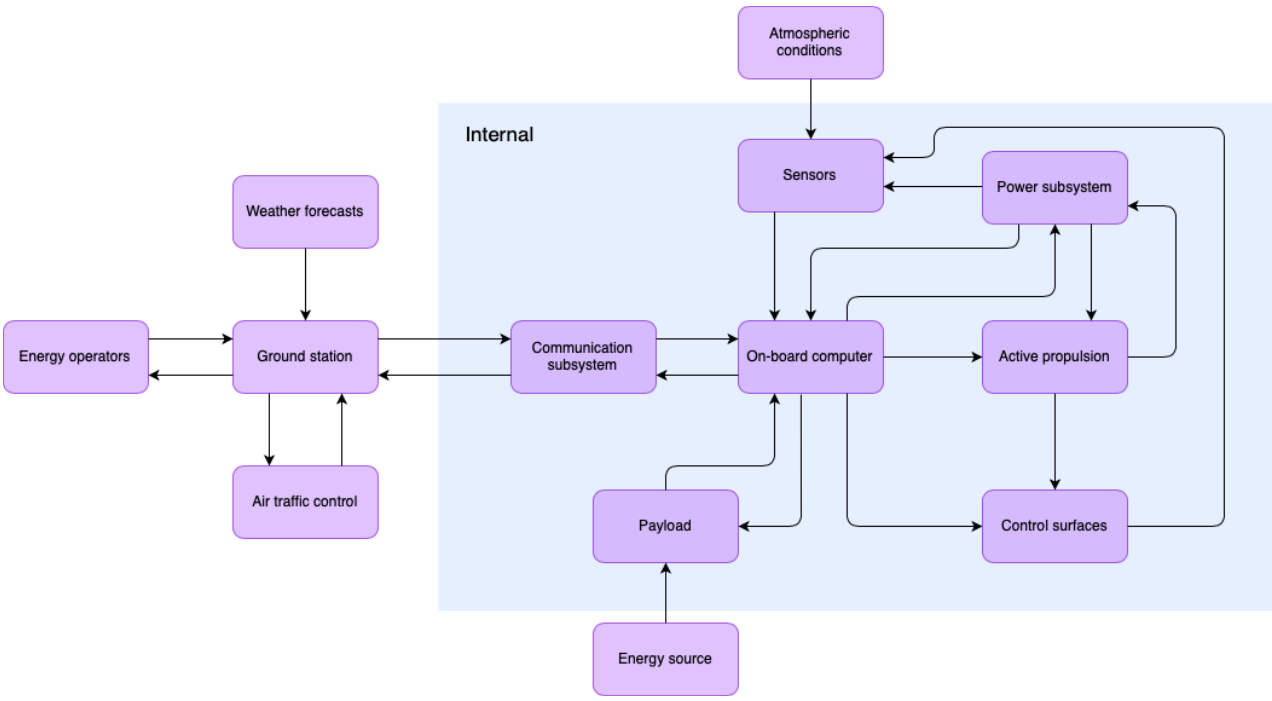


Figure 10.1: Communication flow diagram

10.2.1. Communications of concepts

Concept 1 is the free floating solar balloon. An advantage on communication level is that it generates electricity on board. Therefore it does not require an internal energy storage for communication during daytime. It does however need a storage, as the sun goes down in the night. Buoyancy force can be increased easily to bear the sensors, communication sub-system and on-board computer. The balloon is free-floating, therefore wireless communication is needed. As the balloon will likely be at a range of 25 km from the point where the balloon was designed to stay, as explained in subsection 9.2.1, and harvests energy around 10 km altitude, communication distances could be quite large. The combination of this, and the wireless communication makes the design an inconvenient concept for communication and is therefore granted a 2 in the trade-off.

The second concept is a tethered flying rigid glider. As the electricity generation occurs on the ground and not in the air, batteries or solar panels have to be on board to supply the communication chain. The lift generated by the glider is enough to carry communication systems. As the system is attached to the ground system via a cable, it has the option of performing wired communication as well as wireless communication, increasing flexibility of the design option. All these factors combined grant that the kite is acceptable for communication, granting it a 3 in the trade-off.

The third concept is the tethered floating wind energy harvesting system. This system, just like concept 1, has the advantage that is has an energy-generator as payload. As the energy is harvested by always present wind movements, the system can harvest energy constantly. As the sub-systems can take energy straight from the energy harvesting source when needed, on-board storage is not required. The lift generated by the lighter-than-air system is sufficient enough to carry the communication systems. As the system is attached via a cable to the ground, it has the option of performing wired communication as well as wireless communication, increasing flexibility of the design option. This system is great for communication, therefore granted a 5 in the trade-off.

10.3. Horizontal positioning of the system

Due to regulations, the system is unlikely to fly above TU Delft. This would also be preferred for safety reasons. This does introduce complications to the operational aspect of the system. On topo of that, to minimise the effect of cable loss for the energy generated, the distance to a high power grid should be as small as possible. With a minimal distance to a high power grid and with a preference for coastal regions one can identify three ideal areas in the Netherlands: de Maasvlakte; Wijk aan Zee; and Eemshaven [1]. Unfortunately, all three locations are located near airports. Eemshaven would be the location situated furthest from an airport, thus the most likely option. At the target altitude the wind speeds are similar for all three options (Bechtle et al. 2019).

10.4. RAMS

In *Baseline Report*, a preliminary approach to the RAMS was made. The assumption was made that the RAMS could be thoroughly approximated already for the different concepts (Arblaster et al. 2019). This, unfortunately, would still be too ambitious for the current design phase. In this section a more thorough RAMS will be presented.

10.4.1. Reliability

In this section a failure mode and effect analysis (FMEA) is applied to the system concepts to determine reliability of these system concepts. To fully comprehend the FMEA table, one should know the classifications of severity:

1. Catastrophic (death or system loss)
2. Critical (severe injury, major property damage, major system damage)
3. Marginal (minor injury, minor property damage, minor system damage, delay or loss of availability or system degradation)
4. Minor (no injury, property damage, or system damage, unscheduled maintenance or repair necessary)

These classifications are the same in *Baseline Report* (Arblaster et al. 2019). The latest FMEA can be found in appendix C.1.

[1] `https://www.tennet.eu/fileadmin/user$_$upload/Company/Publications/Gridmaps/ENG/Gridmap$_$TenneT$_$ENG.pdf` [cited 5 December 2019]

10.4.2. Maintainability

Maintainability is defined as the ability of an item to be maintained. Like reliability, it is an inherent design characteristic. Maintainability pertains to the ease, accuracy, safety, and economy in the performance of maintenance actions. The four different aspects with which the maintainability of the concepts is rated are defined as the following (Hamann et al. 2016):

- **MTTR:** Mean time to repair refers to the time needed to repair or restore the system to its full operational status.
- **MPMT:** Mean preventive maintenance time refers to the time required to perform preventive maintenance action.
- **MTTM:** Mean time to maintain refers to the time required to perform both preventive and corrective maintenance action.
- **MDT:** Mean down time, when besides the active maintenance elapsed times logistic delay times are included, one speaks of the mean down time.

In this design phase quantifying the maintainability factors would be a rather coarse approximate. Therefore, the decision was made to put the factors through a qualitative approach instead. The scale runs from 1 (unfavorable) to 5 (excellent). How the different maintainability factors are rated for each concept can be found in table 10.1.

Table 10.1: The maintainability factors rated for each concept

Concept	MTTR	MPMT	MTTM	MDT	Maintainability
Design 1	4	4	2	3	3.3
Design 2	4	3	2	2	2.8
Design 3	1	3	2	3	2.3

10.4.3. Availability

For this phase in the project the availability is defined as the system uptime divided by the system uptime and the downtime. This property follows naturally from the reliability and maintainability. Considering, these parameters are approached qualitatively, the choice has been made to approach the availability qualitatively too. The concepts are rated on a scale. The scale runs from 1 (unfavorable) to 5 (excellent).

The weight of the operational availability is rated higher than the weights of the achieved availability and the operational availability. The operational availability was considered the most value due to a power grid's inconsistent demand.

- **Ai:** Inherent availability is the probability that a system will operate satisfactory at any point in time as required.
- **Aa:** Achieved availability is similar to inherent availability except that it also includes maintenance.
- **Ao:** Operational availability is the probability that a system will operate satisfactory when called upon.

The trade-off is visualized in table 10.2. The lower availability aspects of design 1 are from the dependency of wind speeds, but it has low maintenance time. Design 2 is most available as weather conditions affect the aspects the least, but maintenance is not optimal. For design three it goes that the poor control makes availability a poor performing aspect of the system.

Table 10.2: The availability rated for each concept

Concept	Ai, 1	Aa, 1	Ao, 2	Total
Design 1	3	4	3	3.3
Design 2	4	3	4	3.8
Design 3	2	2	3	2.5

10.4.4. Safety

Safety of the system includes the safety of human beings, animals, the system itself and the surrounding environment. For the first, an FMEA is made to check whether the safety equipment is adequate to deal with a possible hazard. Safety is related to the RAMS-analysis in the way that hazard elimination or minimisation results in reiterating the design which may cause new design challenges. The functions identified with severity '1' can be considered to be the safety critical functions. The safety is rated for each concept by averaging the severity classes for each applicable functional identification. The averages are then translated to a scale of 1 to 5. The values can be found in table 10.3

Table 10.3: The final trade-off for the safety parameter

Concept	Safety
Design 1	2.6
Design 2	4.0
Design 3	2.8

10.5. Trade-off table and sensitivity analysis

For operations, all concept will be traded off on their communication flow diagram and RAMS components. Horizontal positioning made no difference for the three concepts, so it will not be taken into account in the trade-off. As reliability comes back in both safety and availability, it has not been given grades, since design characteristics should occur only once in the trade-off. Availability is rated the most relevant aspect, as it directly influences the feasibility of the project. Flying devices cause great challenges to safety, therefore making it a really important criterion as well. Maintainability is a little less important, since it is mostly linked to cost, which is in this stadium a little less important compared to creating a feasible design. Communication flow has the lowest scoring, as it will most likely influence the design less than the other parameters.

For the sensitivity analysis all weights were, one by one, adjusted to one weight lower and one weight higher to see if the outcome would change. The only switch which made a concept come closer to Design 2 was to increase the weight of communication flow by one. However, the change was still not significant enough to actually make a significant difference. Design 2 remained the the obvious winner throughout the sensitivity analysis.

Table 10.4: Final trade-off table for operations

Concept	Communication flow, 2	Availability, 4	Maintainability, 3	Safety, 4	Total
Design 1	2	3.3	3.8	2.6	3.0
Design 2	3	3.8	2.8	4.0	3.5
Design 3	5	2.5	2.3	2.8	2.9

11
Energy harvesting, storage, and transfer overview

In this chapter, the various energy-related aspects of each system design is evaluated. The energy harvesting method is discussed in section 11.1, after which the transfer method is discussed in section 11.2. Section 11.3 gives a performance analysis on all the designs. Then, the electrical block diagrams are shown in section 11.4. Finally, in section 11.5 a trade-off is done for the energy part of the designs.

11.1. Energy harvesting method

In this section the energy harvesting method is discussed for each of the three designs. In subsections 11.1.1, 11.1.2 and 11.1.3 the methods for design 1, 2, and 3 can be found, respectively.

11.1.1. Design option 1: free-floating solar platform

Energy is harvested in design option 1 through the use of solar panels. How this is done and what sizing this would give is discussed in this section. Multiple assumptions were made to simplify calculations for the energy harvesting method. These include the following:

- **Ideal conditions:** It is assumed that clouds only reach to 2 km and are not present above this altitude. In reality, in times of storm, the solar panel would not be able to harvest energy underneath 10 km. Diurnal cycles were taken into account. However, the night time is assumed to be eight hours. This is inaccurate for winter times, but the design option is checked for feasibility under ideal conditions first.
- **Maximum output:** It is assumed that the solar panels are always able to produce maximum output, while this would not be the case in reality: the solar altitude is not always being equal to 90 °C and the zenith angle of the Sun changes too. The latter would, for example, depend on the latitude, which is different at the testing site.

The solar panels that were used are XTE-LILT triple junction solar cells, with an efficiency of 31.6% at maximum output (Spectrolab 2014). The solar cells are resistant to the cold temperatures at the desired altitudes and have a temperature coefficient of -0.4 %/°C. The maximum power output of these solar cells are 1.155 W with a solar cell area of 27 cm^2. The required energy for the TU Delft is 67,908 MWh for 2018 [1]. From this, the total number of solar panels can be determined. However, these depend heavily on the altitude, due to the colder temperatures and less solar radiation absorbed by the atmosphere when moving to a higher altitude leading to more efficiency.

11.1.2. Design option 2: tethered glider

Unlike the other two design concepts, the energy harvesting method and the aerodynamic characteristics are highly correlated. For example, the amount of lift the glider generates directly influences the power generated by the motor. Additionally, the energy harvesting method is not highly dependent on Sun and therefore daylight and allows it to operate independently of it. There were a few assumptions made for the energy harvest of the glider:

- Generator efficiency was quite conservatively set to 80%, according to expert opinion.[2]
- No energy is lost between the tether and the generator.
- TU Delft power demands are approximately 8.7MW. An energy loss of 15% was taken to give a total demand of 10MW. This loss includes transformer loss, high-voltage cable loss, and heat loss.
- The reel speed is the average reel speed

The power generated by the tether is equal to a multiplication of the force and the reel speed of the tether. The reel speed was varied between 10 and 20 m/s according to section 9.1.2. In that section also the optimal flight characteristics were elaborated on. As a result of these characteristics, a corresponding reel speed could be determined

[1] `http://emonitor.tudelft.nl/index.php/campus/[cited2December2019]`
[2] Braber, T.I., Kitepower, personal communication, 3 December 2019

and was found to be equal to 20 m/s. With a tether force F_{tether} of 29.33 kN this results in a power of 469 kW with a generator efficiency of 80%, according to the formula of work in 11.1.

$$P = F_{tether} \cdot V_{reel} \cdot \eta_{generator} \tag{11.1}$$

From the harvested power per kite, the total amount of kites could be determined from the design power of 10 MW, as stated in sub-section 11.2.2. Resulting from the former, a simple quotient determines that approximately 22 of these stations are needed to provide the TU Delft with their energy consumption.

11.1.3. Design option 3: tethered wind turbine

The wind energy is converted to mechanical energy of the turbine. The power of the turbine is calculated as follows (Schmehl et al. 2013):

$$P = \frac{1}{2} \rho_{air} V_{wind}^3 S_{turbine} c_p \tag{11.2}$$

Where c_p is the power coefficient of the turbine and $S_{turbine}$ is the swept area of the turbine. The following assumptions were made for equation 11.2:

Assumptions

- The turbine rated power scales linearly with $\frac{\rho}{\rho_0}$.
- The power coefficient (c_p) of the turbine is constant.

Equation 11.2 shows that power output scales cubically with the wind speed which makes the operational altitude vital. Because of the available knowledge on current wind turbines and their optimisation, proven rated power outputs are taken from existing commercial wind turbines for the iterations.

Mass of the airborne wind turbine is most important. Currently, turbines are already designed for maximum power-to-mass ratio. The problem is that mass scales to the power three, and power to the power two [3]. It was decided to select turbines with different rated wind speeds, to find the optimal turbine and altitude for the system. Above assumptions were made to find the optimal turbine and airfoil. [4].

Lots of research has been done into wind turbines. The turbines are designed to have minimum cost in terms of production and maintenance. Therefore the complexity of the technology is relatively low.

11.2. Energy transfer

The energy transfer methods of design 1, 2 and 3 can be found in subsection 11.2.1, 11.1.2 and 11.2.3, respectively.

11.2.1. Design option 1: free-floating solar platform

The free floating balloon with solar panels is going to use microwaves to transfer the energy to a ground station wirelessly. To be able to do this first the direct current (DC) produced by the solar panels needs to be converted to radio frequency (RF). Then, it can be transmitted using a microwave power transmitter and collected by a receiving rectifying antenna. This system is often used in designs and studies for space-based solar power satellites, operating in geostationary orbit. An efficiency of 45% can be reached when operating at a frequency of 5.8 GHz (McSpadden et al. 2002). However, when operating at a frequency of 2.45 GHz an efficiency of 61% is reached (Jaffe et al. 2013). For this reason it was decided that a microwave frequency of 2.45 GHz will be used for this design.

$$P_r = \frac{P_t A_t A_r}{\lambda^2 D^2} \tag{11.3}$$

$$\lambda = \frac{c}{f} \tag{11.4}$$

Equation 11.4 is used to calculate the wavelength needed for equation 11.3, which is used to calculate the area of the transmitting antenna. The calculated area was plotted against the altitude the balloon will be flying at. Putting this in the same plot as the solar panel area against the altitude gives an optimum for the sizing, when assuming the antenna area should be equal to or lower than the solar panel area. This is assumed because the solar panel area should be driving for the size of the platform. To calculate the transmitting antenna area, the area of the

[3] Dr. ir. M.B. Zaayer, private communication, 5 December 2019

[4] `https://en.wind-turbine-models.com/turbines?kwrange=0%2C20000&view=table` [cited 5 December 2019]

receiving antenna was fixed. However, after iterating and changing the receiving antenna area it was decided that it is necessary to place the antenna on a platform at sea. This was done because the balloons will not be able to continuously transfer their generated power, so the power will be concentrated. Taking this phenomenon into account, the size of the receiving antenna increases.

11.2.2. Design option 2: tethered glider

The energy transferred from the generator to the grid has to be transferred via power lines after transforming it into high-voltage electricity to mitigate transfer losses. For the losses and transforming of the power, a combined efficiency of 85% is taken into account. This will increase the design power to 10 MW.

11.2.3. Design option 3: tethered wind turbine

After harnessing the wind energy, the energy is transferred to the grid via an electric cable connected to the floating wind turbine. The performance, i.e. efficiency, of the cable is subject to voltage and current through the cable, length and material. Although high voltage transmission is the most efficient, due to the weight of these transformers this is unfeasible. Following from a chosen wind turbine comes the voltage output of the generator. For the NEPC SRC 29.8-200 wind turbine picked in section 9.3.3, this is 400 V. In addition, the efficiency of the cable is set at 80% resulting in a design power of 11 MW. Heat of the cable during long operation hours will have to be further analysed.

11.3. Performance analysis

In this section the performance analysis for the different designs is done. For design 1, 2 and 3 these analyses can be found in subsection 11.3.1, 11.3.2 and 11.3.3, respectively.

11.3.1. Design option 1: free-floating solar platform

For the free-floating balloon, the area needed for the transmitting antennas and for the solar panels were both plotted against altitude in figure 11.1. The transmitting antenna areas were plotted for both a receiving antenna area of 10,000 m^2 as well as for one of 5,000 m^2 (the upper and lower line starting in the left bottom corner, respectively). The solar panel areas depend on the number of balloons used and are the red, orange, and purple lines in the graph.

