Princess Elisabeth Research Station at Antarctica

Renewable Energy Systems design, simulation and optimization

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled "**Princess Elisabeth Research Station at Antarctica - Renewable Energy Systems design, simulation and optimization**" by **K. Van Rattinghe** in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

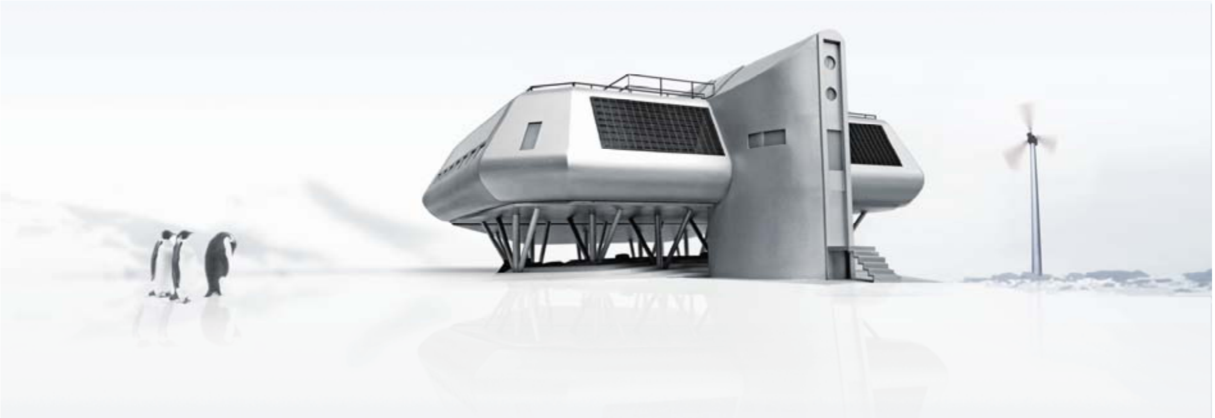
The Earth's climate is changing. A better understanding on the climate mechanism is essential for future sustainable development. As Antarctica has an important role in the Earth system, a new Belgian research station - named Princess Elisabeth - is currently under construction in the Sør Rondane mountains (Droning Maud Land, East Antarctica).

The Princess Elisabeth station is unique in its conception. It is only manned during the austral summer, but remains operational for full year monitoring. In addition, it aims at minimum environmental impact and the highest energy and waste efficiency, fundamental issues in the Antarctic Environmental Protocol. The objective of the energy concept is a 95% sustainable hybrid system consisting of solar and wind power, combined with electrical and thermal storage. A diesel system is mainly foreseen as back-up in emergency situations.

This research investigates the feasibility of the energy concept and the component sizing of the hybrid system. In addition the sensitivity of the design is evaluated on the wind variation as wind power generates most of the energy. For this purpose, a synthetic wind series is created (first order Markov chain) and combined with long term observations of other polar stations. Finally, the current design is evaluated under the assumption the station is permanently manned. A dynamical simulation tool is developed to validate the design decisions.

The hybrid system consists of 6 small wind turbines of 6 kW each, a 50 kWp photovoltaic system, a 6000 Ah battery bank (VRLA) and 2 back-up diesel generators of 35 kW each. For the thermal applications, 21 m^2 flat solar thermal collectors and 1.5 m^3 heat storage is foreseen. To keep the station up and running under normal conditions, the annual diesel consumption ranges between 1750 and 1250 litres, depending on the wind climate. 97% of the energy originates from renewable sources, which makes the Princess Elisabeth station the most environmental friendly manned polar station. The design is a benchmark for future polar stations.

If the station is permanently manned, annual diesel consumption ranges from 17000 to 14000 litres. The renewable energy fraction is reduced to approximately 72%. Sensitivity analysis showed further diesel reduction is possible by adding wind turbines and electrical storage capacity; however the marginal gain is limited. Significant reduction on the loads is needed to achieve the low emission objective. Specific attention is needed on the generator selection and battery control algorithm if the station is manned permanently.



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Acronyms

AC	Alternating Current
AGM	Absorbed Glass Mat
ATEX	ATmosphère Explosible
AWS	Automatic Weather Station
BELSPO	Belgian Federal Science Police Office
BERLARE	Belgian Antarctic Research Expeditions
BIPV	Building Integrated Photovoltaic
BMS	Building Management Systems
CCTV	Closed Circuit Television
CFD	Computational Fluid Dynamics
DC	Direct Current
DFA	Diesel Fuel Arctic
DOD	Depth Of Discharge
EMS	Energy Management Systems
EPDM	Ethyleen Propyleen Dieen Monomeer
FMEA	Failure Mode Effect Analysis
HMI	Human-Machine Interface
HOMER	Hybrid Optimization Model for Electric Renewables
IGY	International Geophysical Year
IPF	International Polar Foundation
kWp	Kilo watt peak
LAN	Local Area Network
LEL	Lower Explosion Limit
Li-ion	Lithium-ion
MPP	Maximum Power Point
NiCd	Nickel Cadmium
NiMH	Nickel-metal-hybride
NREL	National Renewable Energy Laboratory

Pb-Acid	Lead Acid
PLC	Programmable Logic Controllers
PV	Photovoltaic
RPM	Revolutions Per Minute / Rounds Per Minute
SAPV	Stand-Alone Photovoltaic
SCADA	Supervisory Control And Data Acquisition
SOC	State Of Charge
STC	Standard Test Conditions
TRNSYS	TRaNsient SYstem Simulation program
TPM	Transition Probability Matrix
UPS	Uninterruptible Power Supply
V_{MPP}	Maximum Power Point Voltage
V_{OC}	Open Circuit Voltage
VAV	Variable Air Volume
VKI	Von Karmann Institute
VRLA	Valve Regulated Lead-Acid
WMS	Water Management Systems
WTU	Water Treatment Unit

1 Introduction

1.1 Introduction

Human activities increasingly alter the Earth's climate. Scientific evidence strongly indicates that natural influences alone cannot explain the rapid increase in global near-surface temperatures observed during the second half of the 20th century [3]. Human impacts on the climate system include increasing concentrations of atmospheric greenhouse gases (e.g. carbon dioxide, methane and nitrous oxide), increasing concentrations of airborne particles, and land alteration. A particular concern is that atmospheric levels of carbon dioxide may be rising faster than at any time in Earth's history.

Understanding how the Earth system works is essential to establish future sustainable development initiatives. Research highlighted the importance of Antarctica in the global weather system and climate [3]. The Antarctic continent is the most important area for heat losses towards space. It holds the biggest long term water storage for global water circulation. Antarctica is also an irreplaceable archive of the planet's climatic history and its weather patterns are the driving force for the entire world's atmosphere and ocean circulation. Additionally, Antarctica is very suited for biological, geophysical and astronomical observations.

Antarctica is a continent of extremes. It is not only the highest continent, but also the coldest, the driest and the windiest. Approximately 98% of its surface is covered by an ice sheet that holds 70% of the world's fresh water resources. If the ice sheet melted completely, ocean water level would rise with 60 meters [3]. Due snow reflection, its latitude and its elevation, extreme cold is constantly present. The coldest temperature ever recorded is – 89 degrees C. At the center of Antarctica, absolute humidity levels lower than those of the Sahara desert are recorded, which makes Antarctica world's largest desert. Finally the continent is constantly dominated by katabatic winds. These gravity driven winds can reach average velocities of 35 km/h and extremes up to 250 km/h at the coastal areas.

Belgium has a long history in Antarctica, dating back to 1897: the "Belgica expedition" of Adrien de Gerlache. This was the first scientific expedition overwintering in the Antarctic ice sheet and revealing lots of secrets on the last "terra incognita". Sixty years later, in 1958, Belgium returned to Antarctica to build the Roi Baudoin station to celebrate the 1957-1958 International Geophysical Year (IGY). International scientific collaboration was enforced with the establishment of the Antarctic treaty in 1959. This legal agreement ensures that all member countries work together in Antarctica solely for peaceful and scientific objectives [50].

110 years after the first expedition of Adrien de Gerlache, Belgium is back on Antarctica to celebrate the 2007-2008 International Polar Year. The Princess Elisabeth station is being built, world's first polar research station functioning entirely on renewable energy. The station combines eco-friendly construction materials, clean and efficient energy use, optimized energy consumption and optimal waste management techniques to reach a low emission objective. Scientists are provided with state of the art facilities for research on the understanding of climate change. The station is a benchmark for future station design and a technological launch pad for climate research and climate awareness.

1.2 Objective

The objective of this research is to investigate the feasibility of a research station on Antarctica functioning mainly on renewable energy. A first focus is on the correct sizing of the energy system and its components. Secondly the impact of wind variation on the performance is investigated. Finally, the consequences of having the station manned continuously (permanent station) is considered.

1.3 Methodology

The first part is the result of a continuous effort in collaboration with all the technical partners. An iterative design process is applied to integrate all the constraints and needs within a feasible design. The sizing of the energy system, and thus its subcomponents, is done with a step by step engineering approach based on dynamical simulations[1]. Each change in the design is remodeled, recalculated and validated with the technical partners to obtain an optimized integrated design.

Detailed sensitivity analyses are use to highlight the key design parameters such as renewable resources and technology selection. These sensitivity analyses are also used for the component sizing, as they indicate the marginal gain of increasing the installed capacity of a specific resource, or even using a different technology. The shortest path (option with the highest marginal gain) is chosen till the predefined objectives are reached.

Throughout the complete design process, the following principles are maintained:

- Reliability: the selected components are "proven" technology. All solutions are kept simple if possible.
- Redundancy: a FMEA (Failure Mode Effect Analysis) approach is used to ensure maximum redundancy.
- Flexibility: future adaptations and extensions are important design drivers.

For the second part, the same design tool is used to investigate the performance sensitivity, primarily on wind variation. Existing wind analysis tools[2] and other mathematical tools[3] are used to understand existing observations and the regeneration of new input files for the model. Finally, these inputs are used to validate the current design. The iterative design tool is also adapted for research on a permanent station and other locations.

[1] Dynamical analysis: TRNSYS (HOMER as validation tool)
[2] Wind analysis tools: WAsP, WindPRO2, Windographer
[3] Mathematical tools: Matlab, Excel.

PART 1: RENEWABLE ENERGY DESIGN

2 Site and concept description

2.1 Location

In order to find a suited location for the new research station, a first expedition[4] has been organized in the austral summer of 2004. A number of potential sites had been selected within the western sector of the Sør Rondane mountains based on topographic maps and on satellite and aerial images. The selection criteria are the accessibility of the location (by air and overland), the presence of water, the stability of the terrain, the topographic protection against katabatic winds and the potential for scientific research.

The selected site (71°57'S 23°20'E) is situated at approximately 1 km north of Utsteinen Nunatak (Granite rock formation in the north of Sør Rondane Mountains), on a small relatively flat granite ridge[5] at 1397 m above sea level. The site is located at 55 km South West from the former Japanse Asuka base (1986-1992) and 173 km inland of the former Roi Baudouin base (1958-1967). The nearest neighboring operational station is the Russian Novolazarevskaya at 431 km West and the Japanese Syowa at 684 km East [43]. Figure 1 shows in more detail the location and the ridge.

Figure 1: Utsteinen ridge [43]

More pictures on the location can be found in Appendix A.

2.2 Meteorological data

An automatic weather station was installed at the foot of the Utsteinen ridge in December 2004. The system delivers 10 minute data on meteorological parameters such as air temperature, wind speed and direction, atmospheric pressure and sunshine duration at a height of 4 m (temperature is measured at 1.5 m). For further analysis on the renewable energy potential and building design, all values are resampled to hourly or daily values.

2.2.1 Temperature and solar radiation

Table 1 and Figure 2 show the temperature observations on the site for 2005.