The transmitting antenna area can not exceed that of the solar panels, due to the fact that the antenna is placed underneath the solar panels. The maximum altitude ranges are therefore the intersections between the solar panel and transmitting antenna areas.

The power output per area in the air increases much more in the thermally gradient layer of the atmosphere due to the temperature coefficient. In the isotherm layer, the solar panel efficiency does not increase significantly as can be seen in the figure 11.1. Therefore, 11 km is the maximum altitude in which the balloon shall operate. Based on the graph, a receiver antenna area of 5,000 m^2 with 75 balloons is chosen. The transmitting area would then equal the solar panel area at 300 m^2. The transfer efficiency is a combination of the dc to radio-frequency and atmospheric efficiency and equals 61.4%. The power output per area on ground and air is 0.5 W/m^2 and 334 W/m^2, respectively.

11.3.2. Design option 2: tethered glider

The power as determined in sub-section 9.3.2 yielded 469 kW for a single unit, as a result of the aerodynamic lift generated by the glider. With a design power of 10 MW accounting for the electrical losses in the cable, there will have to be 22 of these systems in order to provide TU Delft with their energy needs. Based on sub-section 9.3.2, the determined spacing is equal to 809 m. The total area, based on a square grid land allocation for the total area required is equal to 14.4 km^2. The power per area in the air is determined to be $469000/40 = 11.73$ kW/m^2. When one takes the required spacing for the system into account, the power per area on the ground is equal to the conservative value of $469000/809^2 = 0.72$ W/m^2

11.3.3. Design option 3: tethered wind turbine

Following from the data of the NEPC SRC 29.8-200 wind turbine, a single unit delivers on average 120 kW to the grid at an altitude of 5 km [5]. To meet the energy requirement, 75 units are required. As the altitude of the turbines is almost 5 km, one turbine can cover as much as 78 km^2, assuming the wind can blow it in all directions and the blow

[5] `https://en.wind-turbine-models.com/turbines/460-nepc-src-29.8-200` [cited 6 December 2019]

down angle is fixed at 45°. A rule of thumb for the spacing between wind turbines is six times the rotor diameter [6]. Therefore by placing 75 turbines 90 m apart from each other in a rectangle and keeping an clear area of 5 km surrounding the outermost airborne wind turbines, approximately 95 km^2 of ground area is covered. This leads to a power density with respect to ground, after considering power losses, of 0.09 W/m^2.

The power density with respect to air is calculated by using the swept area of the wind turbine, 706 m^2. The power density is 170 W/m^2.

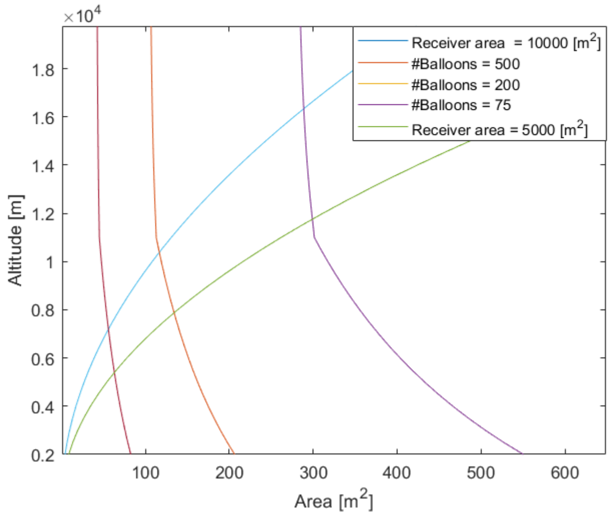


Figure 11.1: Area of transmitting antennas and area of solar panels per balloon plotted against altitude for a different number of balloons and receiver antenna areas

11.4. Electrical block diagram

To show the electrical equipment of the design and its mutual relations and interactions, electrical block diagrams are made for all three design options. The diagrams can be seen in figures 11.2, 11.3, and 11.4.

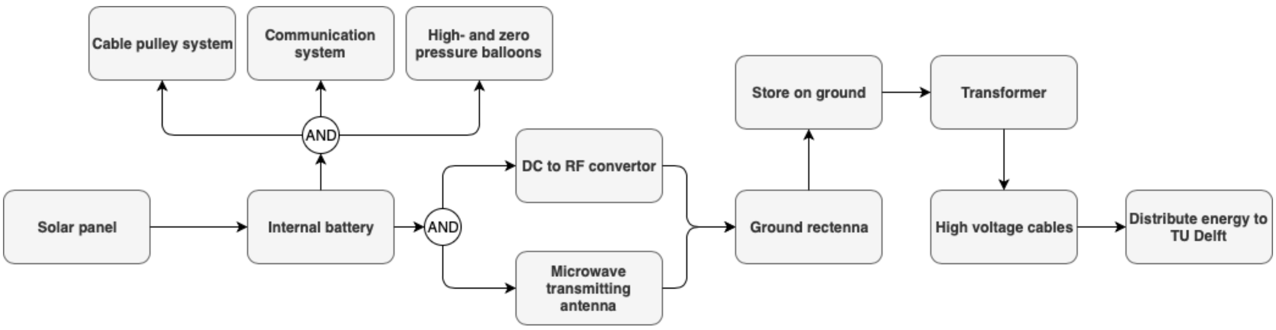


Figure 11.2: Electrical block diagram design option 1

11.5. Trade-off table and sensitivity analysis

In table 11.1 the energy sub-system is traded off. This was done by establishing different trade-off criteria. The power output per area with respect to the ground was decided to be most important, so it was given a weight factor of five. All three design options scored bad due to the large spacing needed. The feasibility received a weight factor of three. Design option 1 scored a one because of the microwave energy transfer which requires the two antennas to be perfectly aligned. Design option 3 scored the best since it only uses a turbine to harvest the energy and has a cable which transfers the energy to the ground, which is a feasible system. Finally, the power output per area in the air was

[6] `https://nl.wikipedia.org/wiki/Windmolenpark` [cited 6 December 2019]

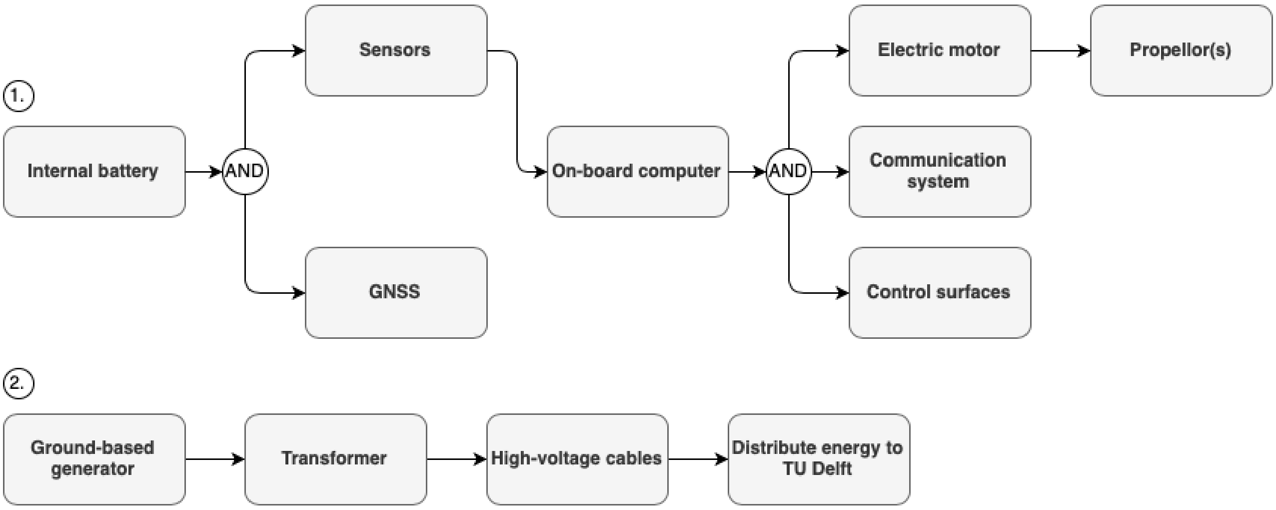


Figure 11.3: Electrical block diagram design option 2

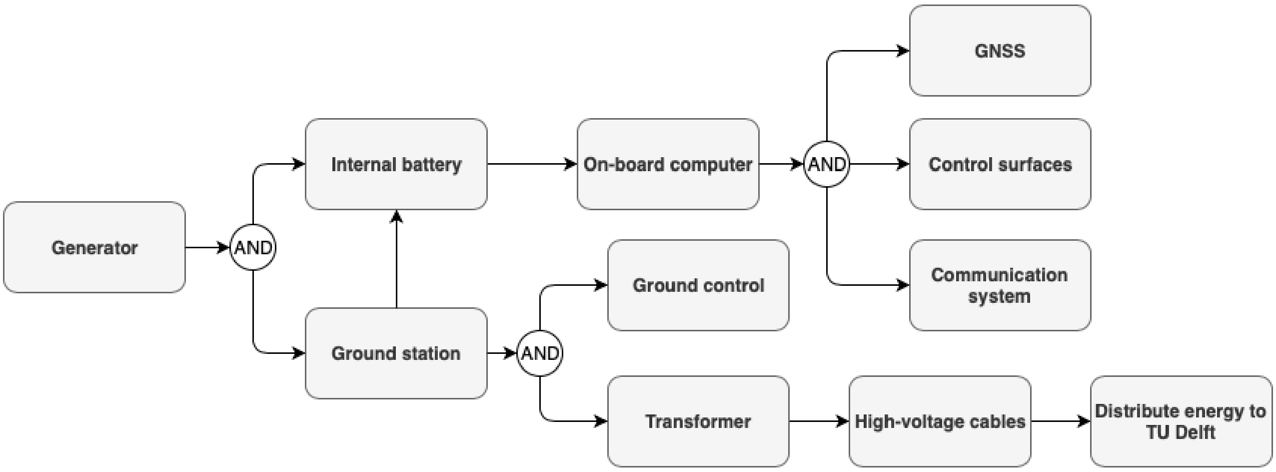


Figure 11.4: Electrical block diagram design option 3

considered the least important, the weight factor is two. For this criteria all the designs scored moderate, however design option 2 obtained the highest score since it benefits the most from operating at high altitude. Adding the scores for each design gives the highest total score for design option 2 and designs one and three are equal.

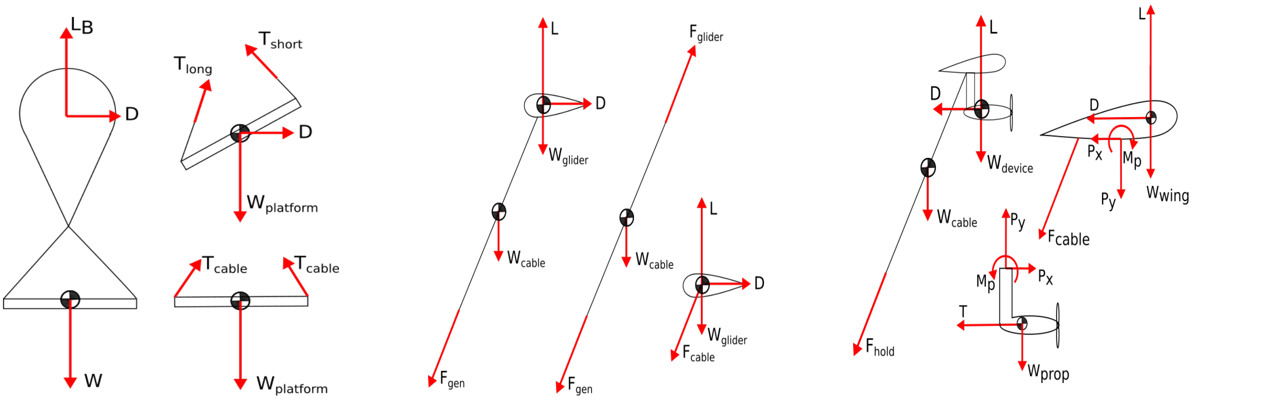
Sensitivity analysis was done by changing the weight for complexity of the energy harvesting sub-system. Lowering the weight from 3 to 2 in terms of feasibility leads to design option 3 scoring lower than design option 2 for energy (2.2, 2.7 and 1.9 for the design options 1, 2, and 3, respectively). Increasing the weight to 4 does not lead to design option 3 prevailing over design option 2 (2.5 and 2.3 for options 2 and three, respectively). For design option 1, ideal conditions were assumed (e.g. 16 hours of sunlight per day), but even under those it will not match design option 2 and will only be worse in more realistic conditions.

Table 11.1: Energy trade-off table

Energy trade-off	**Power output per area w.r.t. ground, 5**	**Power output per area in air, 2**	**Feasibility, 3**	**Total**
Design 1	2	4	1	2.1
Design 2	2	5	2	2.6
Design 3	1	2	4	2.1

12
Structural overview

This chapter discusses the structural and/or material characteristics of the three design options in sections 12.1 through 12.3. Section 12.4 discusses the production plans for the three designs. To give an indication of the loads on the structures, generalized Free Body Diagrams are drawn for all structures in figure 12.1a, figure 12.1b and figure 12.1c.



(a) FBD for the free floating solar balloon

(b) FBD for the tethered flying kite

(c) FBD for the floating wind energy harvesting system

Figure 12.1: The FBDs for the three design options

12.1. Design option 1: free-floating solar platform

Design option 1 has multiple important structural features, namely the frame that supports the solar panels and microwave transmitting antenna, the connection cables, and the DE balloon. It was assumed that the frame and connection cables are feasible structures and therefore not necessary to design for the trade-off. The DE balloon however, is more critical to the design and is therefore discussed in further detail below.

Differential expansion balloons require two balloons, a super-pressure balloon (SPB) and a zero-pressure balloon (ZPB). These balloons require different material properties. The SPB must be made out of a very strong material that can withstand the high pressures inside of it, while the ZPB must be able to expand and contract. Both balloons must be able to hold up in the weather conditions above the clouds.

12.1.1. Structural analysis

The DE balloon will have a total volume of 19,288 m^3, of which 3,160 m^3 will be the super-pressure balloon. This means, that when the DE balloon is at its minimum altitude (and therefore at the SPB is at its maximum density), the pressure inside the SPB is approximately 6 bar, assuming a perfect gas and constant temperature. Using the balloon volume and an assumed (spherical) balloon thickness of 3 mm, the maximum hoop stress was found to be approximately 1 GPa. Hoop stress varies inversely with thickness, so if a stronger (but light enough) material is used, the thickness can be reduced and weight can be saved.

12.1.2. Available materials and material feasibility

As mentioned before, the two balloons making up a DE balloon each require a certain combination of material properties. Additionally, the materials of solar panels will be discussed.

The ZPB requires a thin material that can either stretch or has enough excess to be inflated, to allow for the balloon to expand. Conventionally, ZPBs are made out of the plastic polyethylene. Although this material can be recycled, it is obviously not ideal given the sustainability requirements of this project. A strong alternative was thought to be spider silk; spider silk can be incredibly strong and tough (Ko et al. 2001). However, spider silk has varying properties when exposed to changing humidity and temperatures, making it less suitable for this application (Plaza et al. 2006). Therefore, as of now, polyethylene will have to be used for the ZPB.

SPBs require high tensile strength. They are usually made out of a thin film that consists of three layers: a weatherproof layer (which blocks damaging radiation from the Sun), a woven load-bearing layer, and a gas-tight membrane (Komatsu et al. 2003). Zylon fibres are often used for the load-bearing layer, due to its high strength, low weight and good thermal stability (Komatsu et al. 2003). The maximum tensile stress zylon can take is reported to be 5.6 GPa, matching the 1 GPa requirement from subsection 12.1.1. Reusing the zylon material should be investigated, so that the material does not go to waste.

Recent work has shown that the teeth of limpets approximate to an almost ideal natural composite material (Barber et al. 2015). After taking teeth of limpets and performing tensile strength tests, it appeared that the mechanical strength of the limpet tooth is comparable to that of the strongest man-made fibres (Barber et al. 2015). Future developments might allow for these structures to be 3D-printed (Oskin, B 2015) [1], which would lead to a sustainable high-strength fibre. Unfortunately, this research is in an early phase, so the implementation of these fibres for this system is not feasible.

As discussed in subsection 4.1.1, organic solar cells are excluded since they do not reach the efficiencies non-organic cells reach. As for now, it is assumed that non-organic solar cells will be used. The most important materials that will be used for the solar panels are the non-organic solar cells, a glass plate, an ethylene vinyl acetate (EVA) film encapsulant, and a polyvinyl fluoride (PVF) film backsheet.

To what degree these materials and their sustainable alternatives are available will be taken into consideration as a criterion for the trade-off within this chapter. For the many layers of material required for the balloons of this design, no available bio-based options were identified; neither for the solar panels. However, non-renewable options are expected to be reasonably available. Therefore, the material availability for this design is considered to be marginal.

12.2. Design option 2: tethered glider

The design option consists of a glider, which is similar to conventional gliders, a tether, and a generator located on the ground. The structure required for the generator will not be discussed in this design phase as it does not influence the design enough to be taken into account for the trade-off.

The glider will consist of three functional parts: a fuselage for electronics, the wings, and a tether attachment point. The design of the wing will be hugely determined by the airfoil as this dictates the possible dimensions of the wing box. With the current parameters available it is still complicated to determine many of the wing box properties, however, the maximal bending stress can be found already. From subsection 9.1.2, one can take the wing loading and wing area. With a first class estimation on aspect ratios of gliders, resulting in an aspect ratio of 27.5 (-), one can then find the span. With equation 12.1 the maximum moment can be calculated.

$$M_{max} = \frac{W}{S}\left(\frac{b}{2}\right)^2 \tag{12.1}$$

With the above variables the maximum moment equals 165kNm. This is a reasonable value and it is not likely to be troublesome to deal with. The parameters of the tether have been calculated in subsection 9.1.2.

12.2.1. Available materials and material feasibility

The most critical component of a ground-generator airborne energy system is its tether. The revived development of this technology has become possible by the availability of "durable and lightweight flexible materials that can sustain a large number of load cycles" (Schmehl 2018), further development of which is a crucial enabler for the technology.

As was already assumed in chapter 9, Dyneema SK75 and other materials based on high-modulus polyethylene (HMPE) are highly applicable for this application compared to other materials which are readily available. These could be given a coating to reduce their aerodynamic drag (Schmehl 2018, p. 53).

Currently, there are no materials produced from renewable sources which offer these same characteristics. Materials such as spider silk and 3D-printed limpet teeth are not feasible for this application, as evident from

[1] `https://www.livescience.com/49844-limpet-teeth-strongest-natural-material.html` [cited 4 December 2019]

subsection 12.1.2.

The material of the structure of the glider will also be some form of light-weight composite. Additionally, it is important that the system can withstand a range of weather conditions; carbon fibres could accomplish this.

The materials required for both the tether and the glider could be manufactured from renewable sources within the foreseeable future. The development of natural fiber-polymer composites, which can be placed in bio-based polymer matrix to obtain the desirable characteristics (Väisänen et al. 2017). What makes these materials particularly appealing is that they can be obtained from the residue of crops after they have been processed for their primary purpose. However, the main drawbacks to this technology – including limited tensile strength compared to existing glass fiber or carbon fiber, limited durability, poor thermal properties, and water resistance (Väisänen et al. 2017) – appear to be particularly impactful for the purpose of this project. Processes have been developed which allow for high-performance bio-based carbon fibers based on lignins. However, the intensive processing required in their production prevents their mass production (Laurichesse et al. 2014).

Because of these reasons, bio-based composites will not be discarded, but will also not be held as a final solution. At this stage, it is assumed that these composites could be implemented in combination with certain coatings to mitigate their drawbacks.

The availability of these renewable materials is considered to be fairly good. Considering the technical readiness required for this project is fairly low, the implementation of bio-based materials becomes a very real possibility. As mentioned, a limiting factor could be a material to function as tether, considering the intense cycles it experiences. Still, the availability of these materials is good.

12.3. Design option 3: tethered wind turbine

It is assumed that the wing, propeller, and pylon are similar to existing systems. Therefore, it has been chosen not to take the structure and materials of those systems into consideration during this design phase. They will most likely not be infeasible, thus not creating a difference in feasibility. For the wing this is justified by the amount of aircraft already flying around. The propeller and pylon are similar to have a propeller-aircraft which delivers enough reference material to state that it is feasible. The key structural system for this design will be the cable. In option 2 the structural part of the cable was already discussed. Design option 3 introduces a completely new type of cable, namely an electrical one. For this phase of the design it is assumed that the cable will just be a summation of the tension cable and the electrical cable. The material used to conduct the electricity is assumed to be copper. The higher you get, the more feasible it is to use aluminium instead of copper, but their weights will be in the same order of magnitude. The mass of the cable is given in equation 12.2

$$m = \rho \pi l \left(\frac{t}{2}\right)^2 \tag{12.2}$$

where m is the mass of the cable, ρ the density of the material, and l and t the length and thickness of the cable, respectively. The length of the cable comes from chapter 9, where it states an altitude and a maximum angle, giving the length of the cable. Thickness can vary. The thicker, the less losses the cable will have. However, it will be heavier. Therefore it can be optimised. The cable should not be too thin with too many losses for it to not burn down. The optimisation can be done by using equation 12.3.

$$\delta U = \frac{\rho_{el} \cdot l \cdot I}{A} \tag{12.3}$$

where δU is the voltage drop, ρ_e the resistivity of the material, I the current, and l and A the length and area of the cable, respectively. It is important to keep the current low, to have more efficiency. The feasibility of the cable is therefore highly dependent on the current coming from the system. For the cable weight it would be ideal to have a high-voltage transformer in the device before running the current through the cable. Using these formulae it has been proven that conducting cables of a few kilometers length are quite heavy, but not so heavy as to be infeasible. For the cable as described in section 9.3.3, a mass of approximately 10,000 kg for 5 km altitude has been found. Understandably, such a cable is extremely driving for the design.

The mass of the wing can be estimated using the same equation used for the glider of design option 2, equation 9.4. From this equation follows a wing mass, using a surface area of 2,912 m^2, of $7.8 \cdot 10^4$ kg. The accurateness of this equation is questionable on this scale, but the order of magnitude of the weight says enough, the apparatus will be heavy. A surface area of 2,912 m^2 delivers an enormous bending moment on the fuselage, no matter the aspect ratio. This will make it extremely difficult to design properly with the current structures and materials knowledge. Using equation 12.1 a value of about $2.0{\cdot}10^3$ kNm is calculated. Wings of this size have nowhere on earth been produced, structurally it will be unfavourable to design such a wing.

A calculation of the tension cable reveals that it will, even in the most extreme cases not be heavier than 2,000 kg for this design, making it negligible compared to the copper conductive table. The same holds for a carbon casing for the copper cable to uphold its own weight.

12.3.1. Available materials and material availability

In terms of material requirements, design option 3 is fairly similar to design option 2. Therefore, the discussion regarding materials for the glider and tether of design option 2, found in subsection 12.2.1, is also relevant here.

An important element to consider is the conductive cable. The resistivity of material should be as low as possible to have only small losses in the cable. For this purpose copper was chosen, as it is one of the best conducting materials currently widely available, only slightly beaten by silver. However, silver is heavier and more expensive, making it less suitable for the application at hand. For increasingly higher altitudes aluminium, which is lighter, but a worse conductor, becomes more favourable.

Prioritising bio-based options, conductive composites become a possibility. Of these, carbon nanotubes show properties most competitive to copper, being roughly 20% less conductive, but many times lighter (Huang et al. 2019). However, these composites often incorporate metals such as copper, silver, and aluminium too, so it is still uncertain to what degree they would be an improvement over pure copper. The use of conductive polymers for this project has not been analysed further, but will be reevaluated at a later phase if design option 3 is selected.

The material availability – in this case meaning how feasible it is to acquire the required materials, renewable or otherwise – is fairly low for this design option. Although fossil-based polymers could be largely avoided given the necessary developments, the many kilometers of conductive cable this design requires would need a significant leap in technology. Even if copper were to be selected, the many tonnes needed would be challenging to acquire. Therefore, the material feasibility of this design option is unfavourable.

12.4. Production plans

The production plan includes the manufacturing, assembly, and integration plan (MAI plan). The MAI plan gives a time ordered outline of the activities required to construct the product from its constituent parts (Garcia 2019). In figures 12.2, and figures B.1, and B.2 in appendix B the production plan of each design option can be seen.

In order to make the final assembly of the designs, sub-assemblies need to be produced. Some of those sub-assemblies can not be made straight from the parts, but will require a sub-sub-assembly step. In all design options, there is the possibility to manufacture or buy parts.

Design option 1 requires balloons and solar panels, which is vastly different from the other design options. This also means that more parts must be bought, rather than manufactured, as the team does not have the resources to make solar cells themselves. At the end of the production process, the solar platform (consisting of the solar arrays, support structure and microwave transmitters), the DE balloon, and the cable and pulley system are connected through the final assembly. Hydrogen can be manufactured and does not need to be bought, as electrolysis will be used for the production of hydrogen.

Design option 2 requires the assembly of a glider, cable and dynamo. This also means that a glider (and all its sub-parts) must be assembled first. Third parties must provide large sub-parts such as the dynamo, motor and landing gear. The production plan can be seen in figure B.1.

Design option 3 is similar to design option 2 in the sense that some aircraft-like parts must be assembled for the final product. This means, that just like for design option 2, frames, spars, skin, ribs and stringers are required for the build. More expensive parts, like the generator, must be bought from third parties. The production plan can be seen in figure B.2.

Figure 12.2: Production plan design option 1

As manufacturability is an important factor in the production of a system, it is evaluated for each design.

The solar panels and -platform for design 1 can be bought externally, causing only the hydrogen to be a self-made part. Furthermore, this means that only the super-pressure balloon, zero-pressure balloon and the cable control system need to be build. As these sub-systems are known sub-systems, it is assumed to be easily manufacturable.

For design 2 the propeller, cable and dynamo can be bought. Furthermore, the glider needs to be build as it will not be an off-the-shelf glider. Thus, all parts and sub-systems required need to be made. Making design 2 harder to manufacture than design 1.

For the last design, the turbine, generator and cable can be bought. Furthermore, the pylon and wing need to be build as they will not be off-the-shelf systems. Thus, all parts and sub-systems required need to be made. As there are multiple systems in design 3 that need to be build, it makes design 3 harder to manufacture than design 2.

12.5. Trade-off table and sensitivity analysis

The concepts will be traded off on their structural feasibility, based on the text of this chapter. The result of this is shown in table 12.1. All weights are changed to one higher and one lower to reveal their effects on the final score. Design option 3 is so far away from the other designs that it never gets close in the sensitivity analysis. It can safely be stated that structurally it is the worst design. Design option 1 comes closer to design option 2 if manufacturability is rated of more importance and materials of lower importance. It never gets closer than 0.5 points however, making it safe to say there is a big enough margin to conclude that design option 2 is the best.

Table 12.1: Structural trade-off table

Concept	**Structural feasibility, 3**	**Manufact., 2**	**Materials availability, 4**	**Total**
Design 1	4	4	2	3.1
Design 2	4	3	4	3.8
Design 3	1	2	1	1.2

13
Technical risk assessment

This chapter deals with the identification, assessment, and mitigation of technical risks. This is both important in the selection of the optimal design, as for the general well-being of the project.

Risks are assessed using two values: the likelihood of the risk and the impact it could have. Both are measured on a four-point scale. Likelihood ranges from remote (1), improbable (2), and possible (3) to probable (4). Impact ranges from acceptable (1), tolerable (2), and critical (3) to catastrophic (4).

Highly problematic risks – those with a score of seven or above, so (3, 4), (4,3), or (4, 4) – are mitigated in section 13.2. This results in an updated likelihood-impact matrix.

The risks specific to a certain design option will be analysed in section 13.3. Here, it will be determined how these designs will be assessed in the trade-off performed in chapter 16.

13.1. Identification and assessment of technical risks

This section identifies technical risks across five main categories. Every risk is given an identifying code, relating to its type and whether it is applicable for all design options (GEN) or a specific design (DES1, DES2, or DES3). The risks associated with a project are inexhaustible, but all main sources of risk should be accounted for here. All identified risks are displayed in a likelihood-impact matrix in table 13.1.

13.1.1. Design risks

- DR-GEN-01 Mission target is revealed to be infeasible (2, 4): It is possible that the results of this project show that the mission requirements cannot be met.
- DR-GEN-02 Final analysis of weight reveals a design flaw (2, 3): The weight estimations used in early stages could result in infeasible weights at a later stage.
- DR-GEN-03 Final analysis of cost reveals a design flaw (3, 4): Early cost estimations might be incomplete when re-evaluated at a later stage.
- DR-GEN-05 Inaccurate ground station estimations (3, 3): A robust ground station is required for a successful mission.
- DR-GEN-06 Connection to grid is infeasible (2, 4): This affects what power outputs are possible.
- DR-GEN-07 Inaccurate meteorological modeling (2, 2): Operational altitudes might need revision later.
- DR-GEN-08 Unreliable design methods (3, 4): Airborne energy-harvesting is still at an early stage.
- DR-GEN-09 Schedule risk (3, 2): There are many opportunities for deadlines to be missed.
- DR-GEN-10 Reliance on low-TRL technologies (4, 2): The feasibility of the project greatly depends on the development of novel technologies.
- DR-GEN-11 Insufficient literature on novel technologies (4, 3): The technologies required might not be broadly investigated yet.
- DR-DES1-01 Incorrect balloon sizing (2, 2): Would influence the operations.
- DR-DES1-02 Incorrect power estimation of solar panels (3,2): Could impact the required scale of the mission.
- DR-DES1-03 Incorrect weight estimation of solar panels (3, 2): Could snowball the weight of the system.
- DR-DES1-04 Insufficient literature wireless energy transfer(4, 3): Impacts the feasibility of this option.
- DR-DES2-01 Incorrect glider sizing (1, 2): Gliders are familiar terrain.
- DR-DES2-02 Incorrect tether assumptions (3, 2): The required length of the tether is a highly conceptual element. The assumptions made associated with its design are therefore unreliable.
- DR-DES2-03 Incorrect estimation of glider power (3, 3): Power estimates of AWES vary greatly and might be unreliable.
- DR-DES2-04 Insufficient literature on high-altitude AWES (3, 3): AWES – especially high-altitude AWES – have only been studied up to a certain level.

- DR-DES3-01 Incorrect wing sizing (1, 2): See DR-DES1-01.
- DR-DES3-02 Incorrect tether assumptions (3, 2): See DR-DES2-02.
- DR-DES3-03 Incorrect turbine sizing (2, 2): This influences the weight, power, and system layout.
- DR-DES3-04 Incorrect estimation of turbine power (2, 3): See DR-DES2-03.
- DR-DES3-05 Insufficient literature on high-altitude AWES (3 2): See DR-DES2-04.

13.1.2. Manufacturing risks

- MR-GEN-01 Materials unavailable (3, 1): Would result in manufacturing delays.
- MR-GEN-02 Materials unacceptable (2, 2): The structural requirements of the material might be incompatible with safety requirements or sustainability requirements.
- MR-GEN-03 Material costs (3, 1): Novel materials could heavily influence mission costs.
- MR-GEN-04 Production costs (3, 1): Novel production methods likely require new machines.
- MR-GEN-05 Production schedule (3, 1): Assembly and implementation would need to be pushed back.
- MR-GEN-06 Production impossible (2, 2): Production methods required might not yet be developed.
- MR-GEN-07 Assembly costs (2, 1): Intricate assembly would drive up costs.
- MR-GEN-08 Assembly schedule (3, 1): Implementation would need to be pushed back.
- MR-GEN-09 Assembly impossible (2, 2): Assembly methods required might not yet be developed.
- MR-GEN-10 Inspection errors (2, 4): A significant fault being missed during inspection could result in a dangerous situation.
- MR-GEN-11 Storage unavailable (1, 2): Sufficient storage space could be scarce.

13.1.3. Operations risks

- OR-GEN-01 Loss of communication (3, 3): Operations heavily rely on constant communication.
- OR-GEN-02 Structural degradation (environment) (4, 2): The environment will be a driving factor in the structures of the system.
- OR-GEN-03 Structural degradation (fatigue) (4, 2): Fatigue is likely to play a vital role in maintenance.
- OR-GEN-04 Malfunction due to weather (3, 2): Airborne systems must withstand a variety of weather conditions over time.
- OR-GEN-05 Short circuit (2, 2): Possible damage to electronics should be accounted for.
- OR-GEN-06 Sensor failure (3, 3): Operations such as the autopilot could fail.
- OR-GEN-07 In-flight battery degradation (4, 1): Could create toxic effects and dangerous situations.
- OR-GEN-08 Bird-strike/other object (3, 3): The structures and flight performance of the system must not be compromised.
- OR-GEN-09 Power transfer failure (2, 3): Requires precautions, also regarding the connection to the grid.
- OR-GEN-10 Parts inaccessible for maintenance (3, 3): Life-cycle goals could become compromised.
- OR-GEN-11 Extended downtime for maintenance (3, 1): This would reduce overall efficiency.
- OR-GEN-12 Spare parts unavailable (3, 1): Novel technologies result in scarce off-the-shelf options.
- OR-GEN-13 Termination of funding (2, 4): Would likely require the project to be terminated.
- OR-DES1-01 Balloon structural failure (3, 4): Especially a large concern regarding safety.
- OR-DES1-02 Solar panel degradation (4,2): Could heavily impact the power output of the system.
- OR-DES1-03 Loss of GPS connection (1, 3): Could result in the system leaving its assigned airspace or causing a dangerous situation.
- OR-DES1-04 System hijacked (1, 4): This would result in an enormous safety problem.
- OR-DES2-01 Cable structural failure (2, 4): See OR-DES1-01.
- OR-DES2-02 System tampered with (1, 4): An amount of ground-level security will be required.
- OR-DES2-03 Glider structural failure (1, 4): See OR-DES1-01.
- OR-DES3-01 Cable structural failure (2, 4): See OR-DES1-01.
- OR-DES3-02 Wing structural failure (3, 4): See OR-DES1-01.
- OR-DES3-03 System tampered with (1, 4): See OR-DES2-02.
- OR-DES3-04 Structural turbine failure (1, 4): See OR-DES1-01.

13.1.4. End-of-life risks

- EOLR-GEN-01 Impossible disposal of non-recyclable materials (2, 2): Disposal must happen.
- EOLR-GEN-02 Separation of materials impossible due to integration (3, 2): Intricate manufacturing and assembly complicates disassembly.
- EOLR-GEN-03 Spillage of toxic materials during separation of materials (1, 3): A risk likely inherent to the process.
- EOLR-GEN-04 Loss of recycling documentation (1, 2): The intended disposal method being lost would greatly impact environmental impact of disposal.
- EOLR-GEN-05 Unexpected end-of-life (3, 2): A lower lifespan or unexpected loss of equipment would impact costs, disposal opportunities, and operation.
- EOLR-GEN-06 Degraded recyclable materials (3, 2): Recyclability and reusability might degrade with time.
- EOLR-GEN-07 Recycling facilities no longer available (1, 2): As standards change, certain materials might not be accepted anymore.
- EOLR-GEN-08 Reusing worn out materials (2, 4): Reusability might not be appropriate.
- EOLR-DES1-01 Hydrogen fire hazard (3, 4): In the decommissioning of the system it is important to safely remove hydrogen.
- EOLR-DES1-02 Connected batteries during separation (1, 3): Could affect recyclability and reusability.
- EOLR-DES1-03 Hydrogen leakage (3, 3): See EOLR-DES1-01.
- EOLR-DES2-01 Magnetic disturbance (1, 2): Magnets of the generator could affect other equipment.
- EOLR-DES3-01 Hydrogen fire hazard (3, 4): See EOLR-DES1-01.
- EOLR-DES3-02 Connected batteries during separation (1, 3): See EOLR-DES1-02.
- EOLR-DES3-03 Hydrogen leakage (3, 3): See EOLR-DES1-03.
- EOLR-DES3-04 Magnetic disturbance (1, 2): See EOLR-DES2-01.