[4] BELARE 2004: Site Survey Expedition

[5] length: 600m, width: 16m, height: 20m

Table 1: Meteorological data 2005 – temperature [4]

Mean temperature	- 18 °C
Max temperature	- 1 °C
Min temperature	- 36 °C
Lowest monthly mean: September	- 25 °C
Highest monthly mean: December	- 8 °C

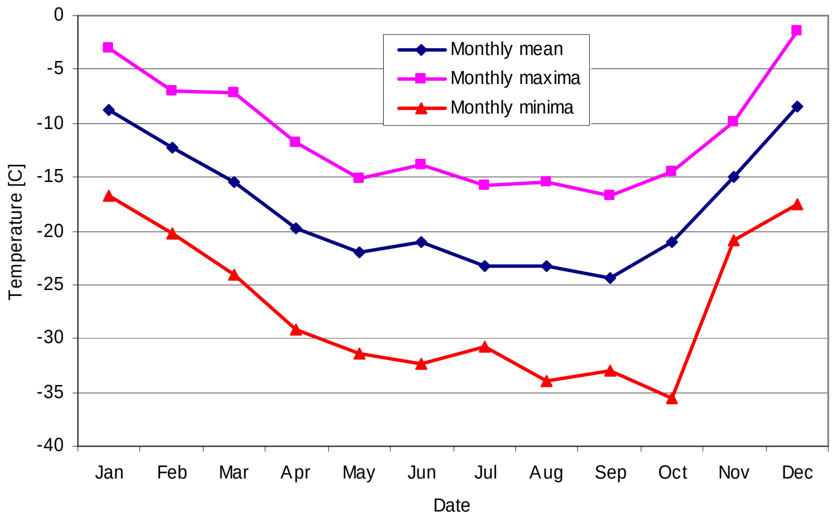

Figure 2: Monthly temperatures 2005 (Mean, maxima and minima) [4]

In 2005, average temperature is -18 degrees C, varying between -25 degrees C (September) and -8 degrees C (December). The maximum temperature never reaches 0 degrees C and the minimum temperature is -36 degrees C. Other records in the vicinity however reveal extremes up to -50 degrees C occurring during the winter period. The annual temperature variation reveals the typical winter of the more continental stations. The Antarctic continental climate is characterized by a rapid temperature drop in the fall, a first minimum in May, a second (more important) minimum in August/September and a very steep rise towards the December/January maximum. This typical winter results from the lack of radiation during the polar night. The temperature for the year 2005 is analogous to the records of the former Asuka station [4].

In order to calculate the solar radiation at the surface, the horizontal irradiance at the top of the atmosphere is investigated. This horizontal irradiance depends on the location on the globe, more precisely on the solar zenith angle. Before reaching the surface, part of this radiation is absorbed by the atmosphere and part is scattered by clouds and aerosols. The scattered radiation is thereby redirected and some of the radiation reaches the surface as diffuse radiation. The solar radiation at the surface finally depends on the atmospheric turbidity coefficient[6], the cloud cover[7] and the cloud albedo[8] [4].

When integrating the solar radiation at the surface, the amount of energy per square meter per day is calculated. During the austral summer, peaks of approximately 800 Wh/m^2/day are reached. The sun stays permanently below the horizon from May 16 to July 28 (73 days), but some twilight remains at noon, even at midwinter [4]. Figure 3 shows the monthly global horizontal variation based on Meteonorm. More details on day length, solar elevation and solar radiation can be found in Appendix B.

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[6] Turbidity coefficient equals 0.93 for arctic pack ice simulations [4]

[7] The recorded sunshine duration is used to approximate the daily sunshine duration. By scaling the daily sunshine duration to the theoretical day length, the mean daily cloud cover was obtained [4]

[8] Cloud albedo equals 0.4, since the dominant cloud type is cirrus and altostratus [4]

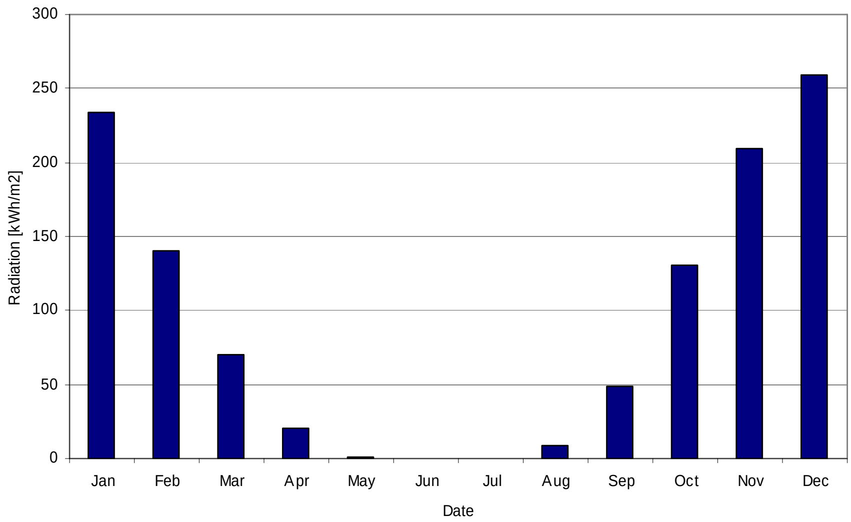

Figure 3: Monthly global horizontal radiation 2005 [kWh/m^2] - [32]

2.2.2 Wind speed and direction

The local wind climate in 2005 is characterized by a mean wind speed of 5.9 m/s (at 4 m height) with a prevailing wind direction from E to SSE. The most energetic wind direction is East with 90% of the energy content. Figure 4 shows the monthly mean wind speeds, the value for July is estimated as the weather station failed unexpectedly. The mean wind speed is rather low compared to other records in Antarctica mainly because the wind is obstructed and canalized by the mountain range. The region is dominated by katabatic[9] winds, which is a gravity driven phenomenon typical for Antarctica. These winds are formed at the center of the continent where the lowest layer of the atmosphere is in contact with the cold ice sheet. The air cools down and becomes denser. This cold heavy air flows down along the continental slope and accelerates towards the coast (due to increasing surface gradient). The wind at the site is constant and very unidirectional. Table 2 summarizes some important parameters for the wind profile of 2005 [5].

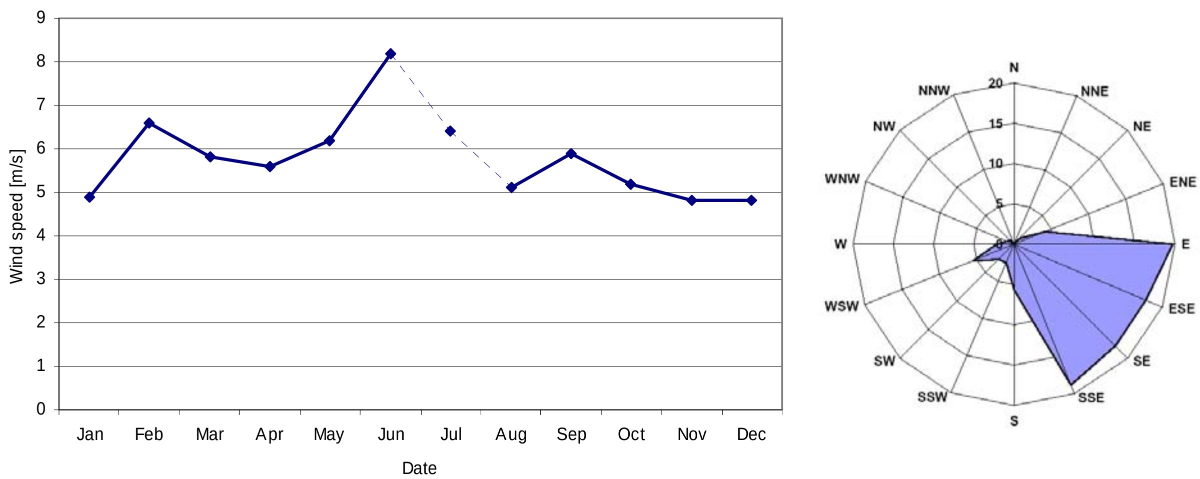

Figure 4: Monthly wind speeds 2005 (Mean and frequency) [5]

[9] Katabatic originates from the Greek word katabasis which means "descend".

Table 2: Meteorological data 2005 - wind climate [5]

Mean wind speed (4 m)	5.9 m/s
Main wind direction	E – SSE
Extreme wind speed (50 year recurrent)	54 m/s
Weibull scale parameter (c)	6.14 m/s
Weibull shape parameter (k)	1.33
Roughness length	0.03 m
Maximum recorded gust	32.9 m/s

2.2.3 Atmospheric pressure

Atmospheric pressure is relatively constant with a mean value of 827 hPa. The pressure curve lacks the double minima observed at coastal areas where cyclonic activity is present [1].

2.3 Design specifications of the station

The design of the Princess Elisabeth station is subjected to the following specifications [1].

Station occupation and use:

- The station is manned during the austral summer (from November to February), but it can be upgraded to a full year station (permanently manned) with minimal effort.
- Optimal use for 12 people with accommodation extension for an additional 8 people.
- All facilities (kitchen, sanitary, installations, offices, etc.) are suited for the extended occupation of 20 people.
- The station will have year-round monitoring and remote sensing capabilities.

Station and system design:

- Building surface: the main building has a floor area of 445 m^2; the garage/storage consists of 2 separate sections of 220 m^2.
- The design and layout of the facilities will minimize snow management.
- The building is designed for easy repair and damage control; a risk contingency plan is being developed.
- The system design of the station is based on sustainable technology and high energy efficiency. Nevertheless safety, health, comfort, functionality and cost are equally important design drivers.
- Redundancy, low maintenance and reliability are main design drivers.
- Recycling and lifetime maintenance strategies will reduce the running costs.
- Expected design life: 25 years.

Environmental impact

- All activities (construction, operation, maintenance and dismantling) must comply with the requirements of the Environmental protocol. The environmental impact will be minimal.
- The station will have a comprehensive energy and waste management. Waste treatment will include the treatment of water and the recycling capability for non-potable water applications.
- Renewable energy is used as primary energy source thereby minimizing the use of fossil fuel. (2 back-up generators are installed)
- An annual fuel consumption of 2000 litres for normal operation of the station is allowed. The objective is to achieve an annual fuel consumption below 1500 litres.

- A low emission objective is targeted. The aim is to have 95% of the energy from renewable sources.

Table 3 gives an overview of the main quantified design parameters.

Table 3: Design constraints Princess Elisabeth station [1]

Operational (research / monitoring)	Continuously
Manned	Austral summer (Nov – Feb)
Maximum occupation	20 people
Lifetime	25 years
Allowed annual fuel consumption	2000 litres
Renewable energy fraction (target)	95%

2.4 Building concept

The station design is based on a hybrid concept to maximize the on-site potential[10]. The main building is situated above ground and anchored with struts to the snow-free granite ridge. In its close vicinity, the garage section is situated under the snow surface. The main building and its interconnection to the garage are aerodynamically tested by the Von Karmann Institute (VKI) to ensure limited snow accumulation/erosion effects, reduced wind-induced forces and an optimized indoor/outdoor comfort level (by reducing the noise and vibrations). Field measurements, simulation models (CFD) and wind tunnel testing are applied to validate the final building concept and orientation [2]. Figure 5 is a graphical presentation of the final building concept.

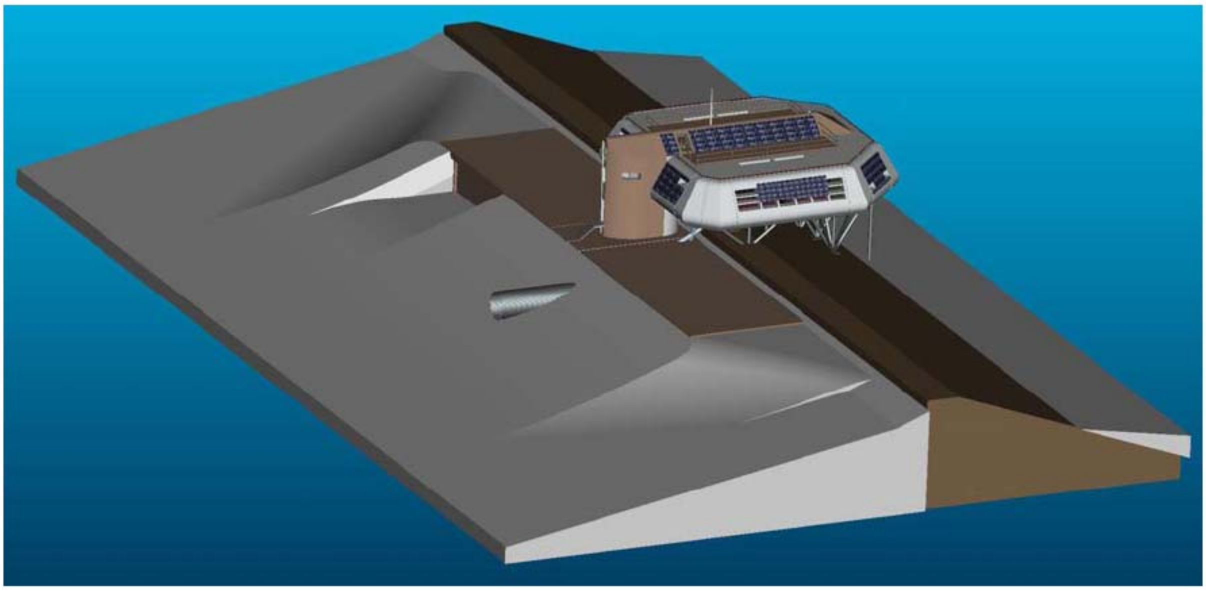

Figure 5: Final building concept [Source: IPF]

The main building consists of concentric layers around a central technical core. Within this core, all temperature-sensitive equipment (main electronics, water treatment system, batteries, etc.) is installed. A first concentric layer around this core is equipped with active (wet) systems such as the kitchen, the sanitary and the toilets. The final concentric layer is a "passive" area for sleeping, living and daily research activities. During the winter each zone is sealed to create a thermal buffer around the technical core. This concept guarantees acceptable minimum temperatures for each zone with

[10] Previous international Antarctic experience revealed some important issues on building concepts. Heated buildings in direct contact with the snow surface tend to sink and become destabilized. Next to this, buildings placed on the surface are very vulnerable to snow accumulation and erosion.

minimal heating demands. The “layer-based” design results in a high level of integration and compactness and has a significant effect on energy efficiency, reliability, maintenance and costs [1]. Figure 6 shows the final building layout.