13.1.5. Sustainability and legal risks

- SLR-GEN-01 Unsustainable manufacturing increasing environmental footprint (EF) (2, 3): Requirement EHAC-SH-11-09, relating to the environmental footprint of the system (Arblaster et al. 2019), could become a killer requirement.
- SLR-GEN-02 Unsustainable operations increasing the EF (2, 3): See SLR-GEN-01.
- SLR-GEN-03 Unsustainable EOL increasing the EF (1, 3): See SLR-GEN-01.
- SLR-GEN-04 Habitat disturbance (3, 3): Requirements EHAC-SH-11-06, EHAC-SH-04-01, EHAC-SH-04-02, and EHAC-SH-04-03 (Arblaster et al. 2019) must be met.
- SLR-GEN-05 Habitat loss (2, 3): See SLR-GEN-04.
- SLR-GEN-06 Ecologically sensitive site (2, 4): See SLR-GEN-04.
- SLR-GEN-07 Resident disturbance (3,3): Requirements EHAC-SH-09-01, EHAC-SH-09-02, and EHAC-SH-09-03 (Arblaster et al. 2019) must be met.
- SLR-GEN-08 Airspace unavailability (4, 4): Airspace above the Netherlands is very restrictive, but a vital requirement for this project.
- SLR-GEN-09 Ground area unavailability (2, 4): Should there not be a suitable location for the ground station and area needed around it, the project would fail.
- SLR-GEN-10 Restrictive grid regulations (3, 3): The system might be limited to a large degree to what grid operators allow.
- SLR-GEN-11 Regulations changing disadvantageously (2, 3): These would require design changes.
- SLR-DES1-01 Health hazard due to wireless energy transfer (1, 4): This has not been studied in depth.
- SLR-DES1-02 Wildlife mortality due to balloon (2, 2): This demonstrably an issue (Schmehl 2018), but should be mitigated as much as possible.
- SLR-DES1-03 Restrictive balloon regulations (3, 4): See SLR-DES1-02.
- SLR-DES2-01 Wildlife mortality due to tether (4, 2): See SLR-DES1-02.
- SLR-DES2-02 Wildlife mortality due to glider (4, 2): See SLR-DES1-02.
- SLR-DES2-03 Restrictive UAV regulations (4, 4): This will hinder operations.
- SLR-DES2-04 Noise pollution (2, 2): Requirement EHAC-SH-09-02 (Arblaster et al. 2019) must be met.
- SLR-DES3-01 Wildlife mortality due to tether (4, 2): See SLR-DES2-01.

- SLR-DES3-02 Wildlife mortality due to wing (2, 2): See SLR-DES1-02.
- SLR-DES3-03 Restrictive balloon regulations (4, 4): See SLR-DES1-03.
- SLR-DES3-04 Noise pollution (1, 2): See SLR-DES2-04.

13.2. Risk mitigation

As can be seen in section 13.1, several risks have a combined score of seven or greater (e.g. possible and catastrophic). These pose too great of a threat to the project and must be mitigated. How this will be approached will be discussed in this section.

13.2.1. General risks

Four general risks are identified as too big of a threat and must therefore be mitigated: DR-GEN-03 Final analysis of cost reveals design flaw, DR-GEN-08 Unreliable design methods, DR-GEN-11 Insufficient literature on novel technologies, and SLR-GEN-08 Airspace unavailability.

DR-GEN-03 can be mitigated by negotiations regarding development costs. The project should have a return of investment of 10 years according to requirement EHAC-SH-11-04 (Arblaster et al. 2019), which is the reason for this risk. However, after negotiations with the client this requirement is flexible to 15 or even 20 years, therefore lowering the likelihood. Additionally, costs can be lowered by waiting with the development until another party develops the technologies needed. This way, development costs can be reduced, so the impact is lowered as well.

Unreliable design methods (DR-GEN-08) can be mitigated by using extensive verification and validation, especially by using various different design methods to verify the others. This way the likelihood of using unreliable design methods is lowered. In addition, the impact of the use of unreliable design methods will be lower, as the discrepancies will be less after comparison with other models.

DR-GEN-11 can be mitigated by the use of experts. Though the team may not be able to find the necessary literature, experts can point the team to the right direction. This way, the impact on the design of the project is lowered, as the team will not be stuck on literature study as long. Additionally, the likelihood of insufficient literature will be lowered, as experts will provide us with more literature.

Airspace unavailability (SLR-GEN-08) is a great threat to the execution project. However, the client has specified that this project is meant to be a technological feasibility study, rather than a legal feasibility study. This means that, although it is probable that airspace is restricted, the project can tolerate this. If the product were to be taken to the execution phase, extensive lobbying would have to be done to make the project work legally as well, which would be aided by promising energy yields.

The results of the mitigation discussed in this section are shown in the new likelihood-impact matrix in table 13.1.

13.2.2. Risks associated with design options

From table 13.1, it can be seen that more risks are identified that are mitigated. These risks are associated with specific design options (printed in italics). These specific design risks must be mitigated should the design be chosen as final design. As of now, these design specific risks can be used for the trade-off, as risk mitigation makes the system more complex. At this point, too little information on the designs is known to mitigate these design-specific risks, though all risks seem to be able to be mitigated during the in-depth design of the systems.

13.3. Trade-off table and sensitivity analysis

This trade-off is based on the design-specific risks per risk type. A score was given according to the sum of the likelihood and impact of the design-specific risks. The sums of the design risks were 21, 20, 22 for design 1, 2 and 3 respectively, which was determined to be too insignificant for the trade-off. Operational risks has been given twice as much weight, as the operations are the greatest part of the lifetime of the system and crucial for the effect of this project. The trade-off table is shown in table 13.2.

A sensitivity analysis could be performed on the ranges of numbers associated with the ranking from one to five. However, when considering the sums of the design risks for each risk type, design 1 has the lowest cumulative risk in all risk types, except for sustainability and legal risks. However, a large component of the high score in SLR is

Table 13.1: Post-mitigation technical risks shown in a likelihood-impact matrix

I / L	**Remote** (1)	**Improbable** (2)	**Possible** (3)	**Probable** (4)
Catastrophic (4)	*OR-DES1-04* *OR-DES2-02* *OR-DES2-03* *OR-DES3-03* *OR-DES3-04*	DR-GEN-01 DR-GEN-06 MR-GEN-10 OR-GEN-13 EOLR-GEN-08 SLR-GEN-06 SLR-GEN-09 *OR-DES2-01* *OR-DES3-01*	*OR-DES1-01* *OR-DES3-02* *EOLR-DES1-01* *EOLR-DES3-01* *SLR-DES1-03*	*SLR-DES2-03* *SLR-DES3-03*
Critical (3)	SLR-GEN-03 *EOLR-DES1-02* *EOLR-DES3-02*	DR-GEN-02 DR-GEN-03 DR-GEN-08 OR-GEN-09 SLR-GEN-01 SLR-GEN-02 SLR-GEN-05 SLR-GEN-11 *DR-DES3-04*	DR-GEN-04 DR-GEN-05 OR-GEN-01 OR-GEN-06 OR-GEN-08 OR-GEN-10 SLR-GEN-04 SLR-GEN-07 SLR-GEN-10 *DR-DES2-03* *DR-DES2-04* *EOLR-DES1-03* *EOLR-DES3-03*	*DR-DES1-04*
Tolerable (2)	MR-GEN-07	DR-GEN-07 MR-GEN-02 MR-GEN-06 MR-GEN-09 OR-GEN-05 EOLR-GEN-01 *DR-DES1-01* *DR-DES3-03* *SLR-DES1-02* *SLR-DES2-04*	DR-GEN-09 DR-GEN-11 OR-GEN-04 EOLR-GEN-02 EOLR-GEN-05 EOLR-GEN-06 *DR-DES1-02* *DR-DES1-03* *DR-DES2-02* *DR-DES3-02* *DR-DES3-05*	DR-GEN-10 OR-GEN-02 OR-GEN-03 SLR-GEN-08 *OR-DES1-02* *SLR-DES2-01* *SLR-DES2-02* *SLR-DES3-01*
Acceptable (1)		MR-GEN-11 EOLR-GEN-04 EOLR-GEN-07 *DR-DES2-01* *DR-DES3-01* *EOLR-DES2-01* *EOLR-DES3-04*	MR-GEN-01 MR-GEN-03 MR-GEN-04 MR-GEN-05 MR-GEN-08 OR-GEN-11 OR-GEN-12	OR-GEN-07

due to legal restrictions, which, as mentioned before, is not of driving importance. Therefore, raising its weight would not be realistic, and design option 2 would win with any realistic ranking range and weight combination.

Table 13.2: Technical risk assessment trade-off table

Risk trade-off	**OR, 2**	**EOLR, 1**	**SLR, 1**	**Total**
Design 1	2	4	4	3.0
Design 2	4	5	2	3.8
Design 3	2	3	2	2.3

14
Sustainable development strategy

This project is fundamentally concerned with sustainability. The high-altitude energy-harvesting system to be designed is driven by a need for energy from renewable sources. In what ways sustainability is significant to this project is discussed in section 14.1.

How sustainability is approached throughout this project is broadly split up into two factors. The first of these is the environmental footprint (EF) of the system, established through a life-cycle assessment (LCA), as explained in section 14.2. For the final design, a full Product Environmental Footprint[1] (PEF) study will be performed, which subsection 14.2.1 elaborates on. Subsection 14.2.2 explores how the EF of the system can be (qualitatively) assessed for the purpose of establishing it as a trade-off criterion.

The second aspect of sustainability which will be considered during this project is the direct impact the system has on its environment, regarding both non-human nature and human activity. The impact areas of the energy-harvesting system on society, nature, and wildlife is assessed in section 14.3.

Finally, sustainability shall be a significant trade-off criterion taken into consideration for the trade-off in chapter 16. This is evaluated in section 14.4, where values are assigned to each design option.

14.1. Significance of sustainability

The sustainability of any project is of great importance. How this project contributes to sustainability is addressed in subsection 14.1.1. How the project globally incorporates sustainability in its design is restated in subsection 14.1.2, as was established earlier in the *Baseline Report* (Arblaster et al. 2019).

14.1.1. Contribution to sustainability

The need to develop energy sources that do not depend on fossil fuels is becoming increasingly pressing. This is important for several reasons, not least of which is mitigating climate change by lowering greenhouse gas emissions. Other motivations relate to the desire to reduce pollution, but geopolitical reasons also play a role (European Commission 2011).

Renewable energies have a significant step-up compared to other energy sources, but still burden the environment to some degree. The system that this project aims to design is no different. If the requirements of this project – presented shortly, in subsection 14.1.2 – are met, the airborne energy-harvesting system would be demonstrably more sustainable than current energy-harvesting methods.

Assuming the system shall meet its requirements, the large-scale implementation of airborne energy-harvesting would have profound effects on the relation of humanity with its home planet. Although this project will not offer a method to obtain complete independence on non-renewable, finite sources, the environmental footprint of energy demands of humanity (or at least, those of TU Delft) would reduce drastically.

14.1.2. Sustainability requirements

The main stakeholder requirements of the project were established in the *Baseline Report* (Arblaster et al. 2019). Some of these requirements are repeated in table 14.1.

14.2. Environmental Life-cycle assessment

To evaluate requirement EHAC-SH-11-09, the environmental footprint of the system must be evaluated using an LCA approach. One way of evaluating this is by conducting a PEF study (European Commission 2013), which is

[1] `https://ec.europa.eu/environment/eussd/smgp/index.htm` [cited 3 December 2019]

Table 14.1: Selected stakeholder requirements which relate to sustainability (Arblaster et al. 2019)

Stakeholder	Identifier	Stakeholder requirement
Primary customer: TU Delft	EHAC-SH-11-01	The system shall be constructed using renewable materials only.
	EHAC-SH-11-02	The system shall harvest renewable energy.
	EHAC-SH-11-06	The system shall be safe for birds.
	EHAC-SH-11-07	The system shall be safe for humans.
	EHAC-SH-11-09	The system shall have a smaller environmental footprint than methods on the ground surface of comparable costs.
Environmental organisations	EHAC-SH-04-01	The system shall be sited <tbd> km away from migration paths of birds.
	EHAC-SH-04-02	The system shall meet the drop shadow regulations.
	EHAC-SH-04-03	The system shall not be placed in a Natura 2000 area.
	EHAC-SH-04-04	The system shall not produce any greenhouse gasses.
	EHAC-SH-04-05	The system shall not produce any harmful radiation.
	EHAC-SH-04-06	The system shall not produce any toxic byproducts.
Residents	EHAC-SH-09-01	The system shall meet the light pollution regulations.
	EHAC-SH-09-02	The system shall meet the noise pollution regulations.
	EHAC-SH-09-03	The system shall meet the visual pollution regulations.

based heavily on ISO standards 14040[2] and 14044[3]. To what level of detail such a test will be performed is beyond the scope of this report, but the goal and scope of assessing the EF of the system has already been established, as can be found in subsection 14.2.1.

How LCA will play a role in this report – so that it may be applied during the trade-off of chapter 16 – is globally established in subsection 14.2.2 and later applied in subsection 14.4.1.

14.2.1. Overview of Product Environmental Footprint study

In the *Baseline Report*, a PEF study was initiated by formulating the goals and scope of the study (Arblaster et al. 2019). These goals are:

1. To create a fair comparison between the system and ground-based energy farms.
2. To gain insight into environmental footprinting and reveal potential areas of improvement.
3. To inform the customer so they may also gauge the environmental impact of the energy-harvesting system relative to others.

The scope of the PEF study was defined to include the full life-cycle of the system, cradle to grave. This means the LCA will consider inputs from the moment the raw materials are extracted to the moment the system is disposed/recycled/reused.

To further define the scope, relevant EF impact categories were defined. These EF impact categories range from models relating to global warming, toxicity, health, scarcity, etcetera. None of the 14 default EF impact categories have been discarded, as each is bound to be affected by the life-cycle of the system to come extent. However, it is anticipated that some categories will be impacted to such a marginal degree that only the most relevant ones will be analysed in depth.

The third phase in a PEF study consists of creating a profile inventorying resource use and emissions (European Commission 2013). This phase will not be completed to any considerable degree during this report, but it will be partially investigated to assess the design options for the purpose of a trade-off. This approached is defined in subsection 14.2.2.

[2]`https://www.iso.org/standard/38498.html` [cited 4 December 2019]
[3]`https://www.iso.org/standard/37456.html` [cited 4 December 2019]

14.2.2. Major factors which influence resource use and emissions

To conduct a full PEF study, specialised LCA tools are often consulted (European Commission 2013; ApS 2011). This will inevitably also be the case for an airborne energy-harvesting system (Schmehl 2018, p. 730). However, these tools will not be used during this phase of the project. Still, some methods must be established to analyse the EF of each design option.

The life-cycle of the energy-harvesting system can be divided into five phases: raw material acquisition and pre-processing, production, product distribution and storage, usage, and end-of-life. Literature suggests that the largest part of the EF of an airborne energy-harvesting system originates from its lifetime up to and including its assembly (Schmehl 2018, p. 741). This means that the EF of the designs can largely be assessed by investigating the materials required for their production. For this purpose, the materials investigated in chapter 12 will be taken into consideration.

Based on (Schmehl 2018, p. 741), the second largest contributor to EF consists of parts which need replacing. However, what the life-cycle of individual parts is will not be investigated at this time.

14.3. Impact on society, nature, and wildlife

This section defines how the direct impact of the system on its surroundings will be assessed. This assessment includes its impact on non-human nature; subsection 14.3.1 explores how this will be quantified. In this report, a focus will be put on flying animals – birds, in particular. The impact the system has on humans will also be assessed. This will be limited to noise pollution and visual pollution, as explained in subsection 14.3.2. For these purposes, the impact of a single unit (with ground station, when mentioned) of each design will be assessed, with no regard for the total amount of units required.

14.3.1. Ecological impact

The ecological impact of wind farms is a broadly-studied subject (European Commission 2011; Backes et al. 2018). This means that a good reference is present to compare airborne energy-harvesting systems to. Each design concept will be evaluated in its ecological impact, using wind farms as reference case.

Ecological impact is a broad subject. For the purpose of this report, the biodiversity of local wildlife will be considered as main area of interest. The types of impact that may occur are (Backes et al. 2018):

- **Collision risk:** Birds and bats may collide with some part of the airborne system. Evidence suggests this is heavily linked to how the system is sited with respect to areas important to wildlife.
- **Disturbance and displacement:** Local species are typically displaced by two effects, the first being the human activity related to the construction and operation of the system, while the other is caused by visual, noise, and vibration impacts characteristic to the system.
- **Barrier effect:** Energy farms made up of many systems placed closely together can force birds or mammals to change direction, which becomes a problem during migrations, but also during regular foraging activities.
- **Habitat loss or degradation:** This impact is greatly dependent on the value of a habitat, which is based on how easily it can be replaced – a factor of things such as how rare the habitat is and what role it plays for different species.

The goal of this report is to perform a fair trade-off between the main design options. For this reason, only impact types which can be shown to differ between designs will be discussed at this stage. On the subject of collision risk, the most significant such difference is the airborne presence of the system (e.g. the flying balloon and platform for design option 1, or the tether and glider for design option 2). This is also the case for disturbance and displacement, although the receiving antenna of design option 1 cannot be ignored in this. Barrier effect and habitat loss or degradation are highly dependent on the particular siting of the system, which goes beyond the scope of this report. Mortality and disturbance for each design option are assessed in subsection 14.4.2.

The amount of annual collision mortality for an airborne wind energy system is approximated in (Schmehl 2018, p. 679), based on the Ampyx Power glider – a system fairly similar to the approach this report takes to design option 2. It is estimated that a one-kilometer tether causes an average of 10.95 bird casualties per year. Bat collisions are assumed to be negligibly low. If the system is located in an area of particularly low or high bird activity, this number can be decreased or increased by factor 10, respectively. The tethered aircraft is expected to cause 2–13 bird casualties per year, with one of the variables being its velocity. However, it must be noted that this is based on the comparatively low altitude the Ampyx Power glider flies at (under 500 m, compared to the several kilometer altitude this project aims for). Since collisions above 500 m are relatively rare (Schmehl 2018, p. 689), it will be assumed that the energy-harvesting system operating at several kilometers altitude will result in negligible casualties compared to the tether itself. Conventional wind farms are reported as having a median value of seven fatalities per year (Schmehl 2018, p. 687).

The effect the different design options have on disturbance and displacement are likely most heavily influenced by noise and visual impacts. It is suspected that these effects are relatively small, as – in the case of the glider of an AWES – the system makes a simple, repetitive pattern which local animals could get used to in due time; both effects were classified as “moderate small” (Schmehl 2018, p. 692). An interesting dilemma appears: increasing the visibility of the tether would decrease casualties, but also increase disturbance. Which of these effects is more undesirable has not been established. Although drop shadow would also influence disturbance, it is currently expected that none of the design options will cause a drop shadow of any significance, due to their extreme operational altitude.

14.3.2. Societal impact

Residents living nearby the energy-harvesting system are protected by requirements EHAC-SH-09-01, EHAC-SH-09-02, and EHAC-SH-09-03, which relate to light pollution, noise pollution, and visual pollution. Returning again to using wind turbines as a stand-in for airborne energy harvesting, it’s clear that the associated noise pollution and visual pollution of land-based wind farm is a source of frustration for the local community (Jensen et al. 2014; European Commission 2011).

The most common complaint regarding wind farms is their noise. There is a rich body of work analysing what makes sounds annoying to human perception, with the development of many sound quality metrics[4]. However, the current state of the designs does not allow for this level of analysis. Therefore, noise will be assessed in the same way as was established for wildlife in subsection 14.3.1.

The visual pollution associated with wind farms heavily depends on their siting, as they are experienced as making a landscape less rural and less scenic (Jensen et al. 2014; European Commission 2011). This effect is strengthened by their movement, something this report will also take into consideration.