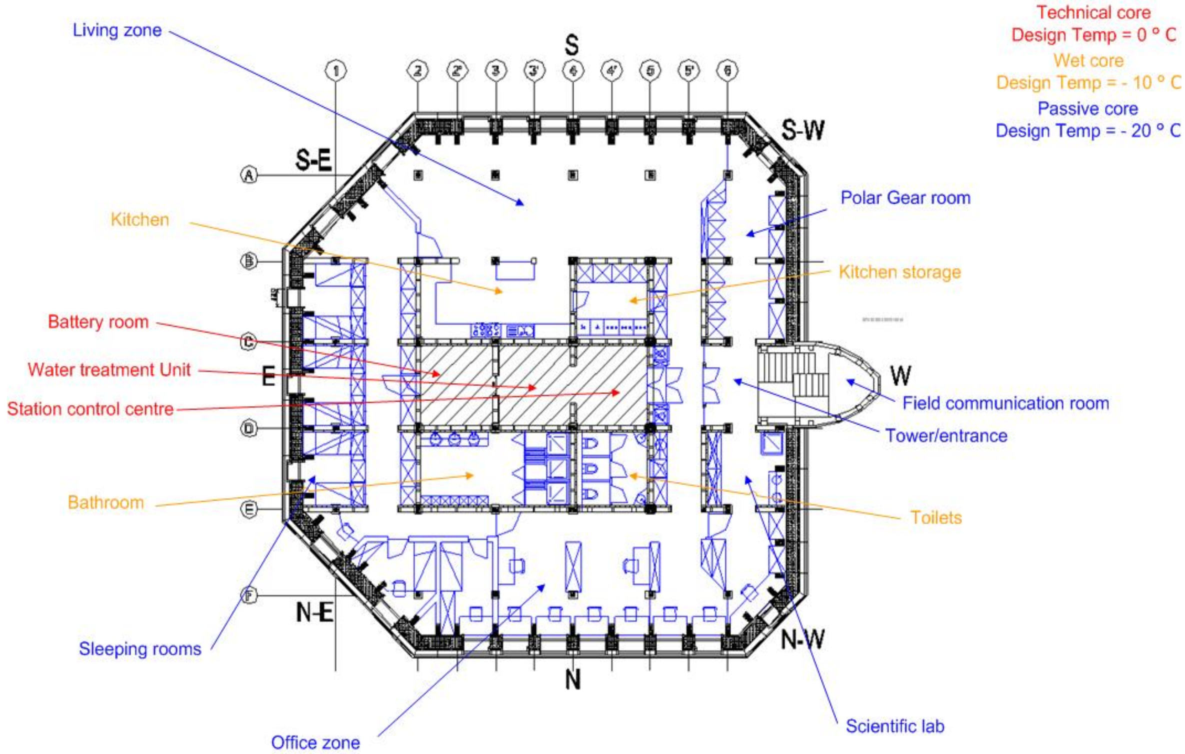

Figure 6: Building layout (dimension: 22 x 22 m) [1]

Next to the zoning, passive house standards are applied in the design to reduce the thermal and electrical demand. All panels, walls, ceilings and floors are wooden sandwich constructions with 40 cm of insulation[11] to ensure U-values of 0.07 W/m^{2}K. A vapour barrier is installed to avoid vapour transfer from the inside into the construction elements. This water vapour would condense and freeze inside the construction, leading to damage. Air-tightness is guaranteed with an EPDM finish on the outside skin, protected with a 1 mm thick stainless steel cladding. Additionally an intelligent ventilation system with efficient heat and humidity recovery is used to maintain thermal comfort. The sizing and configuration of the windows[12] is optimized to create a delicate balance between light and passive solar gains [6, 32]. Figure 7 shows the results of glare analysis.

[11] EPS from Swisspor with a conductivity of 0.029 W/mK

[12] Eurotherm: 2 times double glazed window with a Teflon film in the air filled cavity are used for redundancy. If one window breaks, the base is still protected from the environment. The U-value for each window equals 1.0 W/m^{2}K.

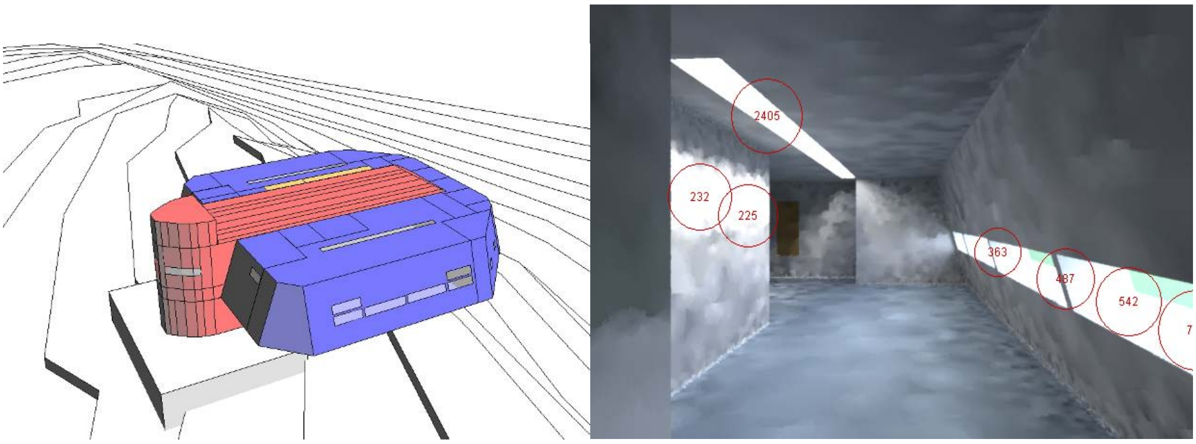

Figure 7: Glare analysis - living room – 15 December, 12h, sunny (cd/m²) [6]

Next to the building layout there is a specific field layout. On the north side of the ridge, all renewable energy sources are installed. On the south side of the ridge, a scientific shelter is constructed to house the main scientific experiments. This shelter is located at 100 m from the station to avoid any interference with the instruments. The different implementations are investigated upon safety, aerodynamic requirements (wake effects), electrical requirements (cabling and housing of cables), geological properties (anchoring), etc. Figure 8 shows the field layout. More details on the building concept, design and construction can be found in Appendix C.

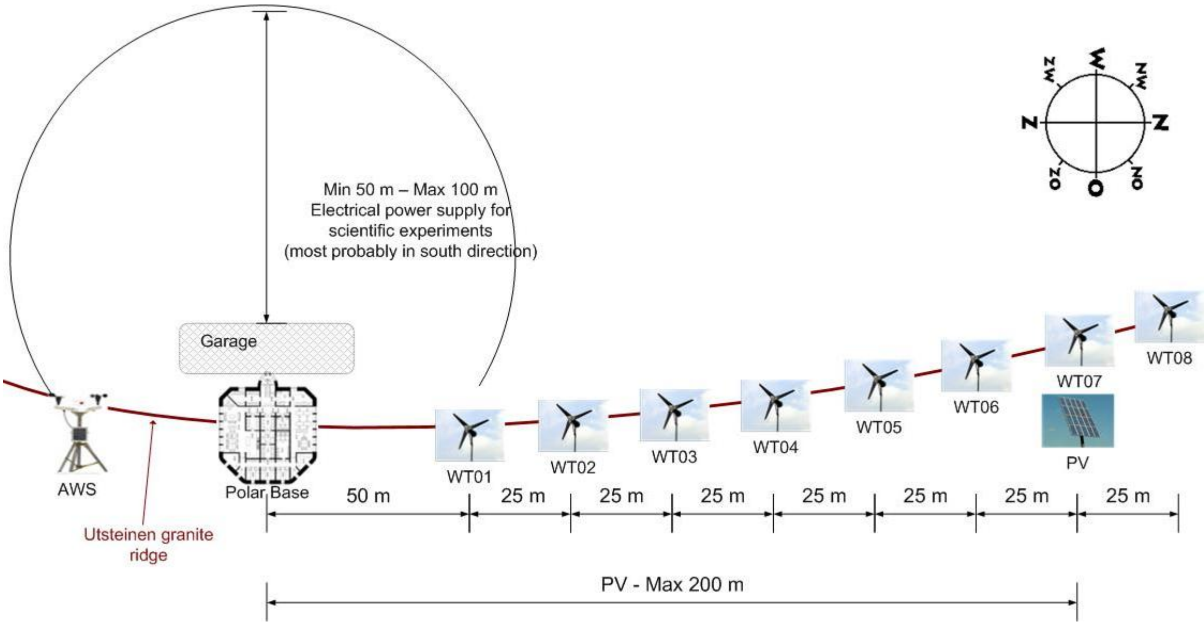

Figure 8: Field layout

3 Renewable energy design

3.1 Methodology

3.1.1 Energy system: electrical and thermal

The complete energy system of the station is tailor-made and thereby fully adapted to its specific environment. The energy system consists of 2 main parts which interact with each other, the electrical one and the thermal one. Figure 9 is a graphical representation of all the subsystems that interact with each other.

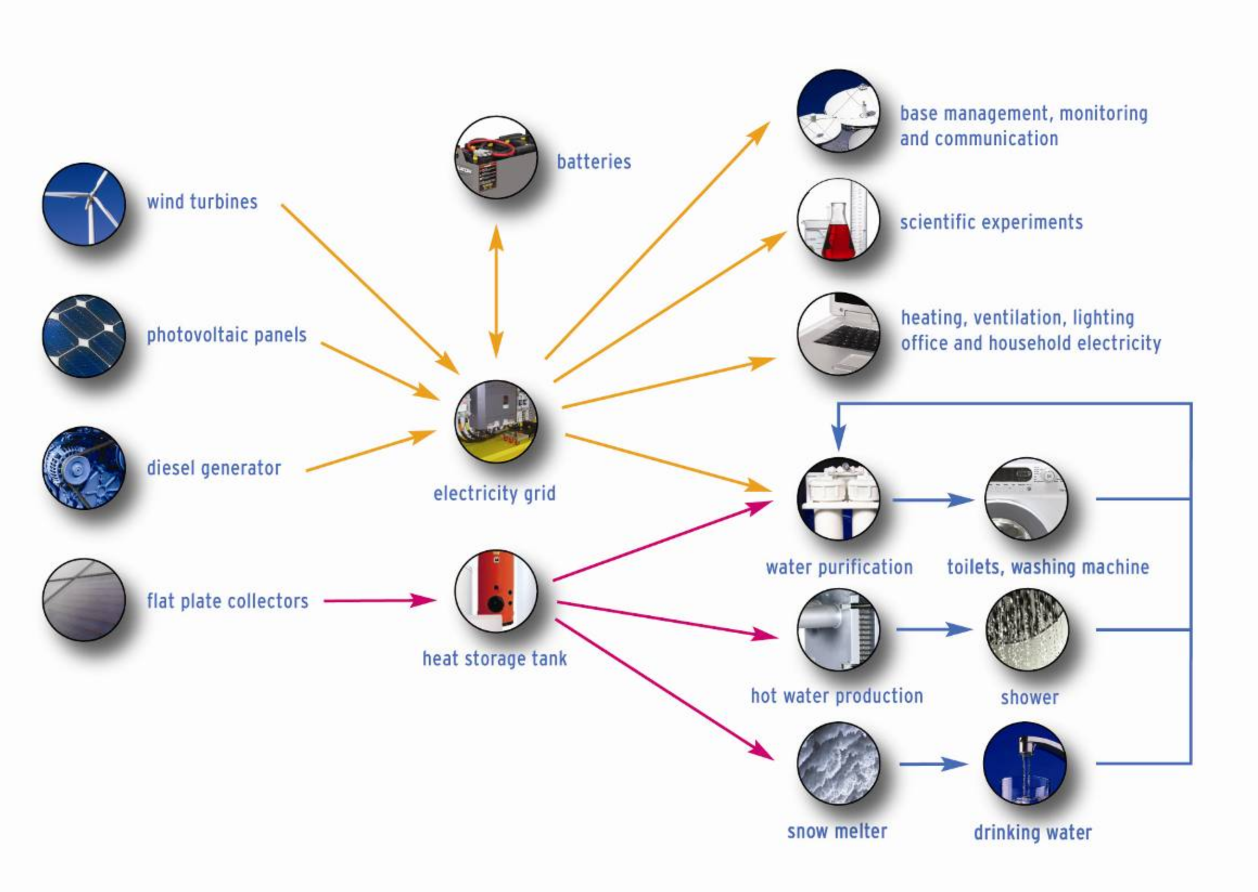

Figure 9: Energy systems of the station [Source: 3E]

The design procedure for the electrical part consists of the integration of all energy sources on an electricity grid, the storage of energy to cope with fluctuation of the resources, the accurate description of the energy consumers and the complete management of the electrical system. The thermal system copes with the active solar heating with solar thermal collectors, storage of heat and the different thermal consumers. Within the energy system, special attention is paid to the coupling and interaction of those 2 parts.

3.1.2 Modeling tool - TRNSYS

The dynamic modeling tool TRNSYS[13] is used for the simulation of the energy system as it allows to combine electrical, hydraulic and thermal parameters. The model consists of individual blocks (system

[13] TRNSYS: Transient Energy System simulation tool - http://www.trnsys.com

components) which are linked to each other to describe the complex energy system. A detailed model is developed for the Princess Elisabeth station[14] which takes into account the environmental conditions, the building properties (layout, materials and orientation), the crew occupation (electricity and water consumption), the specific properties of all active systems (PV modules, wind turbines, batteries, solar thermal collectors, storage tanks, pumps, tubing, ventilation, water treatment) and the control algorithms for all the systems. Step by step this model is adapted to the design changes to end up with an accurate representation of the real building on site. This model allows validation of new design decisions and the potential of future changes.

The model is a key element in the dimensioning of the hybrid energy system. It is used to size each of the individual components and the interaction of these components.

A visual representation of the TRNSYS model and its components can be found in Appendix D.

3.2 User profiles

The user profiles, or station occupation over time, are important to estimate the electrical load and water demand. The number of crew members over a representative year is based on available logistics and the experience of other polar science projects. Table 4 shows the crew occupation over a representative year.

Table 4: Crew members [1]

Scenario	Start date	End date	Max crew	Avg crew	Main activity
Winter	01/03	30/09	0	0	Remote sensing / monitoring
Start up unmanned	01/10	31/10	0	0	Heating / water treatment
Start up manned	01/11	07/11	4	4	Technical systems
High season 1	08/11	30/11	20	14.3	Science
High season 2	01/02	22/02	20	14.1	Science
Low season	01/12	31/01	12	8.6	Science
Closing down	23/02	28/02	4	4	Preparing for winter

The number of people on the station varies throughout the season and the planned activities. There is always a minimum support staff of 4 people, although this number may increase depending on the support required for scientific work. Next to the fixed staff, on average half of the other crew members are present at the station. The rest of the crew performs field exploration.

Next to the seasonal occupation, the daily profile of the activities at the station is important for more detailed energy calculations. Figure 10 represents a typical day.

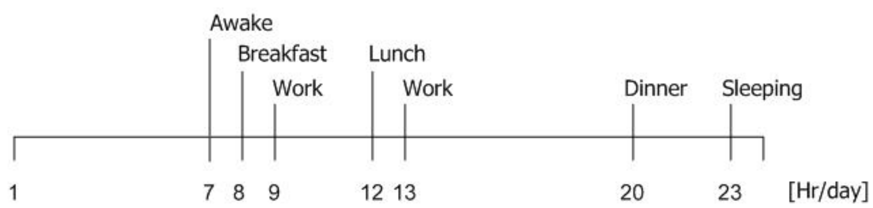

Figure 10: Typical daily profile [1]

The seasonal occupation and daily profiles are not only used to estimate the electrical consumption, but also to generate the water demand and the coupled internal gains (thermal gains due to presence

[14] A first TRNSYS model for the Princess Elisabeth station is developed by Ir. R. De Coninck in 2006.

of active systems and human bodies in the building). These data are used as inputs for the sizing of the energy system and its components. More details on the user profiles can be found in Appendix E.

3.3 Electrical equipment

The electrical loads from the equipment have a major impact on the energy system design. Sufficient energy (electrical and thermal) needs to be supplied at the right moment to sustain proper functioning of the station. Each electrical load is described in detail and listed in cooperation with the project partners. Parameters such as nominal power, operating hours, timing, correlation with users and reactive power are investigated and taken into account. The loads can be either three-phase or single-phase.

The loads are regrouped to:

- Household and office equipment: standard electronics, lighting and white goods.
- Research equipment: scientific equipment.
- Life support equipment: water management, heating, ventilation and station management.

3.3.1 Household and office equipment

All electronics for the office and living zone are standard equipment that is commercially available. Even the kitchen equipment (white goods) is standard. Each item is selected on the basis of its compactness and energy efficiency. The lighting for the complete station is designed for year-round operations. Table 5 shows the standards[15] used for dimensioning the lighting.

Table 5: lighting levels for the station – [6]

Office / living / kitchen	500 lux
Sleeping rooms / circulation	200 lux
Sanitary	300 lux
Technical core	200 lux

For each lighting zone, a technology tradeoff is established, based on efficiency, reliability, lifetime, allowed temperature, harmonic distortion and cost. Table 6 shows the technology that is used:

Table 6: Lighting technology – [6]

Technology	Location
TL5	All locations in the station with temperature > 0°C.
Compact fluorescent	Locations in the station where TL5 can not be installed due to geometrical constraints.
LED	Locations where temperature can drop below 0°C (Tower and garage)

Additional portable lighting is available for specific operations such as maintenance in the technical core. More details on the technology tradeoff and station implementation for the lighting can be found in Appendix F.

3.3.2 Research equipment

Scientific diversity is guaranteed due to the unique location of the station. At the foot of an important mountain range (Sør Rondane) and close to the edge of the polar plateau (Nansenisen), the station

[15] NBN EN 12464-1 Light and lighting – Lighting of working spaces - Part 1 : Interior working spaces

acts as a hub for field exploration. Daily field trips (up to 30 km) and longer field explorations (up to 200 km) are organized. The station itself is also well situated for monitoring environmental change in Antarctica. Due to its remote location (nearest neighboring station at 431 km), the station is an important node in the network of geophysical observatories in East Antarctica. The following scientific programs are currently planned [1]:

- Geophysical measurements: gravimetric, seismic and GPS measurements to evaluate ice mass change.
- Microbial diversity and biogeography research: research on distribution of micro-organisms.
- Dynamics of eastern Antarctic ice flows: study on ice movements and ice sheet stability.
- Atmospheric research: Stratospheric and troposheric research with high precision ozone measurements.
- Paleoecological research: anlaysis on former ice sheet thickness.
- Dynamic interaction of Antarctic ice sheet and subglacial environment: relation between glaciers and lakes.
- Climate modeling: regional climatic modeling
- Meteorite research: study on meteorites and micrometeorites.

Sufficient energy is foreseen to supply all these research activities. Additional margin and flexibility is taken into account for future experiments.

3.3.3 Life support equipment

Reliable life support equipment is essential for scientific research in Antarctica. It contains the complete water management (production, treatment, distribution and storage), the heating, the ventilation and the station management (SCADA, emergency and communication).

Water management

Efficient water housekeeping is an important design driver. Water production, treatment and distribution are energy intensive and all possible means are applied to reduce the electrical loads. For example highly efficient dish and cloth washing machines and water efficient showers are used to reduce the water and energy demand significantly. Figure 11 is a schematic representation of the water management. The following flows can be distinguished:

- Antifreeze: the antifreeze circuit is mainly the primary circuit of the solar thermal system.
- Heating water: the heating water is a closed circuit that is used to keep the water treatment at the desired temperature and to feed the heat exchanger for hot sanitary and recycled water.
- Grey water: waste water from showers, sinks, kitchen, etc.
- Black water: waste water from the toilets.
- Meltwater: melted snow for potable use such as cooking.
- Recycled water: grey and black water recycled by the water treatment unit, ready for non potable reuse.

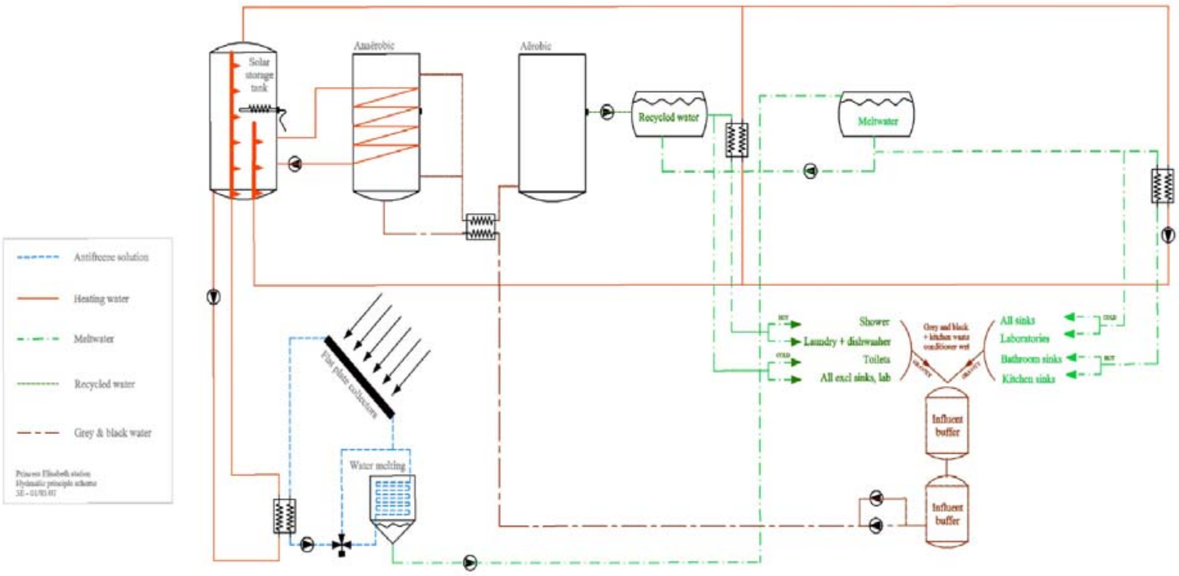

Figure 11: Water management [32]

The water management has 3 main functions:

- Water production: Snow is melted mainly using the primary antifreeze circuit of the solar thermal system. An additional electrical heating is foreseen in the melting unit to ensure water production under all conditions. The location of the snow melting unit is primarily defined by aerodynamics. As the wind blows on the ridge and building, snow is accumulated. The collected snow is dumped into (the lower positioned) snow collector in the garage. If needed a snow tractor can be used to collect the snow and dump it in the melting unit. Once the snow is melted, it is transported in heat traced ducts to the technical core for filtering and storage.
- Water treatment: Grey and black water are collected separately in influent buffer tanks of 2 m^3. These tanks are located in the bottom part of the tower to ensure a gravity driven drainage. The stored black water is fed continuously into an anaerobic biological reactor, which uses a bacteriological substance[16] to break down the waste in an ecological manner at a temperature of 55 degrees C. After the anaerobic process, the filtered black water is mixed with the grey water and fed to the aerobic membrane bioreactor for further filtering. After the complete process, all water passes an active carbon filter, UV treatment and multiple measuring units. The resulting treated water has hygienic, non-drinking quality. Under optimal operations, only a minimum of the total water amount needs to be renewed each cycle. Due to the elevated efficiency of the cycle (+90%) only a limited amount of filtered water is discharged into the snow surrounding the base. None of the sludge or waste is discharged into the nature, but will be stored in specific containers located in the garage. These containers will be shipped at the end of the season for recycling. Figure 12 is a schematic representation of the water treatment unit.

[16] The biological substance will be flown in each year at the beginning of the Antarctic season.

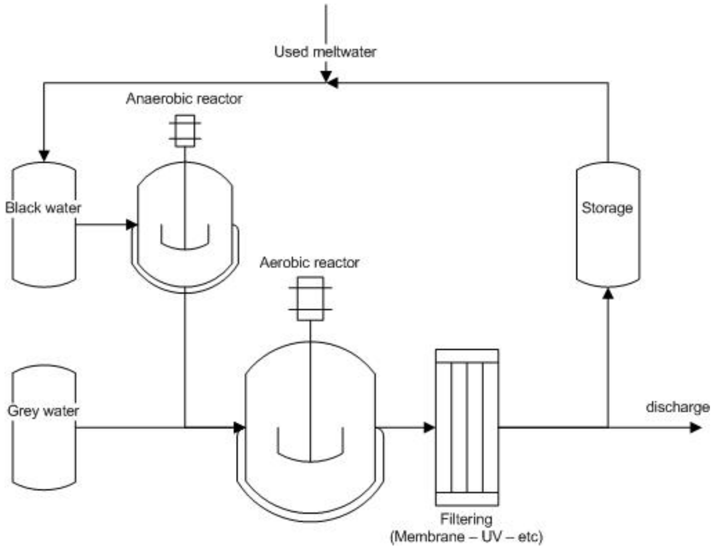

Figure 12: Schematic overview water treatment unit (WTU)

- Water distribution and storage: both meltwater and recycled water are stored in tanks in the upper level of the technical core. Sanitation systems (UV treatment) guarantee the water quality in those tanks. The water is put under pressure and connected to the water distribution terminals (cold water directly, hot water is coupled to the heat exchangers and then to the distribution terminals).