14.4. Trade-off table and sensitivity analysis

The sustainability of the different design options shall play a role during the trade-off of chapter 16. For this purpose, this section establishes what values the different design options will be assigned during the trade-off.

Each of the three categories (EF, ecological impact, and societal impact) is given its own weight, which is chosen to be five, three, and two, respectively. Since LCA takes a fairly holistic view of sustainability, the EF of the project is considered to be the most important factor. Ecological impact is weighted higher than social impact as it is considered to relate more directly to the safety and well-being of local life.

However, to establish the value of each category, it is split up into a few subcategories. Each of these subcategories is again given their own weight, with the subcategory weights adding up to 10, as to not interfere with the weighting of the categories. How this is done for each category is explained in the subsection of the relevant category.

14.4.1. Environmental footprint as criterion

As mentioned in subsection 14.2.2, it is too early in the design process to perform an in-depth LCA. Therefore, the EF of the designs will be roughly estimated by the amount of material needed to construct sufficient units to meet the energy demand. This will be done on the general five-point scale used for this report, ranging from unfavorable (1) to great (5).

The EF of design option 1 is without a doubt very unfavorable (1). Not only will construction of the receiving antenna require more material (by weight) than either of the other designs to meet the energy demand, but the end-of-life of such a massive construction is not promising either. Additionally, solar panels are commonly assessed as having a larger EF than wind turbines, by energy output. This difference is roughly a factor of five (World Energy

[4] `https://www.salford.ac.uk/research/sirc/research-groups/acoustics/psychoacoustics/sound-quality-making-products-sound-b` `accordion/sound-quality-testing/sound-quality-metrics` [cited 6 December 2019]

Council 2004) – largely attributed to the amount of rare materials required in constructing solar panels, as well as the complications this bring to their end-of-life.

In examining the life-cycle of airborne wind energy, it was established that the most impactful elements to the environmental footprint of the system were the ground station and electrical cabling required (Schmehl 2018, p. 741). Electrical cabling for design option 2 simply means connecting its ground station to the grid and providing the glider with the internal wiring it requires to fly. For design option 3, however, this includes several kilometers of copper cabling for each unit, as it needs to transfer electricity to the ground. The impact this amount of copper has on the overall EF of the design will undoubtedly be considerable. Therefore, while the EF of design option 2 can be expected to be great (5), design option 3 is expected to be no better than satisfactory (3).

14.4.2. Ecological impact as criterion

As discussed in subsection 14.3.1, ecological impact will be based on collision risk as well as disturbance and displacement. Both subcategories are given equal importance, meaning both have a weight of five.

For collision risk, a value from a five-point scale will be assigned based on the expected number of yearly casualties of the design, relative to the median seven yearly casualties of contemporary wind farms. The resulting scale is: 2 or less yearly casualties (5), 3-5 yearly casualties (4), 6-8 yearly casualties (3), 9-11 yearly casualties (2), and 12 or more yearly casualties (1). Note that this only takes the airborne system into account; in actuality, the amount of casualties will also immensely depend on the siting of the system.

Disturbance and displacement will also be evaluated on a five-point scale. Here, the scale ranges from negligible impact (5), to marginal impact (4), small impact (3), moderate impact (2), and large impact (1).

It was stated in subsection 14.3.1 that most casualties of any of the systems will be caused by birds colliding with its tether, at roughly 11 casualties per year for a tether of 1 km. Design option 1 does not have a tether. Additionally, as these balloons are clearly visible and moving at relatively slow speeds, it can be predicted that collisions will be very rare. Design option 2, being very similar to the subject of the study in (Schmehl 2018, p. 679), can be assumed to cause a similar amount of casualties with its tether. As mentioned, as most activity takes place under 500 m, the glider itself will not be taken into account, nor will the length of tether above the initial kilometer. This brings annual casualties of this design to 11 birds per year. Finally, design option 3 is also tethered, but its tether has several advantages in terms of collision risk: it is thicker, while also relatively stationary; both factors add to birds' ability to avoid it. It is hard to judge the exact effect of these factors, but it will be assumed that design option 3 claims roughly eight casualties per year, placing it between design option 2 and traditional wind turbines

The main factors influencing disturbance and displacement are noise and visual disturbances, as mentioned in subsection 14.3.1. Solely assessing the airborne parts of each design, design option 1 – the floating balloon with attached solar panel – is expected to create barely any disturbance, due to its relatively slow movement and lack of tether. However, the receiving antenna of design option 1 – with a diameter of a few hundred meters – cannot be built and operate without causing heavy disturbance, giving the design as a whole a large impact. Design options 2 and 3 will create similar impacts to each other, due to their relative similar configuration. Both should create little noise and visual disturbance (Schmehl 2018, p. 693), but it is expected that the tethered glider will be slightly more disturbing, as it makes larger movements and its tether – the element closest to the ground – also contributes to these effects. This results in design option 2 receiving the same impact classification of 'small' that the Ampyx Power glider received. Since design option 3 is expected to be less disturbing, its impact is classified as marginal.

14.4.3. Societal impact as criterion

To indicate what effect the different design options have on the local human population, their visual and auditory impact are assessed. At this time, none of the design options are anticipated to produce a significant amount of light, so this is not taken into account for the purpose of this trade-off.

As was mentioned in subsection 14.3.2, noise contributes more heavily to annoyance than visual pollution does. Both factors will be evaluated on the same five-point scale as used for disturbance in subsection 14.4.2, but will each be given a different weight: noise a weight of six; visual pollution a weight of four.

Noise was already assessed for ecological reasons in subsection 14.4.2. The same reasoning found there still applies. Therefore, the same classifications will be used: design option 1 creates negligible noise, design option 2 a small amount of noise, and design option 3 a marginal amount of noise.

The visual pollution of each design option can also be related to the visual disturbance, as discussed in subsection 14.4.2, but changing the made assumptions will likely prove useful. In subsection 14.4.2, the movement of design option 2 was considered as being more impactful than the thicker cable of design option 3. Because it is unclear to what degree the moving element of the tether compensates for its relative thinness, both tethers are assumed as having a small impact. The enormous receiving antenna required for design option 1 is once again assumed as having a large visual impact.

14.4.4. Trade-off table

The weights and values established earlier in this section are summarised in table 14.2. The score of each design option is shown per sub-category and in total. The total score of each design is normalised to a score on a five-point scale, based on the maximum score that could have been obtained of 500. These results, in the rightmost row of the table, will be used in the trade-off found in chapter 16.

Table 14.2: Sustainability trade-off table

Category, weight	**EF, 5**	**Ecological, 3**		**Societal, 2**		**Total score**
Sub-category, weight	**Production, 10**	**Collision, 5**	**Disturbance, 5**	**Noise, 6**	**Visual, 4**	
Design 1	1	5	1	5	1	**2.1**
Design 2	5	2	3	3	3	**3.9**
Design 3	3	3	4	4	3	**3.3**

14.4.5. Sensitivity analysis

As is the case for any trade-off, it is useful to perform a sensitivity analysis for the trade-off shown in table 14.2. This table shows design option 2 to be the most sustainable.

Should the direct impact of the system on its local environment be weighted much higher, design option 3 would come out on top. However, to meet the energy requirements, design option 3 needs about three times the amount of units compared to design 2, which decreases the significance of this advantage – the amount of collision casualties of the entire system could reasonably be higher for design option 3 compared to design option 2, something the trade-off table does not reflect.

Another way design option 3 might come out higher relates to its EF. Should a renewable material become available which can conduct electricity with similar characteristics to copper, the EF of design option 3 could be improved considerably. Even then, however, it is not expected to surpass design option 2 even under these conditions, as this design does not require a conductive cable at all.

Some attention should also be paid to design option 1. The irony of this design is that its method of energy transfer – microwave transmission – is both the cause for it to perform well in some areas (collision risk, noise), but terribly in others (disturbance, visual pollution). It does not seem that this characteristic of wireless energy transfer can be significantly mitigated.

On the other hand, should this design be given a conductive cable after all, the assessment of its sustainability could be somewhat improved. However, the improvements to disturbance and visual pollution are limited and not sufficient for it to become preferable over either other option.

15 Design & development logic

In this chapter, the project design & development logic for the post-DSE period is described. This comprises the steps which need to be taken to bring the product to the market. It gives a good indication of the specialisms and resources needed for the follow-up steps. The project design & development logic is given in figure 15.1.

Once the DSE has been completed, a lot still has to happen to develop and market the design. First of all, the design needs to be made into a testable prototype, which will be used to test the system. During this testing, verification and validation will be important. It is reasonable to say that a few iteration loops will be needed during this period.

While the testing and iteration process is running, the financial department should start to find resources for funding. Starting up the production can only be done when the funds are fully raised. When the design is finished, it needs to be certified by a variety of instances, regarding the airworthiness of the design, its potential impact on its surroundings, and its connection to the grid. In the meantime, a definite site needs to be located which can appropriately host the system. This could be somewhere in the sea, above TU Delft, or elsewhere in the Netherlands. As investigated in section 10.3, a coastal location with access to the high-voltage grid is desirable, while not being too close to an airport – a fairly rare combination in the Netherlands.

Once certification is complete, insurance companies can be contacted to provide insurance in case something goes wrong with the system. Marketing to clients other than the initial client, TU Delft, can also get off the ground in this phase. Finally, the logistics will be planned and the end product produced. Together with the completion of funding, this will result in the market entry of the system.

For a trade-off one can look at which design option fits the D&D logic best. The development of a prototype, results from DSE, testing prototype, V&V, design iterations, location and client contact are the same for all designs. Production is already discussed in manufacturability. Funding and certification remain open.

For funding it is difficult to make an informed decision on which design option will be best. All of them are in the airborne sustainable energy market, a branch which is likely to get funded for the solutions it can provide to global environmental problems. For certification they all go beyond current regulations, making it difficult to estimate which ones are most likely to be certified. Therefore D&D logic will not enter the trade-off, as no differences can be drawn from it.

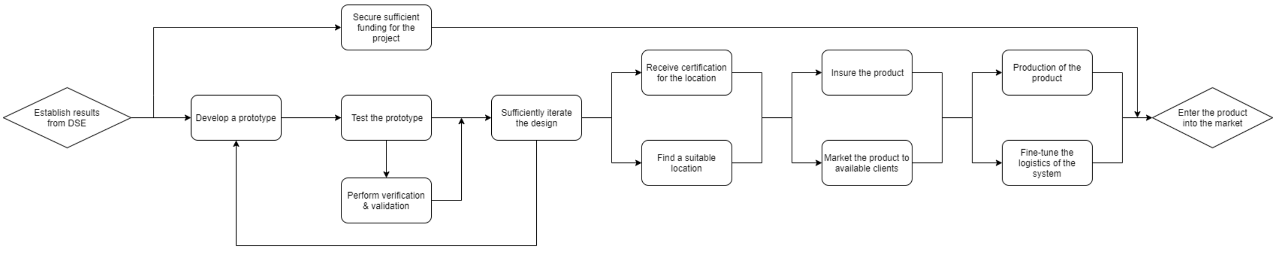


Figure 15.1: Project design & development logic

16
System trade-off

In this chapter the final system trade-off will be performed. First, in section 16.1 the weights of trade-off categories will be explained, following the trade-off table itself in 16.2. Finally, a sensitivity analysis is performed in section 16.3.

16.1. Weight factors

To perform a proper trade-off, weights have been assigned to the different criteria, which add up to 100. The biggest part of success of the project is based on the amount of energy the system can generate. Therefore, the performance on energy is granted a score of 30%. Since an important requirement of the client is to be sustainable, the sustainability is granted a weight of 20%. As the availability and safety of the designs are utter important, operations (Ops) is also granted a score of 20%. As risk involves all aspects during the life-time of a system, it is granted a score of 15%. The main function of the system is the energy delivery, it is not designed for optimum flight performance. However, the system does need to be able to fly, thus flight performance is granted a score of 5%. The amount of material depends on the size and strength of your structure and it affects the sustainability, therefore structures and material is granted a score of 10%.

16.2. Trade summary table

Table 16.1 gives the scores given in all the previous chapters of the report, and adds a weight factor to that as described in 16.1. Columns are scaled to this weight factor to give a visual overview of the trade-off.

Table 16.1: Trade summary table

Concept	FP, 5	Ops, 20	Energy, 30	S&M, 10	Risk, 15	Sustainability, 20	Total
Design 1	3.0	2.6	3.1	2.1	3.0	2.1	2.7
Design 2	3.8	3.6	3.5	2.6	3.8	3.9	3.6
Design 3	2.3	3.1	2.9	2.1	1.2	3.3	2.7

16.3. Sensitivity Analysis

For the sensitivity analysis only the weights can be evaluated, since the grades were previously analysed in the respective chapters. As can be seen in table 16.1, design 2 scores the highest grade for each trade-off criteria. For this reason, changing the weight factors will not affect the outcome of the trade-off and thus design 2 will always be the best option.

17

Alternative designs

In section 17.1 the possibility for a tethered solar balloon is discussed. The tethered flying turbine is elaborated on in section 17.2. Finally, a stationary flying turbine is considered in section 17.3.

17.1. Tethered solar balloon

A good alternative to the free floating solar balloon would be a tethered solar balloon. An advantage of being attached to the ground is that it is easier to keep the balloon within a certain area. Also, a very large receiving antenna, of for example 10,000 m^2, does not have to be built.

Limiting the power output per area on ground to 0.71 W/m^2 or higher, the tethered balloon would have merely four possible combinations of volume and number of balloons. The most feasible one would be using two balloons of 411,059 m^3 at 2 km altitude. This is disproportionately large since it would put the solar panels in the shade. Furthermore, using two balloons, one would have a solar panel area of 26,833 m^2 and a mass per balloon of approximately 300,000 kg. In terms of structure, it would be infeasible to hold the bending load of this platform. Therefore, it can be concluded that this design option is infeasible.

17.2. Tethered flying turbine

From the determined trade-off in chapter 16, it was interesting to look at a combination of the flying glider and the turbine. Instead of the "lift-mode" with energy generated via a generator on the ground, it generates electricity in the air using "drag-mode" (Schmehl et al. 2013). This has been done before by the company Makani, although at a much lower altitude. The assumptions in sub-section 9.1.2 are used with additional assumptions: lift equals the weight of glider and cable, there are 8 turbines with a volume of 2.84 m^2 each [1], a power coefficient C_p of 0.35 to 0.45 (with the Betz' limit on 0.59)[2], voltage drop over the cable of 20%, power generator efficiency of 80%, and aluminium as cable material (due to its higher specific conductivity than copper, even though it has its own drawbacks like oxidation) (further research is required). Using the equations from the previously mentioned sub-section, a crosswind flying tethered turbine could be sized. Additionally, equation 17.1 and 17.2 are used, respectively for calculating the power of the system and the (electrical) cable diameter.

$$P_{out} = C_p \cdot P_{in} = C_p \cdot \frac{1}{2}\rho \cdot A \cdot V^3 \qquad (17.1)$$

$$d_{cable} = 2\sqrt{\frac{I \cdot \rho_e \cdot l_{cable}}{(1-\eta) \cdot \pi \cdot U_{in}}} \qquad (17.2)$$

This resulted in a maximum kite speed of 20 m/s in the following possible design including the generator efficiency: power of 86.6 kW, altitude of 2 km, OEW of 3,923 N, wing area of 15 m^2 and C_L of 1.29, 112 units for a design power of 10 MW, and distance between units of 809 m, resulting in a power per area in the air of 3.8 kw/m^2 and a power per area on the ground of 0.13 W/m. This is much lower than for gliders in lift mode, therefore this design above 2 km is discontinued.

17.3. Stationary flying turbine

The stationary flying turbine is hovering above the ground, its weight can be reduced by using aluminium instead of copper, as in section 17.2, results in better characteristics than those calculated in subsection 9.3.3. The total surface area needed becomes 140,000 m^2, and the total cable mass is 500,000 kg. The number of devices needed would increase by 25%, as an other turbine has to be selected. These new characteristics still can not compete with design option 2, thus the new stationary flying turbine is discarded.

[1] `https://makanipower.com/technology/` [cited 11 December 2019]
[2] `https://www.raeng.org.uk/publications/other/23-wind-turbine` [cited 11 December 2019]

18 Verification & validation procedures

In this chapter, the verification and validation procedures for the final design are presented in section 18.1 and section 18.2 respectively. This is done to determine if the model accurately represents the physical problem as well as the results of the physical problem, respectively. An acceptable error for both the analytical and the numerical model is established and the tools and sources for the verification procedure are given.

18.1. Verification

Verification is the process of checking whether something is well-engineered and error-free (to some extent). The design process for the rest of the DSE involves verifying all the design aspects of the final concept. These aspects were the trade-off parameters in chapter 16 and can be summarised as; structures, energy, flight performance, operations, sustainability and RAMS. The first four are technical aspects that have a conventional development process. An analytical model would be made, followed by a numerical model. From those models, a final (virtual) prototype can be made.

There are two main purposes for the analytical model; to verify the numerical model, and to provide input parameters for the numerical model. To be able to accomplish this, the analytical model must be verified independently. Most analytical models are derived from formulas from existing research and theorems. These sources tend to also indicate relevant assumptions, which may be implemented in the analytical model, and can cause an error in the calculated result when compared to real life. It is for this reason, that the analytical model must be verified using external test data. This can come from scientific reports and/or testing done locally. The acceptable margin of error for the analytical model was chosen to be 10%, which was chosen for multiple reasons. In most scientific research, 90-99% are the acceptable error margins. A project like this has very few scientific research papers that provide the experimental data for comparison, and even fewer are available to the public. Hence, the lower end of the error margin bracket was taken. Furthermore, the power needed for TU Delft is in the order of magnitude of 10^6, so discrepancies in the order of 10^4 would be acceptable. Finally, it is a thousand times less precise than the acceptable error of the numerical model.

The numerical model is the crux of the project and determines the outcome for the customer, this must be verified very carefully. After setting up the numerical model, the numerical model would use the boundary conditions and input parameters defined by the analytical model to keep the calculation method consistent. Upon finishing the numerical model calculations, the values can be verified using the analytical model. If the errors of the numerical model are within the acceptable region, the numerical model can then create run simulations for the final concept. The residuals for the iterative convergence process should be in the order of magnitude of 10^{-5}, as it is considered a point of stable convergence and accuracy[1].

For verification of the flight performance, aerodynamic, mechanical and control analyses have to be performed as well as thermal and electrical ones. The latter two are also needed for the electricity generation, transfer and storage. Functional and operational analysis are required for the operations department. RAMS has its own analysis.

The design is divided in sub-systems, which are energy, flight performance, structures and operations. The sub-sub-systems are for example the energy transfer, control system, materials and maintenance. The sub-sub-sub-systems are, amongst others, the cable, ailerons, thermal properties and fatigue cycles. The sub-sub-sub-systems and sub-sub-systems will be verified by review and inspection, often by hand calculations to check the computed results, by consulting experts, and by comparing with literature. Analysis will be applied to sub-systems and the system as well as comparing it to existing test results from comparable projects.