The daily demand for meltwater and recycled water (hot and cold) depends on the crew occupation on the station. Table 7 & Table 8 show the estimated daily water use of 1 person.

Table 7: Water consumption - recycled water

Recycled water	Litre/user/day
Toilets	10
Laundry	5
Dishwasher	3
Garage	2
Showers (45 °C)	30
Total recycled water	50

Table 8: Water consumption - meltwater

Meltwater	Litre/user/day
Kitchen	10
Sinks	5
Laboratory	5
Total meltwater	20

A more detailed temperature overview of the reactors can be found in Appendix F.

Heating

Different heating technologies are investigated. A water-based heating is abandoned as the building is passive and additional heating is only required in periods without sun. A water-based system is only interesting if the heat source is renewable. A heating system integrated in the ventilation is also abandoned for flexibility and redundancy. Especially during the winter period it is advantageous to heat without having the ventilation operational. A decentralized electrical heating (natural convectors) is chosen because it offers a lot of flexibility.

The maximum heat demand for the building is calculated under the assumption that the station is also manned during the winter. During the austral summer, almost no additional heating is required. The passive solar gains and internal gains (due to human presence and machines) are sufficient to heat all the building zones. The following comfort temperatures are maintained at all times when the station is manned (Table 9).

Table 9: Comfort temperatures [17]

Zone	Comfort temperature
Living / office zone	20 °C
Sleeping rooms / entrance	16 °C
Sanitary zone	23 °C

A total of 28 convectors (1 kW) is installed in the station to ensure sufficient heating under all conditions. Once the station is unmanned, heating is only applied at the technical core to keep the temperature above 0 degrees C. The outer zones of the building will cool off till almost -20 degrees C. The specific layout of the heating elements and the temperature profile for all building zones during a manned week can be found in Appendix F.

Ventilation

The ventilation provides fresh and humidified air in the building. The ventilation also cools the building when overheating occurs. Three identical ventilation groups are installed in the building, one for the office, sanitary and laboratory, one for the living, kitchen and sleeping rooms and one for the technical core.

The technical core is ventilated during the whole year; the ventilation of the other zones is only needed during the manned periods. A highly efficient heating and humidity recovery unit is used to obtain optimal comfort levels at all times. Currently a steam humidifier is installed to guarantee sufficient humidity levels for comfort and static electricity reasons. More research is done on the use of a more energy efficient ultrasonic humidifier. Each room in the station and the main ventilation ducts are provided with temperature sensors and CO_2 concentration sensors to regulate the air flow.

The ventilation has a primary role in the concept and is identified as a major critical part of the concept. If the technical ventilation fails, overheating[17] occurs and the electrical system fails. Not only scientific experiments will stop, but also essential life sustaining components will gradually fail (water treatment unit, batteries, power electronics, servers for control algorithms, remote communications, safety instruments, etc.)

A more detailed layout of the ventilation for the technical core and the other zones can be found in Appendix F.

Station management

As described in the previous section, all equipment in the station originates from the home, office and industrial environment. The interaction of all these systems with the environment needs to be monitored very closely. As the station is only manned during the summer, but partly functions continuously, remote monitoring and communication is needed. A SCADA (Supervisory Control And Data Acquisition) system is used to handle the complete integration of electrical equipment, coupled to a network of sensing units. A more detailed description of the SCADA and its components can be found in section 3.7.

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[17] Due to passive housing norms used in the design of the polar base (high insulation level), overheating can occur very fast in case of failure of the ventilation system. Overheating seems a strange problem in Antarctic conditions, but opening a hatch or window to the external environment is not advised due to elevated temperature gradients.

3.3.4 Load summary

To obtain the electrical loads, all electrical equipment is coupled to a seasonal and daily occupation profile. A distinction is however made in the way they are inserted into the dynamical TRNSYS model. The equipment depending on thermal and hydraulic parameters is modeled directly. This means equipment such as ventilation, water pumps, heating elements and humidifiers are modeled mathematically and coupled in the simulation model with the appropriate control algorithms. This to ensure the impact of a change in input parameters (e.g. meteorological) or in model parameters (e.g. building layout, insulation, chosen technology and control algorithms) can be evaluated on the electrical consumption.

The rest of the loads are only coupled to the seasonal and daily occupation to obtain an hourly electrical load. These are inserted in the model as a total hourly electrical consumer, and are no longer coupled to the design parameters mentioned above. Finally all the loads in the model are summarized for further analysis. Table 10 summarizes the total installed capacity of all the equipment; Table 11 gives an overview of the corresponding annual energy consumption for a representative year.

Table 10: Installed capacity - electrical equipment

Installed capacity	143 kW	
Household and office equipment	40 kW	28%
Research equipment	9 kW	6.3%
Workshop equipment	8 kW	5.6%
Water management	28 kW	19.6%
Ventilation	27 kW	18.8%
Heating	28 kW	19.6%
Station management	3 kW	2.1%

Table 11: Annual energy consumption – electrical equipment

Total annual consumption	70 MWh	
Household and office equipment	3.8 MWh	5.4 %
Research equipment	28.8 MWh	41.1 %
Workshop equipment	0.15 MWh	0.2 %
Water management	15.5 MWh	22.1 %
Ventilation	11.2 MWh	16.0 %
Heating	2.6 MWh	3.7 %
Station management	8.1 MWh	11.5 %

The peak load is approximately 28 kW. This peak occurs in the beginning of November, at the start-up of the season, as the complete building needs to be heated. A graphical presentation of the annual load profile can be found in Appendix F.

Figure 13 shows the monthly electrical consumption for the different equipment. It is important to notice each of the equipment has a different priority scheme. This means some loads can easily be shut off and postponed (deferrable loads) during some time while others cannot. The workshop equipment, cleaning, laundry, kitchen, office equipment, lighting and even the heating can easily be postponed for several hours (some of them even days if needed). The ventilation and the water treatment can be shut off also, but over a more limited time interval. Finally, some applications such as the monitoring, emergency and scientific equipment need uninterrupted power supply under all conditions.

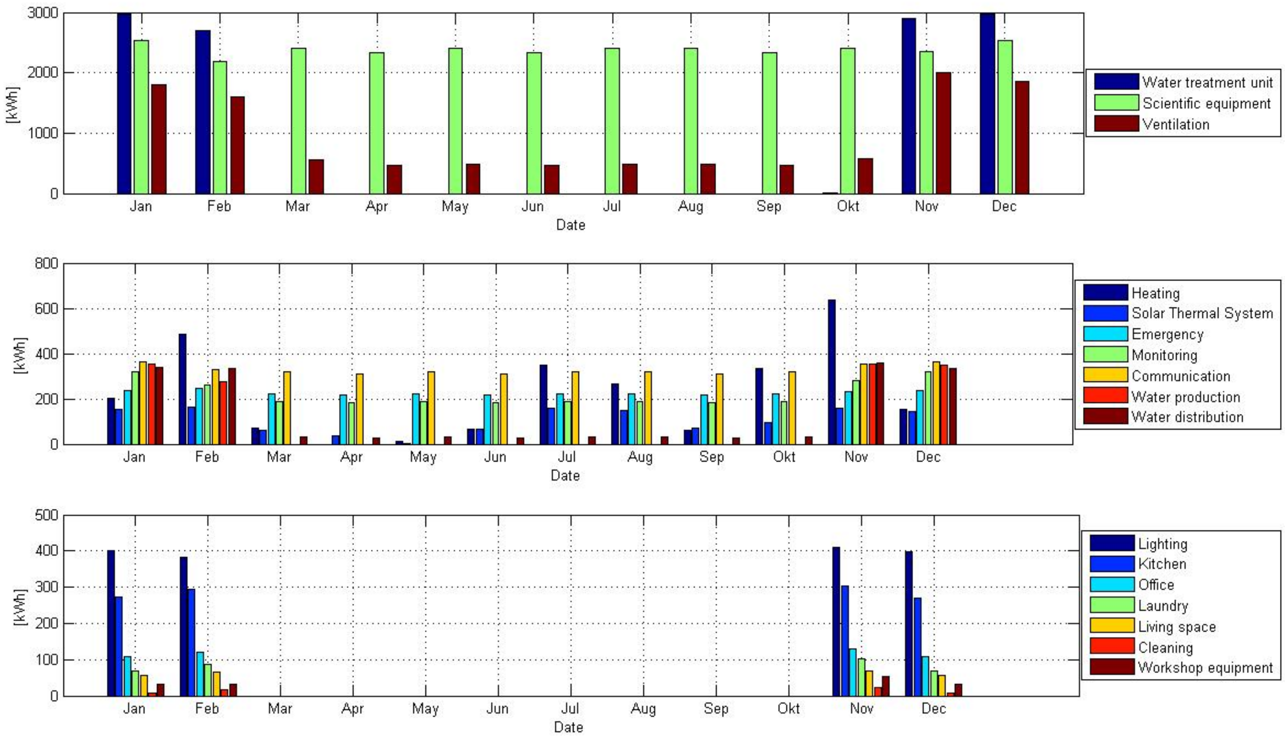

Figure 13: Monthly electrical energy consumption

In the the energy system, the different load prioritization has an important role. As power and energy management need to ensure a balance in the generation and consumption at all times, load prioritization schemes can be used for optimization of the available energy. Section 3.6 and 3.7 give a more detailed overview of the power and energy control systems.

3.4 Sources

3.4.1 Wind turbines

Wind power has been used in Antarctica since several years. The first turbines however did not function well as they were not designed for the polar environment. The strong winds resulted in structural failure and vibrations due to resonance. The low temperatures damaged the electronics and gearboxes. Operation of wind turbines in cold and remote areas imposes high demands on the design.

For the selection of the wind turbine, the following issues are considered [13]:

- Icing: when ice is formed at the blades, the load on the rotor increases and the aerodynamic profile is changed. This changes the resonance frequency of the turbine and thereby increases the risk for structural failure. Icing also delays stall and overproduction can occur, which damages the generator. As the temperature in Antarctica is mainly below zero and air is very dry, the risk for ice formation is low and no adaptations are needed on the wind turbines.
- Low temperatures: due to low temperatures, metals are more fragile and less fatigue resistant. Lubricants become more viscous. There is a preference for a direct driven wind turbine (without a gearbox) as the number of moving parts should be minimized. The use of a synthetic lubricant rated for cold climates is a must as minimum temperatures up to -50 degrees C can be expected.

- Wind climate: as the rotor load is proportional to the square of the wind speed, the strong katabatic winds induce high loads on the wind turbine. The wind climate at Princess Elisabeth is however weak compared to other Antarctic locations, which reduces this risk. A survival speed up to 55 m/s is needed.
- Snow presence: Antarctic snow is characterized as very fine. All parts should be sealed very well to prevent snow intrusion.
- Anchoring: as the wind turbine is heavily loaded, it should be anchored well. In Antarctica, the anchoring is however difficult due to limited presence of solid ground. The use of concrete structures is complicated and other alternatives such as water and composites are used for anchoring. At the site of Princess Elisabeth successful tests are performed on the use of a composite anchoring.
- Erection: the wind turbine must be erected on site by manual forces.
- Logistics and storage: compactness of the wind turbine is important for the transport and storage. Especially a tower existing of multiple parts is preferred.
- Maintenance and reliability: as for each remote area, maintenance should be reduced as much as possible without compromising the reliability of the wind turbine.
- Logistics and installation on site: in terms of maintenance, cost and anchoring reduction, only a few "big" wind turbines need to be installed. A large number of smaller units however facilitate the transport, storage and erection. It also increases the redundancy of the complete system, since failure of a single system would not dramatically decrease total energy production. The second option is therefore preferred.

Based on the selection criteria, different wind turbine models are evaluated. The Proven WT6000, a 6 kW passive pitch controlled downwind turbine has been selected as it scores best on most of the criteria. A feasibility study on wind power for the Swedish[18] polar station confirms this choice [13]. Table 12 gives an overview of the specification of the selected wind turbines.

Table 12: Specifications wind turbine [34]

Manufacturer	Proven
Type	WT6000
Rated output	6 kW
Rotor diameter	5.5 m
No of blades	3
Hub height	9 m / 10 m
Output	300 V wild AC
Cut-in wind speed	2.5 m/s
Nominal speed	12 m/s
Survival speed	65 m/s
Operating limit	–50°C
Gearbox	No, direct driven

A more detailed specification of the wind turbine can be found in Appendix G.

Based on dynamical simulations, approximately 30 kW of wind power needs to be installed on the site. To balance the phases of the grid a multiple of 3 of the selected wind turbines is needed. Therefore a minimum of 6 wind turbines is installed on the site. Based on topographic measurements and erection requirements of the wind turbines, a maximum of 8 wind turbines can be installed on the north side of the ridge

[18] Feasibility study for wind power in Wasa: Proven WT6 is selected due to high capacity factor (32%), highest operating frequency (82%), availability of arctic package and low cost/kW.

Table 13: Installed capacity and energy production – wind turbines

Installed capacity	36 kW (6 x 6 kW)
Annual energy production	93 MWh

To connect each wind turbine to the 230/400 V AC grid, the wild AC output of the wind turbines is rectified (AC – DC) and inverted (DC – AC) using power electronics. The wild AC is transported from each wind turbine to the tower section of the building. This means both rectifier and inverter are placed in a protected environment, which is off course advantageous. In addition, the generated heat of the power electronics helps to maintain the temperature in the tower section.

Special attention is paid to an over-voltage protection (DC) installed in between the rectifier and the inverter. The DC input of the current inverter is limited and therefore a protection is needed to avoid damage when the input voltage exceeds a predefined limit. Figure 14 is a graphical presentation of the power electronics for each wind turbine.

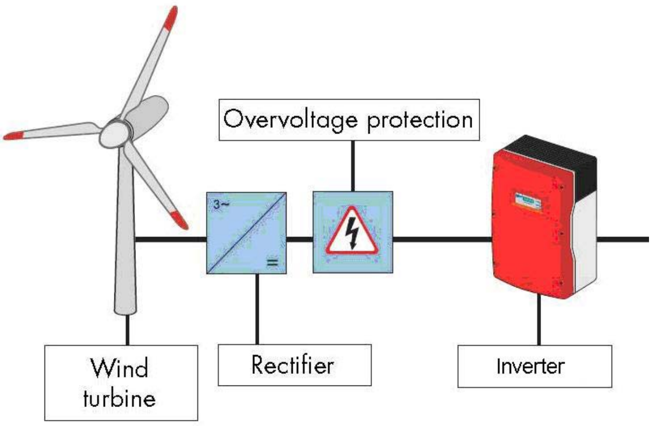

Figure 14: Rectifier and inverter for wind turbines [51]

3.4.2 Photovoltaic arrays

The photovoltaic arrays will mainly provide electrical energy during the austral summer, as the sun is abundantly available. From Figure 3 it can be concluded there is approximately 40% more sun during the Antarctic austral summer than during a Dutch summer [33]. Special attention is paid to the reflection of the radiation on the snow (albedo equal to 0.8) and the low ambient temperatures. PV cells tend to work much better in cold climates (except for amorphous silicon panels). Due to the temperature and the reflection, array currents up to 20% higher than the specified output have been reported [9]. The peak power of the arrays under (ant)arctic conditions is thus estimated as being 120% of the peak power at Standard Test Conditions (STC).

In order to get a first understanding on the solar radiation and the influence of orientation and tilt angle, a general solar assessment has been carried out. A 10kWp PV system is simulated in function of different orientation and tilt angles. The graphical result is shown in Appendix H. The following can be concluded [7]:

- For all tilt angles, the north orientation gives the highest yields.
- For all orientations, the 70 degrees tilt angle gives the highest yields.
- Maximum yield is obtained for the north orientation, at 70 degrees tilt angle.

A part of the PV arrays is mounted on the building (Building Integrated Photovoltaic - BIPV). The exterior walls of the main building are designed with a tilt angle of 70 degrees to optimize the yield of the PV modules mounted on the skin. Detailed radiation calculations for each orientation on the building can be found in Appendix H. The rest of the PV modules are installed on the field in the vicinity of the station (Stand-alone Photovoltaic - SAPV).

Building integrated photovoltaic

In close cooperation with the technical partners, the available skin surface on the main building for integration of PV arrays is calculated. In order to optimize the available surface, two different representative commercial PV modules are selected. Table 14 shows the properties of the reference modules, Table 15 the corresponding optimized module configurations. The specific layout of the modules on the available surfaces can be found in Appendix H.

Table 14: Specification PV module

	Module 1	Module 2
Type	Polycrystalline	
Efficiency at STC[19]	> 13 %	
Peak power (P_{MPP})	200 Wp	130 Wp
Peak power voltage (V_{MPP})	26.3 V	17.6 V
Open circuit voltage (V_{oc})	32.9 V	21.9 V
Length	1500 mm	1500 mm
Height	1000 mm	650 mm
Thickness	50 mm	50 mm

Table 15: Module configuration BIPV

Orientation	Location	Module 1		Module 2	
		# modules	# m²	# modules	# m²
West 1	wall	8	12	12	11.7
West 2	wall	8	12	12	11.7
North	wall	11	16.5	16	15.6
South	wall	7	10.5	10	9.75
South	Roof	18	27	27	26.3
North East	wall	6	9	8	7.8
South East	wall	6	9	8	7.8
East	wall	9	13.5	13	12.6
Total		73	109.5	106	103.3

Table 16: Installed capacity BIPV and annual fuel consumption

	Module 1	Module 2
Installed capacity (STC)	14.6 kWp	13.8 kWp
Installed capacity (@ South Pole)	17.5 kWp	16.5 kWp
Annual fuel consumption	1300 litres	1370 litres

Simulations show that both modules are suited for integration on the building as their annual energy generation only differs 5%. There is a slight preference for reference module 1 since more power can be installed on the available area (Table 16). Module 2 has however advantages in handling and structural rigidity due to its reduced dimensions. Module 2 is finally chosen to be installed on the building (and for further calculations). Table 17 and Figure 15 show the installation and related production.

[19] STC: irradiance 1000 W/m2, module temperature 25 °C

Table 17: Installed capacity and energy production – BIPV

Reference module	2
Number of modules	106
Installed capacity (STC)	13.8 kWp
Annual energy production	11.6 MWh

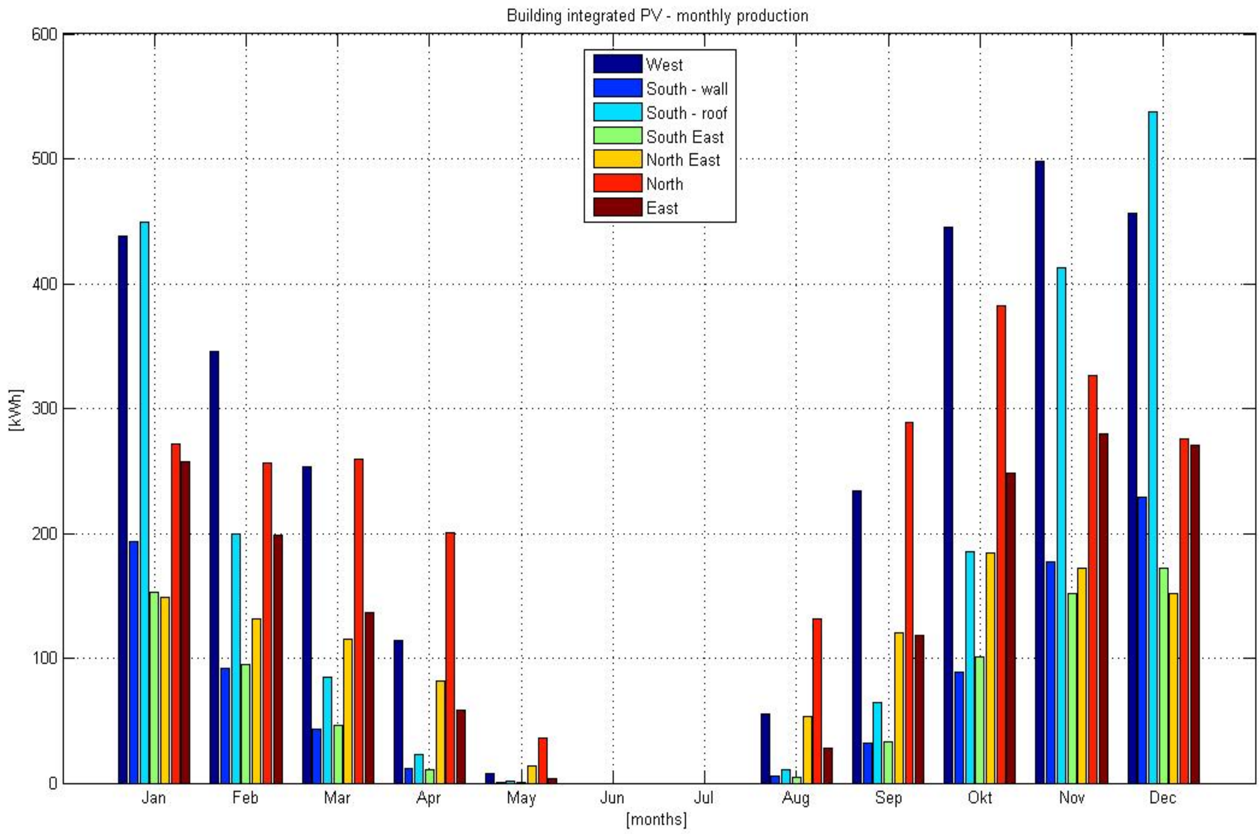

Figure 15: Monthly energy production BIPV - module 2

Next to module optimization, the array configuration needs to be defined. The array configuration handles the number of modules for each string (series connection) and the number of strings connected in parallel. The array configuration mainly depends on:

- Type and capacity of the power inverters.
- Integration in the building structure (module layout).
- Orientation and inclination of the arrays.

Table 18: Array configuration - BIPV

Array	String orientation	Modules per string	# strings	Peak Power [kWp]	V_{MPP} (V) @ 200 W/m² (Vmin)	Voc (V) @ STC	Voc (V) @ -60 deg C (Vmax)	Inverter type
1	W1	12	1	1.56	211	263	270	Multi-string
	N1	16	1	2.08	282	350	357	
2	W2	12	1	1.56	211	263	270	Multi-string
	S3 + S4 (roof)	14	1	1.82	246	307	314	

Array	String orientation	Modules per string	# strings	Peak Power [kWp]	V_{MPP} (V) @ 200 W/m^2 (Vmin)	Voc (V) @ STC	Voc (V) @ -60 deg C (Vmax)	Inverter type
3	S4 (roof)	13	1	1.69	229	285	292	Multi-string
	E	13	1	1.69	229	285	292	
4	SE	8	1	1.04	141	175	182	Single string
5	NE	8	1	1.04	141	175	182	Single string
6	S1	10	1	1.30	176	219	226	Single string
TOTAL		106		13.8				

Table 18 shows the final array configuration of the building integrated PV. The first three arrays are coupled to three identical multi-string converters with a minimal DC power capacity of 5 kW. The multi-string[20] is needed as the strings can have different orientations and inclinations. The final three arrays are connected to single-string[21] converters as they only have a single orientation and inclination. A more detailed sketch on the integration of the different arrays in the building can be found in Appendix H.

Stand-alone photovoltaic

Apart from to the building integrated PV modules, the major part of the modules is installed on the field in the vicinity of the station. As little information is known on the possible orientation and inclination of the stand-alone PV, horizontal mounting is assumed (inclination equal to 0 degrees). As a large amount of PV modules is needed to build up the complete field, reference module 1 is preferred to limit the number of structural and electrical connections. The amount of additional PV modules required on the field is found using sensitivity analysis. Figure 16 is the graphical result of the sensitivity analysis. Each line in this graph represents a combination of the 2 main sources (Wind turbines and PV) corresponding to an identical annual fuel consumption. Annual fuel consumption represent the amount of energy produced with non-renewable resources and is therefore used as the most important decision variable in performing trade-offs.

Based on these calculations, the following is concluded:

- If only 6 wind turbines are installed and none of the PV arrays, the annual fuel consumption is approximately 11000 litres. This is case A in the graph.
- When adding the 13.8 kWp BIPV, the annual fuel consumption becomes 7200 litres, which is still above the initial objective of 1500 litres. (Case B).
- An additional 36 kWp PV needs to be installed on the field, to achieve an annual fuel consumption of 1370 litres (case C).