Limitations apply to the verification. No tests with airborne wind energy have been performed above the clouds, which limits the applicability of specific literature. Financial and time constraints limit verification too, as few tests can be performed. The limitations in review, inspection and analysis should be covered by consulting experts as much as possible.

[1] `https://www.engineering.com/DesignSoftware/DesignSoftwareArticles/ArticleID/9296` [cited 11 December 2019]

For verification, test data, literature, and numerical tools are used. Kitepower performed tests at different altitudes with flying kites. The model could be verified by their test results. Some of which can be found at their website [2]. Besides, the data file of the NACA airfoil tool will be used.

Tools that will be used are CATIA with the 3DEXPERIENCE package to create a CAD file that is tested in ANSYS. For the tether, the material will be tested in the Aerospace Materials Lab and the foil characteristics of the glider can be modeled with XFLR5.

Boundary conditions will be retrieved from the analytical model and verified using literature. Then the programs are run again with different boundary conditions to check the consistency of the results. When the outcomes are unacceptably different, literature is used once more to verify the in- and outputs. When uncertainties remain, experts will be consulted.

18.2. Validation

To meet the mission need statement, providing the energetic demands of TU Delft using renewable energy harvested in a sustainable way above the clouds (Arblaster et al. 2019), requirements of the primary stakeholder have to be met. These requirements are listed below.

- EHAC-MIS-01: The system shall provide TU Delft with its yearly energy needs.
- EHAC-MIS-02: The system shall be located above the clouds.
- EHAC-MIS-03: The system shall be able to fly.
- EHAC-SH-11-01: The system shall be constructed using renewable materials only.
- EHAC-SH-11-02: The system shall harvest renewable energy.
- EHAC-SH-11-06: The system shall be safe for birds.
- EHAC-SH-11-07: The system shall be safe for humans.

The mission requirements can be validated by reviewing whether the design can provide at least 8.9 MW and fly at at least 2000 m altitude. As the terms 'renewable' and 'safe' are subjective to some extend, an inspection of the design should be discussed with the customer. All other requirements should be met as well, but are of less importance to validate the design.

[2] `https://kitepower.nl/resources/ch23_awe35_vandervlugt.pdf`

19
Project logic diagrams

This chapter expands on the project logic diagrams. First, section 19.1 discusses the workflow diagram. The work breakdown structure is discussed in section 19.2. Finally, the Gantt chart is discussed in section 19.3.

19.1. Workflow diagram

The workflow diagram (WFD) has been developed before, however, at that time there was less knowledge of what the project would include. With the final concept chosen, a more complete WFD could be produced. The most recent WFD can be found in appendix D. The WFD only includes the design phase and the symposium phase as the foregoing phases have already passed.

19.2. Work breakdown structure

As with the WFD, a work breakdown structure (WBS) has been produced before, which has now been expanded on. The WBS contains the tasks one level below the WFD. The WBS does not indicate any order besides the phases described at the top of the WBS. The coding of the work packages comes across with those of the WFD. The lower-level tasks included in the WBS are coded with letters instead of numbers, to make the lower-level tasks identifiable by the letter in its code. The most recent WBS can be found in appendix E.

19.3. Gantt chart

The workflow diagram and the work breakdown structure together lead to the Gantt chart. The Gantt chart shows when tasks are planned and how much time they should take. It also shows the links between different tasks using arrows between the tasks that require input from each other. Some tasks run parallel and have links; those tasks require close collaboration to make sure the content is updated regularly. The Gantt chart is shown in appendix F.

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A
Logistics flow diagram

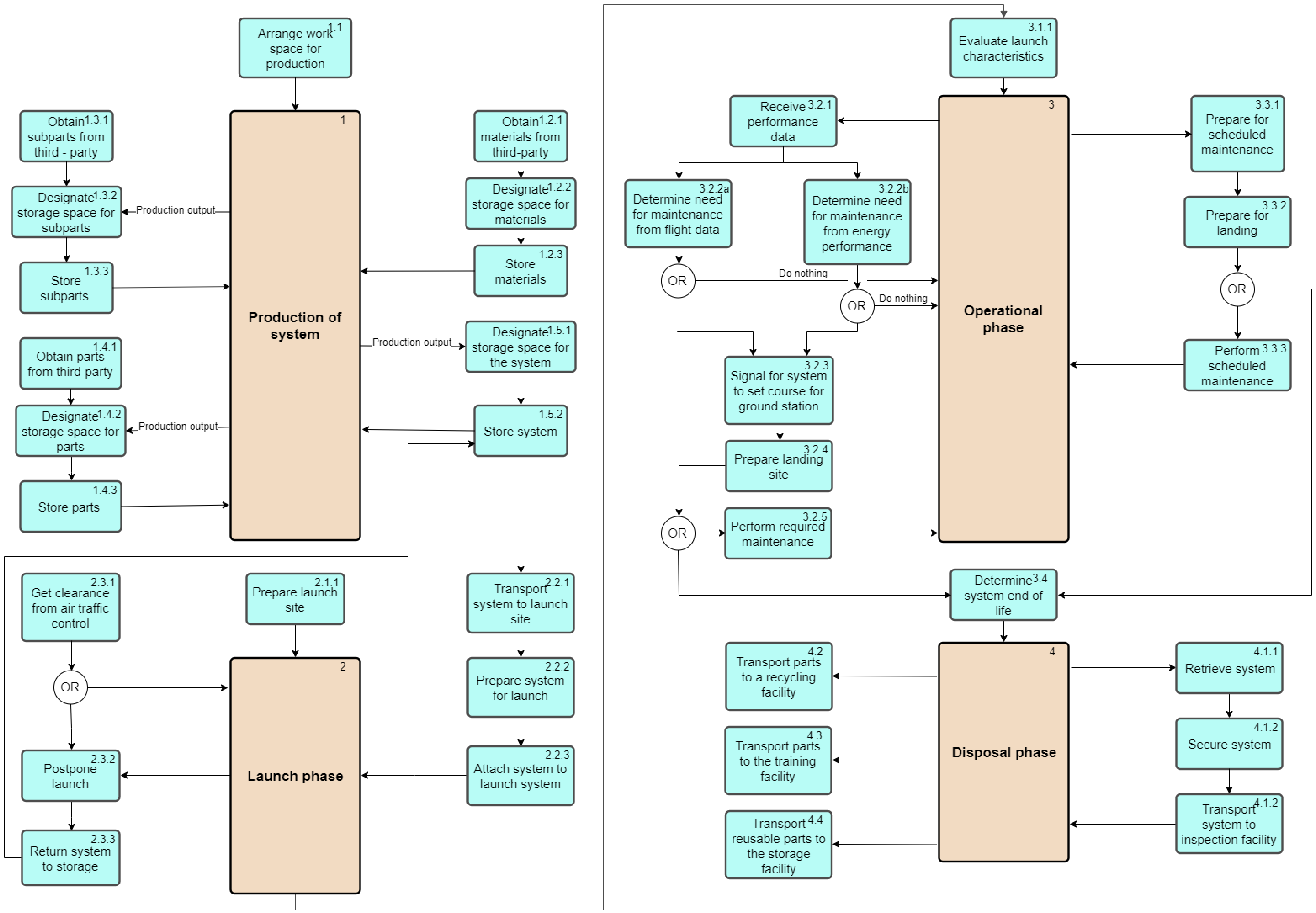

Figure A.1: Logistics flow diagram

B
Production plan

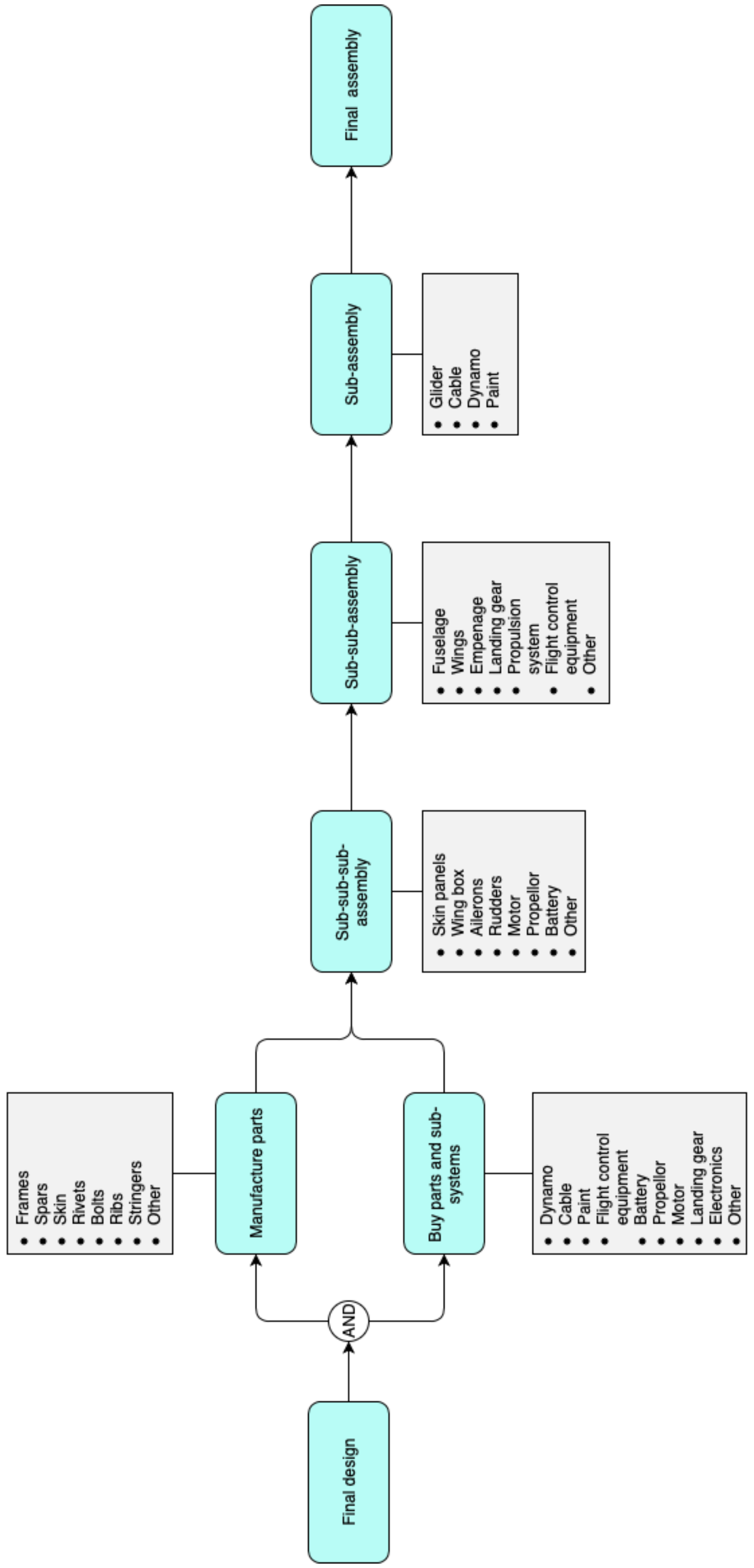

Figure B.1: Production plan of design option 2.

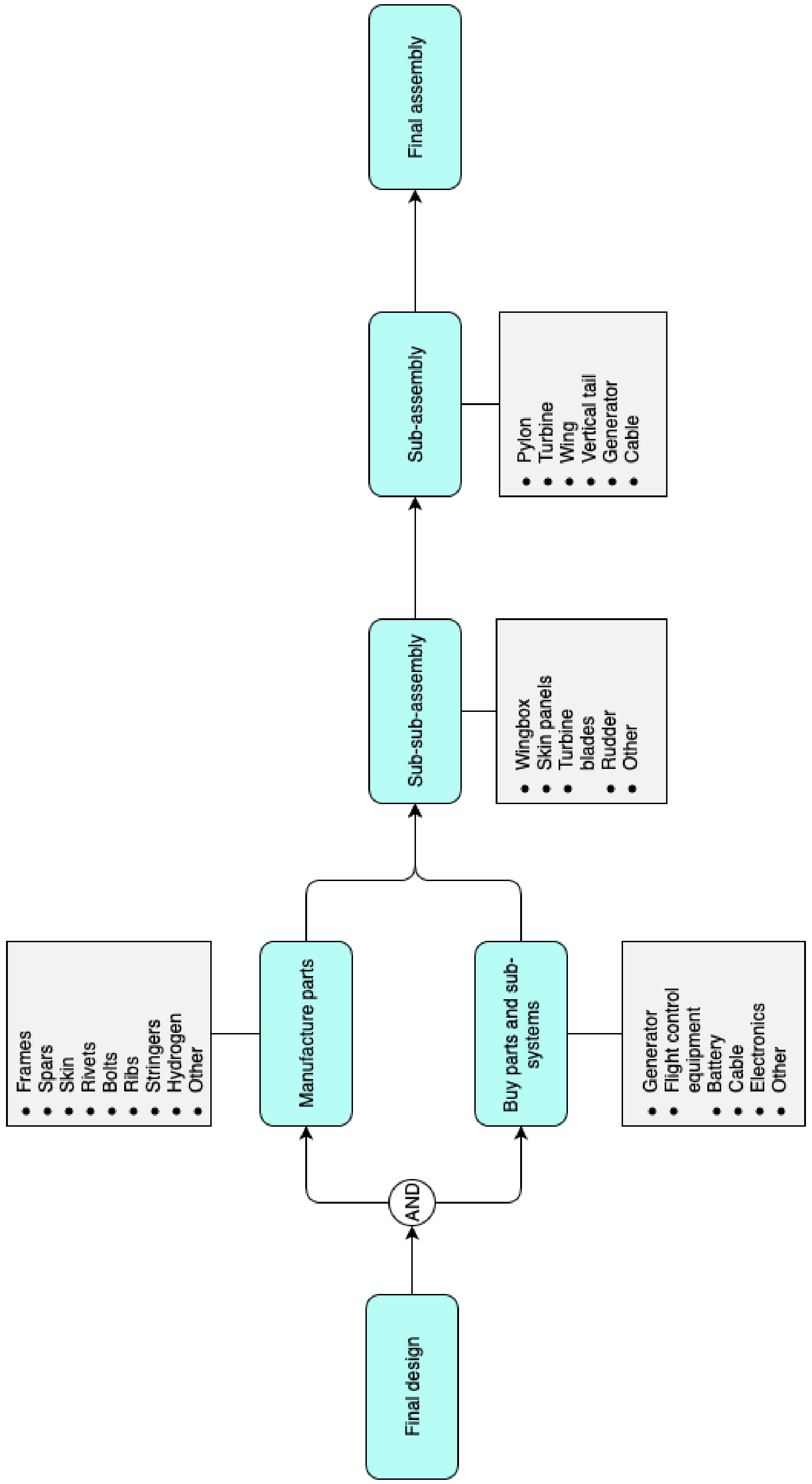

Figure B.2: Production plan of design option 3.

C
FMEA

					Failure effects					
Identification number	Item/functional identification	Function	Failure mode & causes	Mission phase	Local effects	Next higher-level	End effects	Failure detection method	Compensation provisions	Severity class
EHAC-FMEA-01-1-A	Kite	Sustain flight	Tears in kite	Operating	Tears in the material	Loss of controlability and lift	Crash	Visual inspection	Regular inspections	2
EHAC-FMEA-01-1-B			Control failure	Operating	Control surfaces defect	Loss of controlability	Crash	Change in flight pattern	Adjust course for easy control	3
EHAC-FMEA-01-1-C			Material degradation	Operating	Corrosion	Loss of structural integrity	Crash	Visual inspection	Replacement	4
EHAC-FMEA-01-1-D			Wind gust	Operating	Control complications	Loss of controlability and lift	Loss of control	Change in flight pattern	Land system in case of wind gusts	3
EHAC-FMEA-01-1-E			Bird collision	Operating	Structural damage	Loss of structural integrity, controlability, and lift	Crash	Change in flight pattern	Replacement	2
EHAC-FMEA-01-2-A	Tethered floating	Sustain flight	Cable failure	Operating	Cable fibers losening	Cable snapping	Lose floating device	Hard to inspect	Replacement or repair	2
EHAC-FMEA-01-2-B			Leak in gas container	Operating	Hole in material	Gas escaping	Loss of lift	Hard to inspect	Repair hole	1
EHAC-FMEA-01-2-C			Wind gust	Operating	Deformation skin	Drifting floating device	Low altitude	Altimeter	Connection via 3 cables	2
EHAC-FMEA-01-2-D			Lightning strike	Operating	Lightning impact	Loss of structural integrity	Crash	Weather expectations	Land system when lightning risk	3
EHAC-FMEA-01-2-E			Bird collision	Operating	Structural damage	Loss of structural integrity, controlability, and lift	Crash	Change in flight pattern	Replacement	2
EHAC-FMEA-01-3-A	Free floating	Sustain flight	Loss of control	Operating	Deformation of skin	Drifting floating system	Lose floating device	GNSS	Good landing mechanism	1
EHAC-FMEA-01-3-B			Wind bursts	Operating	Deformation of skin	Loosening of fasterners	loss of structural integrity	Strain gauge & inspection	Redundant control surfaces	3
EHAC-FMEA-01-3-C			Leak	Operating	Hole in fabric	Gas escaping	Loss of lift	Hard to inspect	Repair hole	3
EHAC-FMEA-02-1-A	Wind (turbine)	Energy harvesting	Failure of moving parts	Operating	Moving parts stuck	Drifting from position	Damage to blade	Hall sensor	Replacement	2
EHAC-FMEA-02-1-B			Gusts	Operating	Vibrations	Overspeed of blade	Ripple	Accelerometer	Stabilisers added to system	3
EHAC-FMEA-02-1-C			Material degradation	Operating	Corrosion in parts	Loss of blade	Parts falling down	Visual inspection	Coat with anti-corrosion paint	4
EHAC-FMEA-02-1-D			Bird collision	Operating	Deformation of skin	Loss of structural integrity	Lower efficiency	Visual inspection	Scarecrow	2
EHAC-FMEA-02-2-A	Wind (dynamo)	Energy harvesting	Failure of moving parts	Operating	Dynamo stuck	Damage to cable	Damage to dynamo	Hall sensor	Reduce moving parts	3
EHAC-FMEA-02-2-B			High ripple	Operating	Sparks in dynamo	Arcs in dynamo	Dynamo catches fire	Voltage sensor	Capacitors added to system	3
EHAC-FMEA-02-2-C			Overheating	Operating	Dynamo less efficient	Damage to dynamo	Dynamo catches fire	Temperature sensor	Cooling mechanism	2
EHAC-FMEA-02-3-A	Solar (photovoltaic)	Energy harvesting	Damage on panel	Operating	Loss in efficiency	Cell is defective	Whole panel is defective	Voltage & current sensors	Replacement	2
EHAC-FMEA-02-3-B			Panel too hot	Operating	Loss in efficiency	Damage to panel	Panel catches fire	Temperature sensor	Cooling mechanism	3
EHAC-FMEA-02-3-C			higher-level clouds	Operating	Lower energy production	Panel physically breaking	Panel breaking off	Visual inspection	None	4
EHAC-FMEA-03-1-A	Electrical cable	Power transfer	Cable failure	Operating	Damaged cable	Break in cable	Lose floating device	Visual inspection	Visual inspection	2
EHAC-FMEA-03-1-B			Wind	Operating	Extra drag	Cables tangled	Crash	Anemometer	Keep cables tight	2
EHAC-FMEA-03-1-C			Stress differences	Operating	Different stress between cables	Break in cable	Lose floating device	Strain gauge	tbd	3
EHAC-FMEA-03-2-A	Regular cable	Power transfer	Cable failure	Operating	Damaged cable	Break in cable	Lose floating device	Hard to inspect	Replacement or repair	3
EHAC-FMEA-03-2-B			Wind	Operating	Extra drag	Cables tangled	Uncontrolable device	Anemometer	Keep cables tight	2
EHAC-FMEA-03-2-C			Cable can sweep	Operating	Extra stress	Noise pollution	Vibrations in device	Accelerometer	tbd	3
EHAC-FMEA-03-3-A	Wireless transfer	Power transfer	Transmission failure	Operating	Clouds refracting beam	Clouds blocking beam	Energy not transmitted	Voltage & current sensors	tbd	2
EHAC-FMEA-03-3-B			Ground receiver not alligned	Operating	Loss in efficiency	Damaged ground receiver	Damaged infrastructure	Light dependent resistor	tbd	2
EHAC-FMEA-03-3-C			Foreign object in beam	Operating	Light pollution	Loss in efficiency	Damaged property	Light dependent resistor	tbd	2
EHAC-FMEA-04-1-A	Ground storage	Power storage	Overheating	Operating	Loss in efficiency	Damage to storage facility	Fire	Temperature sensor	Cooling mechanism	3
EHAC-FMEA-04-1-B			Overcapacity	Operating	Sparks	Arcs	Danger of explosion	Voltage & current sensors	Large capacitors & max. charge limit	3
EHAC-FMEA-04-1-C			Undercapacity	Operating	Slowly charging	Damage to storage facility	Storage facility total-loss	Voltage & current sensors	Large capacitors & DOD limit	3
EHAC-FMEA-04-2-A	Local storage	Power storage	Overheating	Operating	Loss in efficiency	Damage to storage facility	Fire	Temperature sensor	Cooling mechanism	2
EHAC-FMEA-04-2-B			Precipitation	Operating	Additional weight	Damage to docking device	Insufficient lift for take-off	Water sensor	tbd	3
EHAC-FMEA-04-2-C			Wind	Operating	Reduction in lift	Insufficient lift for take-off	crash	Anemometer	Stabilisers added to system	4

D
Workflow diagram

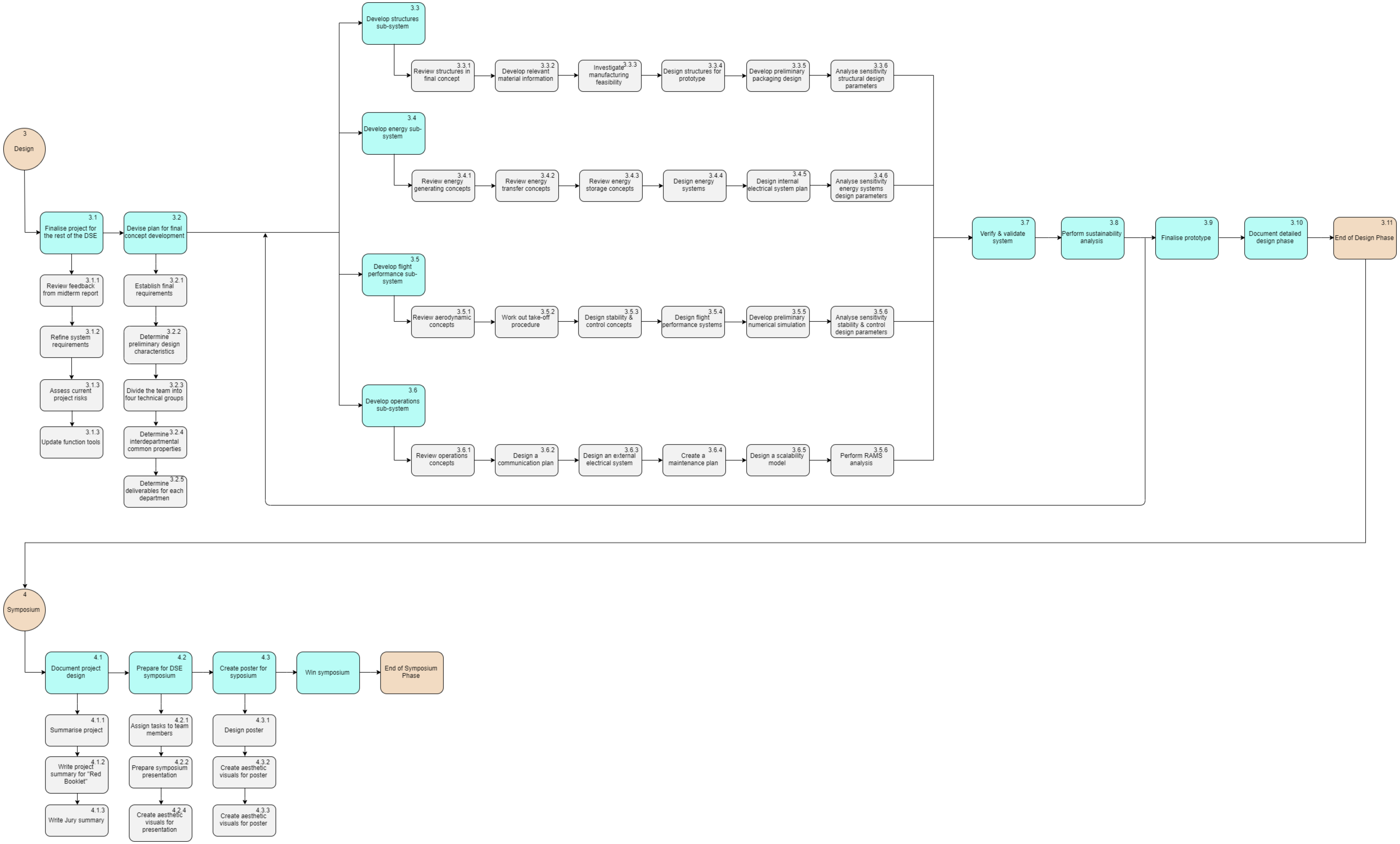

Figure D.1: Workflow diagram for the design phase and the symposium phase

E

Work breakdown structure

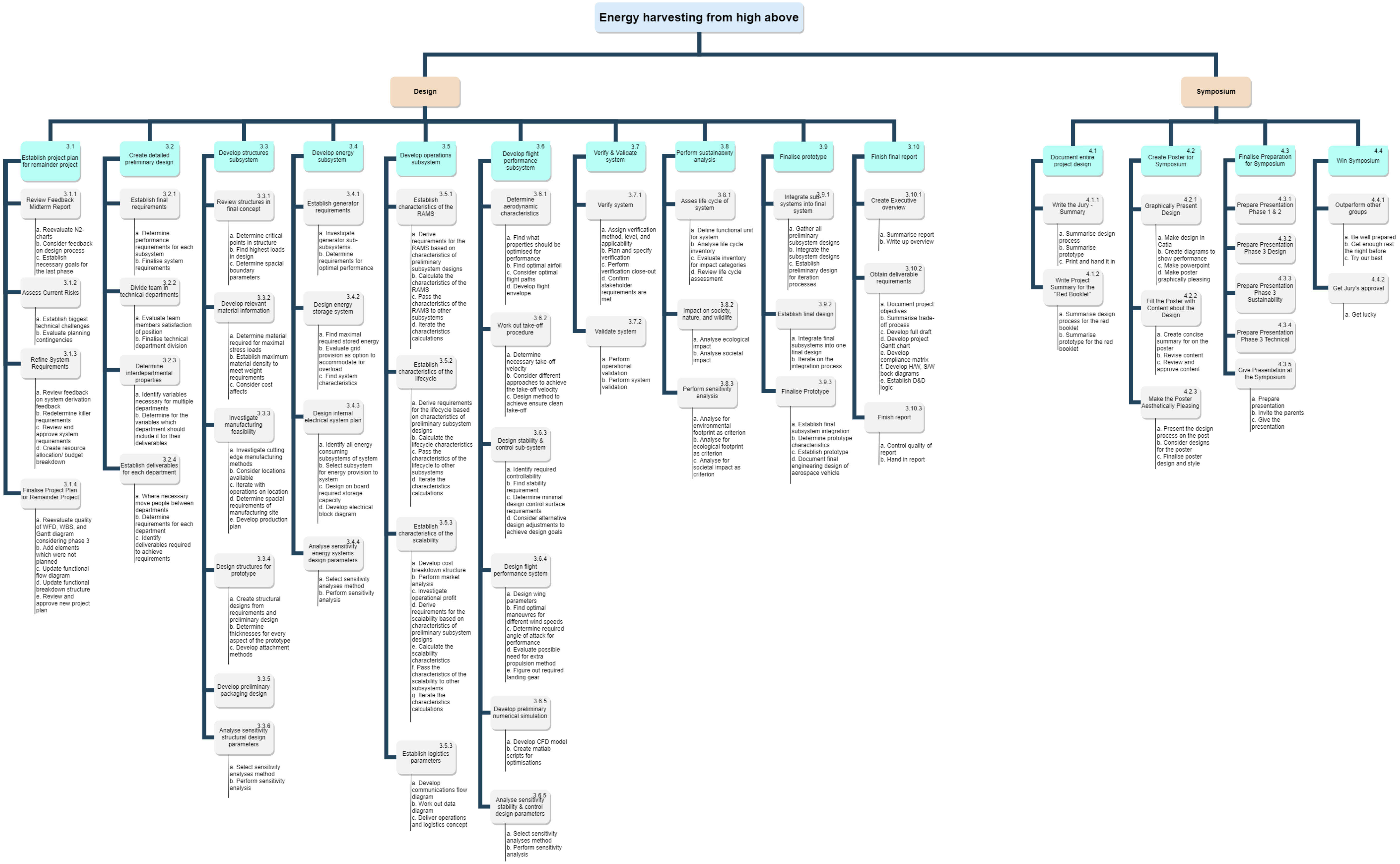

Figure E.1: Work breakdown structure for the design phase and the symposium phase

F Gantt chart

Table F.1: Gantt chart

ID	Outline Number	Task Name	Baseline Work	Resource Initials	Duration
0	0	DSE: Harvesting Energy from High Up	4.156 hrs		59 days
1	1	Phase 1	779 hrs		12 days
65	2	Phase 2	1.218 hrs		16 days
153	3	Phase 3	1.849 hrs		32 days
154	3.1	Establish project plan for remainder project	61 hrs		3 days
155	3.1.1	Review mid-term report feedback	31 hrs		3 days
156	3.1.1.1	Reevaluate N2-chart	2 hrs	MvdV	1 day
157	3.1.1.2	Consider feedback on design process	8 hrs	PM, TL	1 day
158	3.1.1.3	Establish goals for the last phase	4 hrs	PM, TL	1 day
159	3.1.1.4	Interim individual grading	1 hr	Everyone	1 day
160	3.1.1.5	Perform quality control mid-term report	8 hrs	WdV,CvW	2 days
161	3.1.1.6	Finalise mid-term report	8 hrs	WdV,CvW	2 days
162	3.1.1.7	Final mid-term report	0 hrs		0 days
163	3.1.2	Assess risks	16 hrs		1 day
164	3.1.2.1	Establish and mitigate technical challenges	4 hrs	LdK	1 day
165	3.1.2.2	Evaluate planning contingencies	4 hrs	LdK	1 day
166	3.1.3	Refine system requirements	10 hrs		3 days
167	3.1.3.1	Review feedback on system derivation	2 hrs	RV	1 day
168	3.1.3.2	Redetermine killer requirements	4 hrs	CvW	1 day
169	3.1.3.3	Review and approve system requirements	4 hrs	TA	1 day
170	3.1.3.4	Resource allocation / budget breakdown	8 hrs	TL	1 day
171	3.1.4	Finalise project plan for remainder project	8 hrs		1 day
172	3.1.4.1	Reevaluate quality WFD, WBS, Gantt chart	6 hrs	TL,CvW	1 day
173	3.1.4.2	Add elements that are not planned	1 hr	TL,CvW	1 day
174	3.1.4.3	Functional flow diagram	2 hrs	TL	1 day
175	3.1.4.4	Functional breakdown	2 hrs	CvW	1 day
176	3.1.4.5	Review and approve new project plan	1 hr	WdV	1 day
177	3.2	Create detailed preliminary design	49 hrs		4 days
178	3.2.1	Establish final requirements	10 hrs		1 day
179	3.2.1.1	Determine performance requirements for sub-systems	8 hrs	Chiefs	1 day
180	3.2.1.2	Finalise system requirements	2 hrs	XvB	1 day
181	3.2.2	Divide team in technical departments	2 hrs		1 day
182	3.2.2.1	Evaluate team members' satisfaction of position	1 hr	Everyone	1 day
183	3.2.2.2	Finalise technical department division	1 hr	Everyone	1 day
184	3.2.3	Determine interdepartmental properties	12 hrs		1 day
185	3.2.3.1	Identify variables necessary for multiple departments	8 hrs	Chiefs	1 day
186	3.2.3.2	Determine which department should include the deliverables	4 hrs	Chiefs	1 day
187	3.2.4	Establish deliverables for each department	25 hrs		4 days
188	3.2.4.1	If necessary, move people between departments	1 hr	Everyone	1 day
189	3.2.4.2	Determine requirements for each department	16 hrs	Chiefs	1 day
190	3.2.4.3	Identify deliverables required to achieve requirements	8 hrs	Chiefs	1 day
191	3.3	Develop structures subsystem	294 hrs		10 days
192	3.3.1	Review structures in final concept	54 hrs		9 days
193	3.3.1.1	Determine critical points in structure	4 hrs	MvdV	1 day
194	3.3.1.2	Find highest loads in design	30 hrs	TA	5 days
195	3.3.1.3	Determine spacial boundary parameters	20 hrs	TL	2 days
196	3.3.2	Develop relevant material information	70 hrs		6 days
197	3.3.2.1	Determine material required for maximal stress loads	30 hrs	RV	5 days
198	3.3.2.2	Establish maximum material density to meet weight requirements	20 hrs	CvW	3 days
199	3.3.2.3	Consider cost effects	20 hrs	MvdV	2 days
200	3.3.3	Investigate manufacturing feasibility	50 hrs		7 days
201	3.3.3.1	Investigate cutting edge manufacturing methods	10 hrs	RV	2 days
202	3.3.3.2	Consider locations available	10 hrs	TA	1 day?
203	3.3.3.3	Iterate with operations on location	20 hrs	TL	2 days
204	3.3.3.4	Determine spacial requirements of manufacturing site	10 hrs	CvW	2 days
205	3.3.3.5	Production plan	4 hrs	RV	1 day
206	3.3.4	Design structures for prototype	60 hrs		10 days
207	3.3.4.1	Create structural desings from requirements and preliminary design	30 hrs	MvdV	8 days
208	3.3.4.2	Determine thicknesses for every aspect of the prototype	20 hrs	RV	5 days
209	3.3.4.3	Develop attachment methods	10 hrs	TA	2 days
210	3.3.5	Develop preliminary packaging design	20 hrs	TL	2 days
211	3.3.6	Analyse sensitivity structural design parameters	40 hrs		2 days
212	3.3.6.1	Select sensitivity analysis method	10 hrs	CvW	1 day
213	3.3.6.2	Perform sensitivity analysis	30 hrs	MvdV	2 days
214	3.4	Develop energy subsytem	290 hrs		10 days
215	3.4.1	Establish generator requirements	60 hrs		2 days
216	3.4.1.1	Investigate generator sub-subsystems	20 hrs	XvB	1 day
217	3.4.1.2	Determine requirements for optimal performance	40 hrs	LdK	2 days
218	3.4.2	Design energy storage system	110 hrs		10 days
219	3.4.2.1	Find maximal required stored energy	20 hrs	PM	2 days
220	3.4.2.2	Evaluate grid provision as option to accommodate for overload	30 hrs	DS	4 days
221	3.4.2.3	Find system characteristics	60 hrs	EJdG	8 days
222	3.4.3	Design internal electrical system plan	80 hrs		7 days
223	3.4.3.1	Identify all energy consuming sub-systems	20 hrs	WdV	2 days
224	3.4.3.2	Select subsystem for energy provision to system	40 hrs	XvB	4 days
225	3.4.3.3	Design on board required storage capacity	20 hrs	LdK	2 days
226	3.4.3.4	Electrical block diagram	4 hrs	LdK	1 day
227	3.4.4	Analyse sensitivity energy systems design parameters	40 hrs		3 days
228	3.4.4.1	Select sensitivity analysis method	10 hrs	PM	1 day
229	3.4.4.2	Perform sensitivity analysis	30 hrs	DS	3 days
230	3.5	Develop operations subsystem	285 hrs		10 days
231	3.5.1	Establish characteristics of the RAMS	105 hrs		10 days
232	3.5.1.1	Derive requirements for RAMS based on preliminary subsystem designs	20 hrs	CvW	2 days
233	3.5.1.2	Calculate characteristics of RAMS	30 hrs	TL	3 days
234	3.5.1.3	Pass characteristics RAMS to other subsystems	5 hrs	TA	1 day