[20] Multi-string inverter – Minimal DC power: 5 kW – Voltage range [200 -500] – Minimal current/string: 11A
[21] Single string inverter – Minimal DC power: 1.85 kW – Voltage range [150 -400] – Minimal current/string: 12A

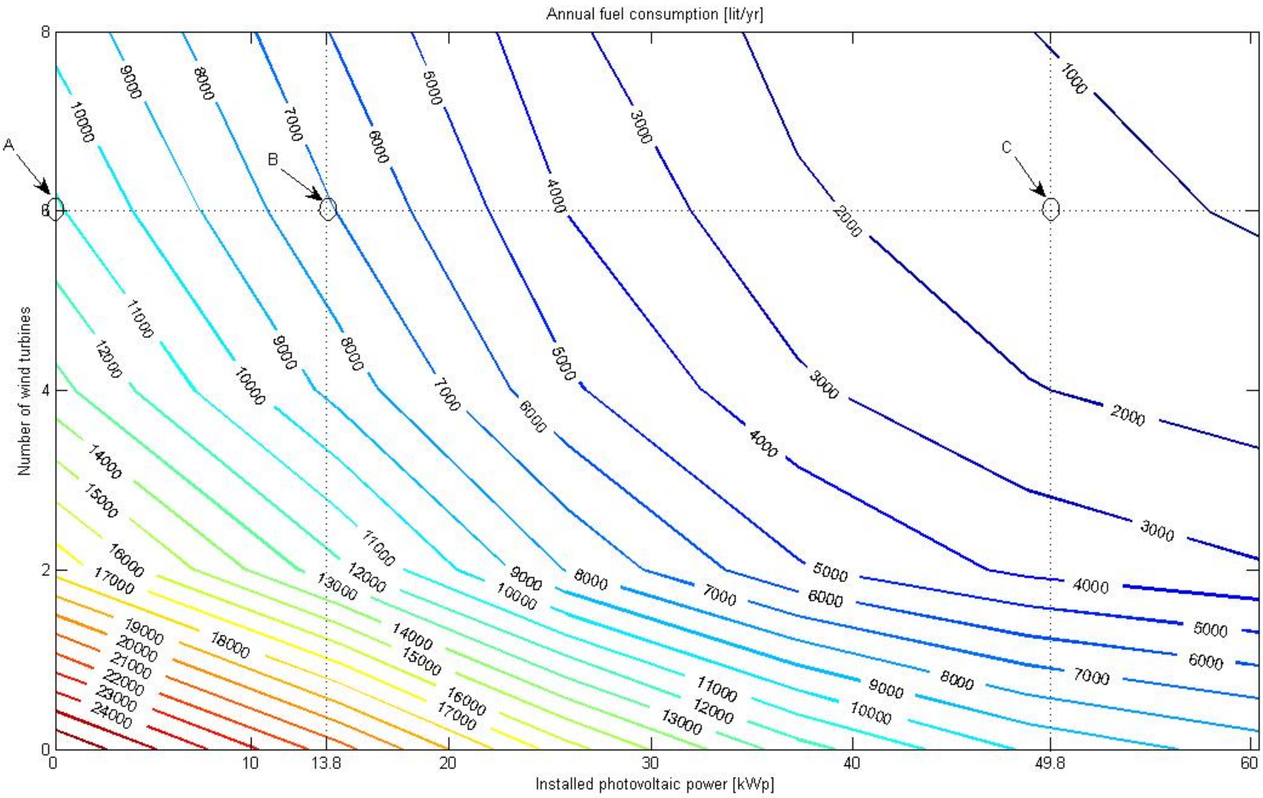

Figure 16: Sensitivity analysis PV – wind turbines

Table 19 represents the final configuration for the stand-alone PV.

Table 19: Installed capacity and energy production – SAPV

Reference module	1
Number of modules	180
Installed capacity (STC)	36 kWp
Annual energy production	34.2 MWh

As for the building-integrated PV, the array configuration also needs to be defined for the stand-alone field. Again an optimization is performed on different types of power converters, the geometrical constraints for the power converters and the required number of PV modules. The final stand-alone PV system exists of 6 arrays. Each array has 2 strings (connected in parallel) with the same orientation and inclination. Each string contains 15 PV modules connected in series. Each array will be coupled to a single string inverter[22] mounted in the tower section of the main building.

Additional investigation is performed on the influence of having different orientations and inclinations for the arrays. Figure 17 compares the yield of 2 different SAPV configurations. The green plot represents the yield when all the arrays are mounted horizontally on the field. The blue one shows the yield when half of the arrays (90 PV modules) is no longer placed horizontally, but oriented to the north and tilted to 70 degrees.

[22] Single string inverter – Minimal DC power: 8 kW – Voltage range [350 - 500] – Minimal current/string: 25A

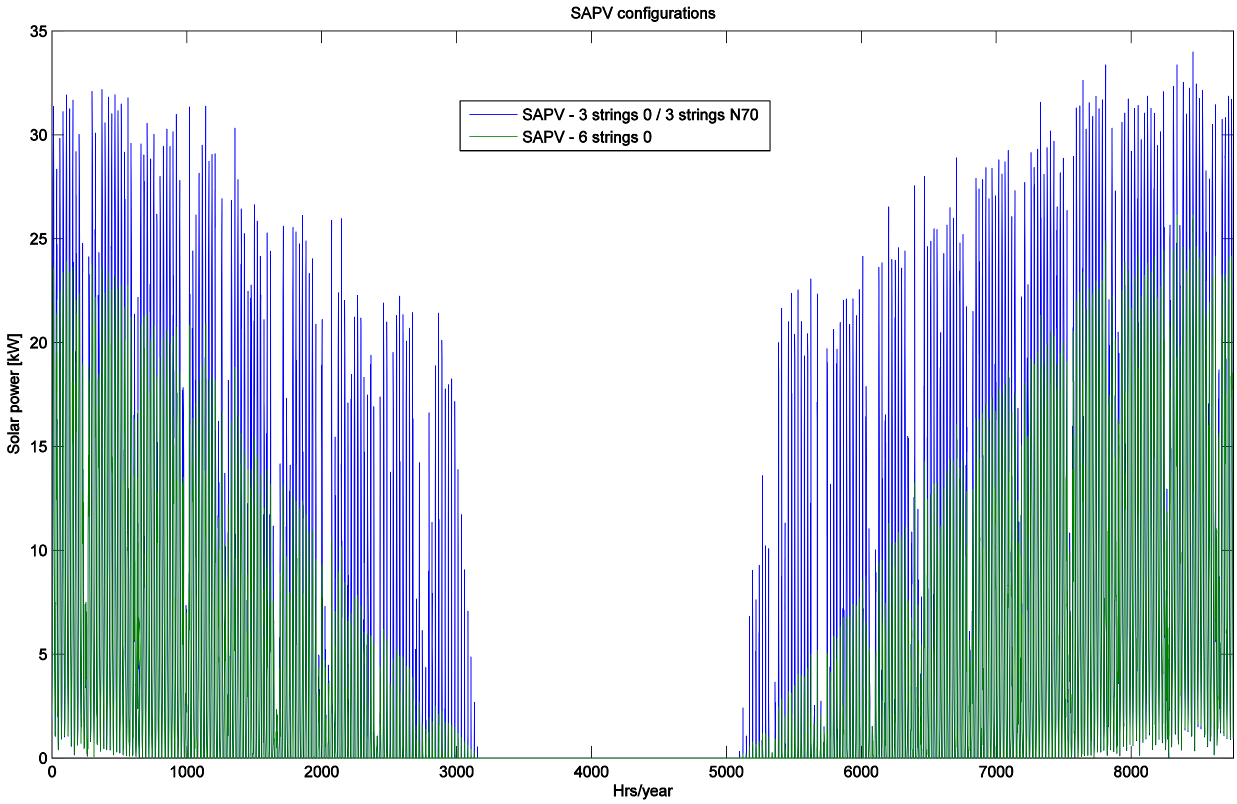

Figure 17: Yields original versus reoriented SAPV

Table 20: Fuel consumption for reoriented SAPV

	Original SAPV	Reoriented SAPV
Annual fuel consumption	1370 litres	886 litres

From Table 20 it is clear the tilt angle has great impact on the performance of the stand-alone PV system. Especially during the Antarctic spring and autumn the differences are significant. Further research is needed on the feasibility of altering the tilt angle. Aspects such as aerodynamic forces, structural integration and anchoring need to be tested.

3.4.3 Generators

The generators are essentially the back-up power sources of the hybrid system. They will also be used for peak-load operations to supply power to large three-phase loads that are used occasionally: drilling, welding, etc. Reliability and robustness are key elements for the generator selection. In case of failure of the power electronics interfacing the renewable energy sources and storage, all power supply of the station can rely on the generators [15].

The following operational modes can be distinguished:

- Prime power mode: a generator is used continuously to provide power on site. The second generator is used as back-up in case the first one fails or downtime is needed for maintenance. This mode is needed during the construction of the station.

- Peak shaving: a generator is used in the fully completed hybrid system when battery reserve doesn't succeed in balancing the essential electricity consumption. The generator will be turned on till the batteries have reached a pre-defined state of charge.
- Emergency: In case of extended failure of the battery bank and the battery bank converters, a generator takes over the grid-forming function.

The selected generator is a low-speed 4-pole diesel generator. Diesel generators are preferred as it has higher fuel efficiency than gasoline engines, they are more robust and diesel fuel is more easily stored for extended periods of time. For Antarctic applications, DFA (Diesel Fuel Arctic) is used. This is a jet-fuel with additives to adjust centane rating and lubricity. Table 21 shows the different generator types and corresponding lifetime.

Table 21: Generator type and estimate lifetime [42]

Generator type	Size range [kW]	Estimated lifetime [hrs]
High speed (3,600 rpm) air-cooled gasoline, natural gas, or propane	1 – 10	250 – 1000
High speed (3,600 rpm) air-cooled diesel	4 – 20	6000 – 10000
Low speed (1,800 rpm) liquid-cooled natural gas or propane	15 – 50	6000 – 10000
Prime power liquid-cooled diesel	7 – 10000	20000 – 40000
Natural gas microturbine	25 – 500	50000 – 80000

The sizing of a single generator is mainly based on the emergency operational mode. A worst-case scenario has been simulated under the following assumptions:

- Winter period
- Station is permanently manned. A crew of 6 people stays in the winter period
- No electricity production from the wind turbines
- No electricity production from the PV arrays
- All comfort levels are maintained (building temperatures, energy use, water use, lighting, etc.)

A peak power consumption of 34 kW is observed. Based on this, a single generator should have a prime power rating of at least 34 kW. The other generator is identical and is foreseen as back-up generator.

The generators are placed in the garage. They are both installed in 2 identical 20 feet containers, each with its own fuel tank, fuel pumps, heater, starter and other auxiliary equipment to ensure maximal redundancy.

Sensitivity analyses are applied to evaluate the annual total operating time of a generator depending on the availability of renewable energy sources and availability of energy storage.

Table 22: Sensitivity analysis generators

Scenario	# wind turbines	SAPV [kWp]	Battery bank capacity [%]	Fuel consumed [litres]	Operation time [Hr]	# start-ups
Base case	6	36	100	1370	180	41
	5	30	100	2200	290	66
	5	30	50	3231	425	98
	4	30	100	2830	372	85
	4	30	50	3823	503	115

Under normal operations, the generators will work 180 hrs/year (total operation hours for both generators). The number of start-ups is 40, so average run-time is 4.5 hrs. Table 22 shows that the sensitivity of the total operation hours is limited in case of multiple small failures. Under complete system failure, the generator however needs to operate continuously to supply all needed power.

Table 23 represents the final configuration and annual energy production for the generators under normal operations.

Table 23: Installed capacity and energy production - generators

Installed capacity	2 x 35 kW
Annual energy production	4 MWh

3.4.4 Solar thermal system

To minimize the electrical energy demand, all thermal applications are driven directly by the sun. A solar thermal system is installed to produce low and medium temperature heat, up to 90 degrees C. The produced heat will be used for:

- Snow melting: the primary circuit of the solar thermal system is redirected to the snow melting unit to provide sufficient heat to melt the snow.
- Bioreactor heating: the anaerobic reactor needs a continuous temperature of 55 degrees C for optimal processing. As the surrounding temperature is lower and the influent of the reactor is at 20 to 30 degrees C, the reactor needs substantial heating. The complete reactor is encapsulated in a double mantle where heating water will flow to heat up the reactor.
- Hot water production: the water (melt and recycled) is directly heated using plate heat exchangers. Water is not stored at elevated temperatures (sanitary storage) as the risk of legionella growth is high.