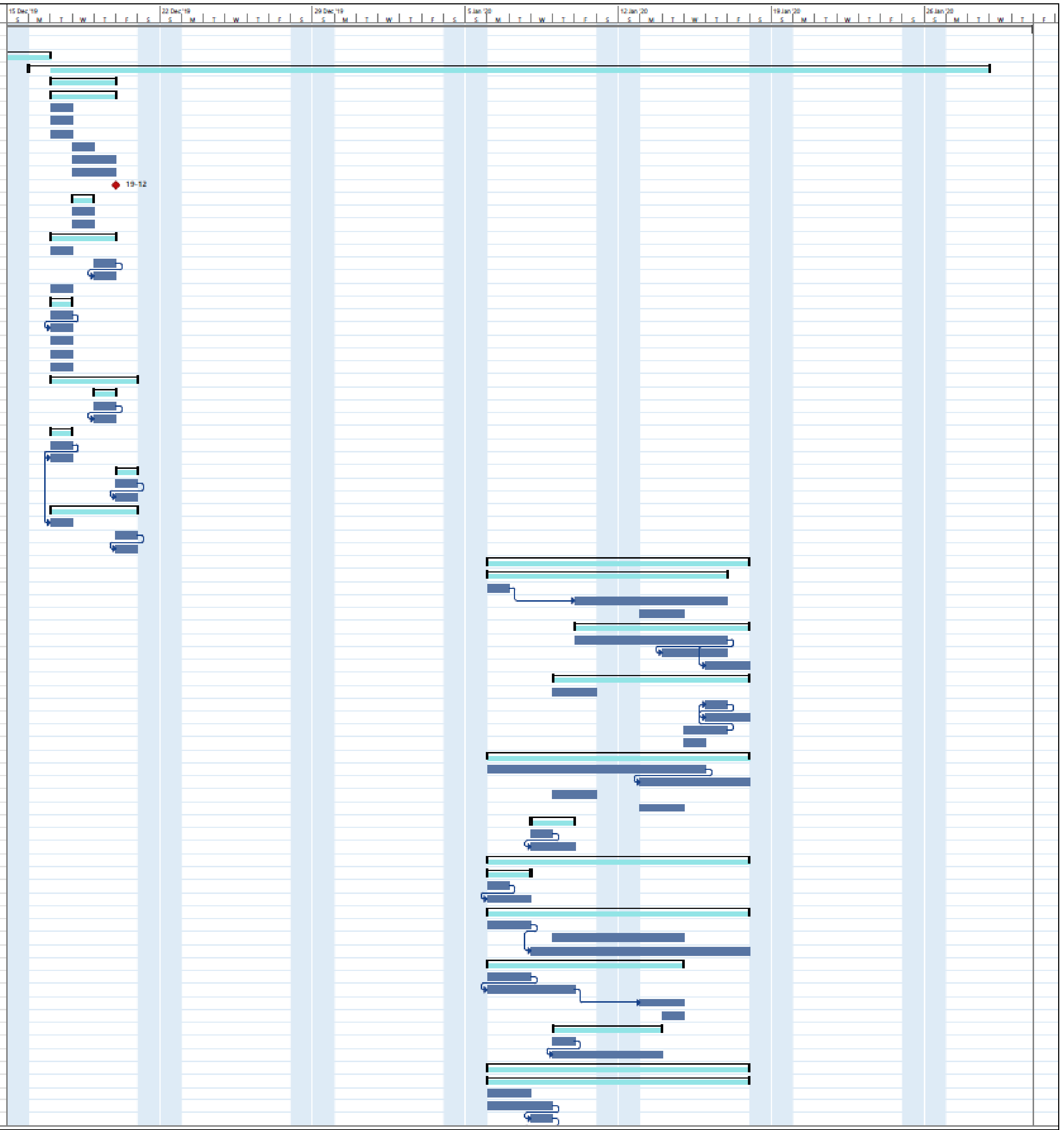

Table E.2: Gantt chart

ID	Outline Number	Task Name	Baseline Work	Resource Initials	Duration
235	3.5.1.4	Iterate characteristics calculations	50 hrs	RV	8 days
236	**3.5.2**	**Establish characteristics of the lifecycle**	**95 hrs**		**10 days**
237	3.5.2.1	Derive requirements for lifecycle based on preliminary subsystem designs	10 hrs	MvdV	1 day
238	3.5.2.2	Calculate characteristics of lifecycle	30 hrs	CVW	4 days
239	3.5.2.3	Pass characteristics lifecycle to other subsystems	5 hrs	TL	1 day
240	3.5.2.4	Iterate characteristics calculations	50 hrs	TA	7 days
241	**3.5.3**	**Establish characteristics of scalability**	**85 hrs**		**10 days**
242	3.5.3.1	Cost breakdown structure	8 hrs	RV	1 day
243	3.5.3.2	Market analysis	8 hrs	CVW	1 day
244	3.5.3.3	Return on investment, operational profit	0 hrs		
245	3.5.3.4	Derive requirements for scalability based on preliminary subusystem disigns	20 hrs	RV	2 days
246	3.5.3.5	Calculate scalability characteristics	30 hrs	MvdV	3 days
247	3.5.3.6	Pass characteristics to other subsystems	5 hrs	CVW	1 day
248	3.5.3.7	Iterate characteristics calculations	30 hrs	TA	6 days
249	**3.5.4**	**Establish logistics parameters**	**0 hrs**		**1 day**
250	3.5.4.1	Operations and logistic concept description	4 hrs	TL	1 day
251	3.5.4.2	Data handling block diagram	4 hrs	MvdV	1 day
252	3.5.4.3	Communication flow diagram	4 hrs	TA	1 day
253	**3.6**	**Develop flight performance subsystem**	**315 hrs**		**10 days**
254	**3.6.1**	**Determine aerodynamic characterisitics**	**55 hrs**		**3 days**
255	3.6.1.1	Find what properties should be optimised for performance	10 hrs	KvB	1 day
256	3.6.1.2	Find optimal airfoil	10 hrs	LdK	1 day
257	3.6.1.3	Consider optimal flight paths	15 hrs	PM	2 days
258	3.6.1.4	Develop flight envelope	20 hrs	DS	2 days
259	**3.6.2**	**Work out take-off procedure**	**50 hrs**		**4 days**
260	3.6.2.1	Determine necessary take-off velocity	10 hrs	EJdG	1 day
261	3.6.2.2	Consider different approaches to achieve take-off velocity	10 hrs	WdV	1 day
262	3.6.2.3	Design method to achieve clean take-off	30 hrs	KvB	3 days
263	**3.6.3**	**Design stability & control subsystem**	**60 hrs**		**10 days**
264	3.6.3.1	Identfiy required controllability	5 hrs	LdK	1 day
265	3.6.3.2	Find stability requirements	10 hrs	PM	2 days
266	3.6.3.3	Determine minimal design control surface requirements	30 hrs	DS	4 days
267	3.6.3.4	Consider alternative design adjustments to achieve goals	15 hrs	EJdG	2 days
268	**3.6.4**	**Design flight performance system**	**70 hrs**		**6 days**
269	3.6.4.1	Design wing parameters	20 hrs	WdV	3 days
270	3.6.4.2	Find optimal maneuvres for different wind speeds	20 hrs	KvB	3 days
271	3.6.4.3	Determine required angle of attack for peromance	15 hrs	LdK	2 days
272	3.6.4.4	Evaluate possible need for extra propulsion	10 hrs	PM	1 day
273	3.6.4.5	Find required landing gear	5 hrs	DS	1 day
274	**3.6.5**	**Develop preliminary numerical simulation**	**40 hrs**		**10 days**
275	3.6.5.1	Develop CFD model	20 hrs	EJdG	10 days
276	3.6.5.2	Create MATLAB scripts for optimisations	20 hrs	WdV	10 days
277	**3.6.6**	**Analyse sensitivity stability & control parameters**	**40 hrs**		**2 days**
278	3.6.6.1	Select sensitivity analyses method	10 hrs	KvB	1 day
279	3.6.6.2	Perform sensitivity analysis	30 hrs	LdK	2 days
280	**3.7**	**Verify & validate system**	**91 hrs**		**10 days**
281	**3.7.1**	**Verify system**	**51 hrs**		**10 days**
282	3.7.1.1	Assign verification method, level, and applicability	11 hrs	PM, TL	1 day
283	3.7.1.2	Plan and specify verification	8 hrs	KvB	1 day
284	3.7.1.3	Perform verification close-out	24 hrs	LdK	3 days
285	3.7.1.4	Confirm requirements are met	8 hrs	CvW	1 day
286	**3.7.2**	**Validate system**	**40 hrs**		**3 days**
287	3.7.2.1	Perform operational validation	20 hrs	MvdV	3 days
288	3.7.2.2	Perform system validation	20 hrs	RV	3 days
289	**3.8**	**Perform sustainability analysis**	**84 hrs**		**8 days**
290	**3.8.1**	**Assess life cycle of system**	**28 hrs**		**8 days**
291	3.8.1.1	Define functional unit for system	4 hrs	TL	1 day
292	3.8.1.2	Analyse life cycle inventory	4 hrs	WdV	1 day
293	3.8.1.3	Evaluate inventory	10 hrs	EJdG	2 days
294	3.8.1.4	Review life cycle assessment	10 hrs	TA	2 days
295	**3.8.2**	**Impact on society, nature and wildlife**	**8 hrs**		**1 day**
296	3.8.2.1	Analyse ecological impact	4 hrs	DS	1 day
297	3.8.2.2	Analyse societal impact	4 hrs	LdK	1 day
298	**3.8.3**	**Perform sustainability analysis**	**48 hrs**		**3 days**
299	3.8.3.1	Analyse for environmental footprint as criterion	16 hrs	TA	3 days
300	3.8.3.2	Analyse for ecological footprint as criterion	16 hrs	CvW	3 days
301	3.8.3.3	Analyse for societal impact as criterion	16 hrs	RV	3 days
302	**3.9**	**Finalise prototype**	**92 hrs**		**10 days**
303	**3.9.1**	**Integrate subsystems into final system**	**30 hrs**		**10 days**
304	3.9.1.1	Gather all preliminary subsystem designs	4 hrs	PM;TL	1 day
305	3.9.1.2	Integrate the subsystem designs	24 hrs	PM;TL	3 days
306	3.9.1.3	Establish preliminary design for iteration process	2 hrs	PM;TL	1 day
307	**3.9.2**	**Establish final design**	**48 hrs**		**3 days**
308	3.9.2.1	Integrate final subsystems into one final design	24 hrs	PM;TL	3 days
309	3.9.2.2	Iterate on the integration process	24 hrs	PM;TL	3 days
310	**3.9.3**	**Finalise prototype**	**14 hrs**		**2 days**
311	3.9.3.1	Establish final subsystem integration	2 hrs	PM;TL	1 day
312	3.9.3.2	Determine prototype characteristics	10 hrs	PM;TL	2 days
313	3.9.3.3	Establish prototype	2 hrs	PM;TL	1 day
314	3.9.3.4	Engineering design and analysis of the aerospace vehicle	16 hrs	PM;TL	2 days
315	3.10	CATIA	51 hrs	RV;WdV	4 days
316	3.11	Virtual Reality Design review	0 hrs		0 days
317	**3.12**	**Finish final report**	**211 hrs**		**24 days**
318	3.12.1	Executive overview	4 hrs	KvB	1 day

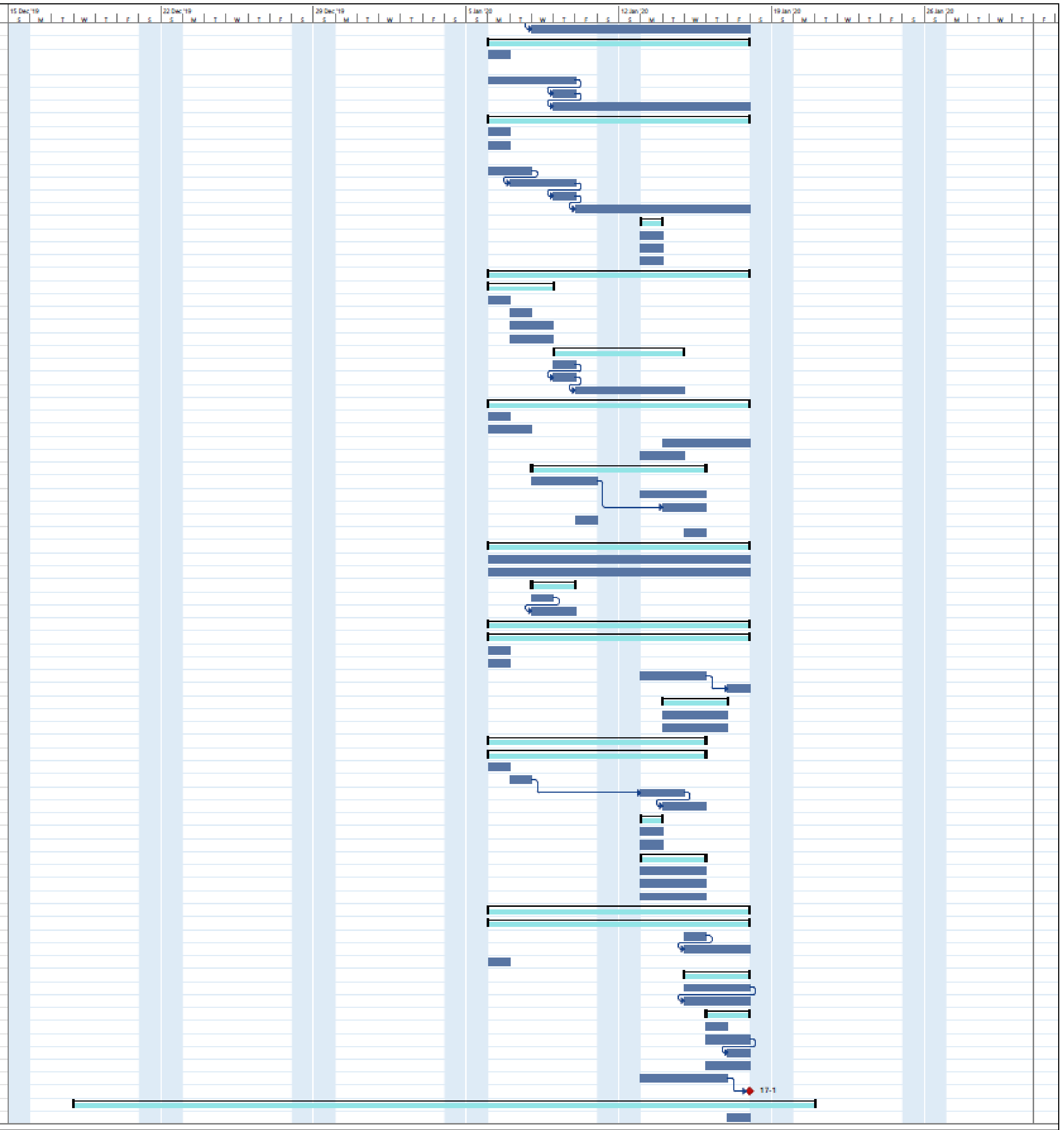

Table E.3: Gantt chart

ID	Outline Number	Task Name	Baseline Work	Resource Initials	Duration
319	3.12.2	**Obtain deliverable requirements**	1 hr	TA	23 days
320	3.12.2.1	Project objectives	1 hr	TA	1 day
321	3.12.2.2	Summary of trade-off	2 hrs	LdK	1 day
322	3.12.2.3	Project Gantt chart	8 hrs	CvW	1 day
323	3.12.2.4	Compliance matrix	8 hrs	LdK	1 day
324	3.12.2.5	H/W, S/W block diagrams (interactions, flows)	4 hrs	RV	1 day
325	3.12.2.6	User requirements and constraints	2 hrs	RV	1 day
326	3.12.2.7	Sub-system requirements	10 hrs	CvW	2 days
327	3.12.2.8	Project design & development logic	8 hrs	EJdG	1 day
328	3.12.3	Write up	88 hrs	Everyone	11 days
329	3.12.4	Perform quality control	88 hrs	Everyone	2 days
330	3.12.5	Full Draft	0 hrs		0 days
331	3.13	Prepare final report presentation	32 hrs	Everyone	4 days
332	3.14	Final review	0 hrs		0 days
333	3.15	**Weekly meetings**	10 hrs		31 days
339	4	Phase 4	326 hrs		11 days
340	4.1	**Reevaluate final report for phase 4**	236 hrs		2 days
341	4.1.1	Review final report feedback	176 hrs	Everyone	2 days
342	4.1.2	Finalise final report	30 hrs	CvW;WdV	2 days
343	4.1.3	Perform quality control	30 hrs	CvW;WdV	1 day
344	4.1.4	Final version	0 hrs		0 days
345	4.2	**Document entire project design**	15 hrs		11 days
346	4.2.1	**Write Jury summary**	7 hrs	TA	1 day
347	4.2.1.1	Describe mission and outcome	1 hr		1 day
348	4.2.1.2	Summarise work done up until now	4 hrs		1 day
349	4.2.1.3	Summarise upcoming weeks of DSE	2 hrs		1 day
350	4.2.1.4	Jury summary	0 hrs		0 days
351	4.2.2	**Write project summary for the "Red Booklet"**	8 hrs	DS	1 day
352	4.2.2.1	Mission statement, objectives, design requirements and constraints	2 hrs		1 day
353	4.2.2.2	Concepts studied and trade-off(s)	2 hrs		1 day
354	4.2.2.3	Details of selected concept (3-view drawing, important parameters)	2 hrs		1 day
355	4.2.2.4	Conclusions and recommendations	2 hrs		1 day
356	4.2.3	Project summary for the "Red Booklet"	0 hrs		0 days
357	4.3	**Create poster for symposium**	28 hrs		3 days
358	4.3.1	**Graphically present design**	10 hrs	WdV;RV	1 day
359	4.3.1.1	Make design in CATIA	2 hrs		1 day
360	4.3.1.2	Create diagrams to show performance	2 hrs		1 day
361	4.3.1.3	Make powerpoint	2 hrs		1 day
362	4.3.1.4	Make poster graphically pleasing	4 hrs		1 day
363	4.3.2	**Fill poster with content about design**	6 hrs	LdK	1 day
364	4.3.2.1	Create concise summary for poster	2 hrs		1 day
365	4.3.2.2	Revise content	2 hrs		1 day
366	4.3.2.3	Review and approve content	2 hrs		1 day
367	4.3.3	**Make poster aesthetically pleasing**	12 hrs	TA	1 day
368	4.3.3.1	Present the design process on the poster	4 hrs		1 day
369	4.3.3.2	Consider designs for the poster	4 hrs		1 day
370	4.3.3.3	Finalise poster design and style	4 hrs		1 day
371	4.3.4	Poster	0 hrs		0 days
372	4.4	**Finalise preparations for symposium**	47 hrs		4 days
373	4.4.1	Prepare presentation phase 1&2	6 hrs	presenters	3 days
374	4.4.2	Prepare presentation phase 3 design	6 hrs	presenters	3 days
375	4.4.3	Prepare presentation phase 3 sustainability	6 hrs	presenters	3 days
376	4.4.4	Prepare presentation phase 3 technical	6 hrs	presenters	3 days
377	4.4.5	**Give presentation at the symposium**	23 hrs		2 days
378	4.4.5.1	Prepare presentation	11 hrs	Everyone	1 day
379	4.4.5.2	Give the presentation	11 hrs	presenters	1 day
380	4.5	Symposium day!	88 hrs	Everyone	1 day
381	4.6	Symposium	0 hrs		0 days