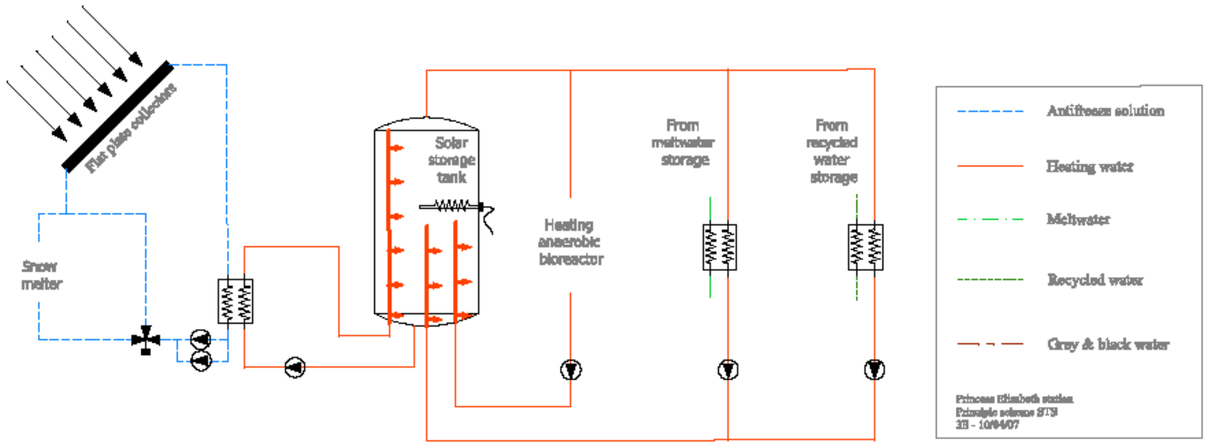

Figure 18: Solar thermal system [18]

High efficiency solar thermal collectors convert the energy of the sun in heat. Due to the elevated radiation at the site, a high quality flat plate collector (efficiency > 37%) can already provide sufficient heat for the thermal demands. Vacuum tube collectors are however also under consideration as additional heating reserve might be needed for future applications.

A total of 21 m^2 collectors are installed on the roof of the technical core, facing north. This surface and orientation ensures good thermal performance of the system. The roof section of the technical core is preferred as the heat storage tanks are placed just below and thus tubing distance is minimized.

More details on the layout of the collectors can be found in Appendix I.

3.5 Storage

Energy storage is an important part of the hybrid energy system. Storage of electrical and thermal energy is needed to cope with the fluctuations of the natural resources. If energy is sufficiently available, the energy is stored to be used later on.

3.5.1 Electrical storage

There exists several commercially viable electrical energy storage systems suited for hybrid energy systems. The most promising technologies for our application are batteries and hydrogen storage. Batteries are preferred as they have been used for many years in all kinds of climates. There are however different types of batteries that are available to do the job. The selection of a battery is often a compromise as no single battery offers a fully satisfactory solution [38].

Table 24: Different battery technology[23]

	Vanadium redox flow battery	Nickel – Cadmium (NiCd)	Nickel-metal-hybride (NiMH)	Valve regulated Lead-acid (VRLA) (Pb-Acid)	Lithium-ion (Li-ion)
Energy density [Wh/kg]	25	40-60	60-120	30-50	100-200
Power density [W/kg]		175	250-1000	180	1800
Cycle life[24]	+ 10000	1250	300-500	300-400	300-500
Fast charging		1 h	2 to 4 h	8 to 16h	1 h
Self discharge/month (room temperature)	Low	20%	30%	5%	<10%
Operating temperature (discharge only)	0 to 60°C	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C
Overcharge tolerance	high	moderate	low	high	low
Toxicity	Very low	High	Relatively low	High	Low
Cost	500 $ kWh	Relatively cheap (high cycle life)	High	Low	40 % more than NiCd
Main applications	Hybrid systems	Power tools	Laptop / mobile phone	UPS , golf carts, wheelchairs	Laptop / mobile phone
Commercial date	1980	1950	1990	1970	1991
Remarks	- long lifetime - easy capacity extension - can be charged or mechanically refueled - unlimited shell life	- memory effect - robust - long term storage possible	- limited discharge current - high maintenance - complex charge algorithm	- charged storage - lifetime is temperature sensitive - no maintenance	- protection needed (voltage / current) - not fully mature technology

Table 24 gives an overview of the properties of the different technologies. The VRLA technology is preferred based on the following parameters:

[23] References:[9, 13, 21, 31, 35, 36, 37, 38, 39, 40, 41, 42, 47]

[24] Cycles up to 80% DOD

- The batteries are stored in the technical core, which is a controlled temperature zone (temperature always above 0 degrees C). The extreme low operating temperatures (up to -40 degrees C) are no longer a critical parameter for the selection.
- Fast charging rates (up to one hour) are not required in the hybrid system.
- Overcharge tolerance is an important parameter as failure of the power electronics can occur and the battery are difficult to replace in a short notice.
- Cell robustness is a must for logistics.
- There is a preference for an inexpensive technology. Limited lifetime is allowed as battery replacement within 7 years is scheduled.
- Low maintenance, low system complexity and limited auxiliary equipment (electrolyte pumps, etc.) are preferred.
- Mechanical refueling is not required.
- Limited power and energy density is allowed as long as there are no problems with logistics and geometrical constraints for installation.
- Technology with existing experience in hybrid systems is preferred.
- Proven track record is a must for the chosen technology. Only mature technology can be selected.
- There is a preference for low toxicity.

Two specific VRLA types can be distinguished, the gel cell and the absorbed glass mat (AGM). In the gel cell the electrolyte has been "gelled" by the addition of Silica Gel, turning the acid into a solid mass. In the AGM type the electrolyte is absorbed in a very fine fiber Boron-Silicate glass mat. Both types have the huge advantage that the electrolyte is immobilized and therefore suited for air transport (lower hazard class).

The following properties are used to perform a detailed technology trade-off:

- Temperature sensitivity: both types are sensitive to the environment temperature. The temperature in the battery room therefore should be maintained at 25 degrees C. An increase of 8 degrees C would reduce the lifetime of the batteries up to 50%.
- Operating temperature: gel cell technology is more suited for operations at low temperatures. As the batteries are installed in the temperature controlled technical core, this parameter is no longer a decision variable.
- Explosion risk: as the batteries are in the centre of the building, the explosion risk is well investigated. Both types are classified under sealed technology, valve-regulated. This means a valve is used to evacuate the hydrogen when the internal pressure of the cell becomes too high. The release of hydrogen can only occur when incorrect charging takes place. However, if this happens, a natural ventilation path is foreseen in the battery room to evacuate the released hydrogen. Additionally, the electrical equipment in the battery room will be ATEX certified to guarantee the absence of an ignition source. More details on the ventilation and presence of electrical equipment in the battery room can be found in Appendix J.
- Robustness for charging errors: Gel cells are more vulnerable to charging errors. Charging at excessively high rates can create voids in the gelled electrolyte that significantly reduces the capacity of the battery.
- Robustness for handling and installation: the plates of the AGM type are tightly packed resulting in higher shock and vibration resistance.

- Lifetime and cycling depth: when considering deep cycling (DOD equal to 80%), AGM technology will take 300 to 400 cycles. Gel batteries can take an additional 50 cycles (10% more cycling). A gel cell can also take at least 5% more cycling depth.
- Cost: the gel cell is approximately 10% more expensive.
- Internal resistance and charging efficiency: the gel type has a higher internal resistance due to the presence of the gel separator. This will result in more heat dissipation during the charging.
- Power/weight density: AGM type has higher power/weight density than the gel cell.
- Power/space density: AGM type has higher power/space density than the gel cell.
- Charging current: For the gel cell, C10 charging rate (10% of the amp hour rating of the battery bank) can not be exceeded. The AGM type can cope with charging rates up to C5.
- Cell weight and dimension: the allowed weight for an individual cell is 100 kg for transport and handling reasons.
- Monitoring: cell and battery bank monitoring is needed to sustain long-term functioning. Weak cells need to be identified and replaced as they are the weakest link in the network.

Based on the properties of both technologies, multiple battery bank configurations are simulated to investigate the sensitivity on charging efficiency, heat dissipation and depth of discharge. Additionally a "peak counting" algorithm is applied to determine the lifetime of the battery bank which is an important design parameter. This algorithm uses a rainflow[25] counting principle on the annual SOC profile. It counts the occurrence of the cycles within a specified range. Based on the peak occurrences, the partial damage of an individual cell for one year is calculated. This number (partial use / year) is used to approximate the lifetime of the battery bank. More information and a detailed graphical representation of the SOC profile can be found in Appendix J.

Different battery bank configurations are simulated to obtain the non-renewable energy produced (annual fuel consumption) and corresponding SOC profile and thus estimated lifetime. Finally a trade off is performed on the results of the simulations and the specific technology characteristics mentioned above. AGM is selected as the best suited technology for the hybrid energy system of the Princess Elisabeth station. All the results of the simulations and the trade-off can be found in Appendix J. Table 25 summarizes the final battery bank layout that is installed in the station. Table 26 gives an overview of the station's performance for this configuration.

Table 25: Specification AGM battery bank, cluster and cells

Type	VRLA AGM
# battery clusters	2
# strings / cluster (parallel)	3
# cells / string (series)	24
Nominal output voltage	48 VDC
Nominal capacity / cluster	3000 Ah
Nominal charging current	100 ADC
Maximum charging current / string	200 ADC
Total maximum charging current	1200 ADC (C5)
Maximum discharging current / string	+ 200 ADC
Total maximum discharging current	+ 1200 ADC (C5)

Single cell						
Type	Capacity [Ah]	Nominal Voltage [V]	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]

[25] Rainflow counting is often applied for structural analysis (fatigue calculations).

DDM100-21	1000	2	214	165	590	73.5

Single cluster						
Type	#Cells horizontal	#Cells vertical	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
DDM100-21	12	6	2946	1620	720	5292

Table 26: Performance with AGM battery bank

Allowed DOD [%]	Fuel consumption / year [litres]	Partial use / year [%]	Estimated lifetime [years]
50%	1370	13.9	7.20

For each battery cluster, battery converters of 15 kVA are used (one of 5 kVA for each phase.) The battery converters are the "brains" of the energy system. They convert the DC electrical power from the batteries in AC power during discharging and the other way around during charging. The same converters also form the grid and maintain the power quality (voltage amplitude and frequency), by controlling the other power electronics (PV, wind turbines). Finally these converters also optimize the charging and discharging algorithms in order to maximize the battery lifetime. They are a critical component in the complete hybrid system.

3.5.2 Heat storage

The storage of the solar heat is an important component of the solar thermal system. A stratified[26] water tank is selected as the most suited technology. This tank is installed on the second level of the technical core. Its minimum dimension is 1.5 m^3. Due to geometrical constraints 3 vertical tanks are coupled in parallel. A horizontal tank also fits, but has a worse stratification and is therefore abandoned. Specific insulation[27] developed by the space industry is used to reduce both diameter and height. An electrical back-up heating is foreseen in each tank to ensure heat supply under all conditions [18].

Figure 19 shows the layout of all the technical systems discussed in the previous section.

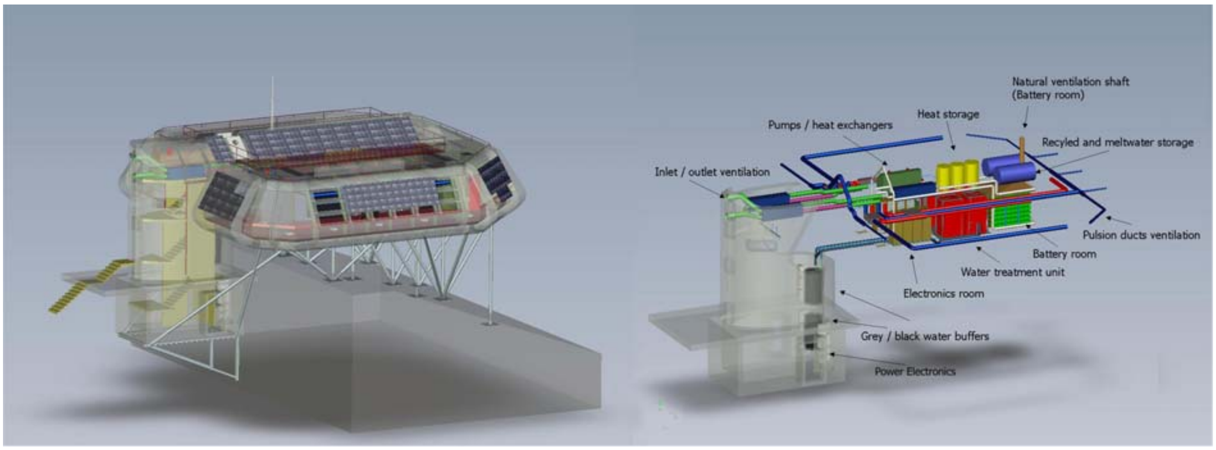

Figure 19: Building layout technical systems

[26] Stratification spears guarantee that the fluid automatically gets in the storage at the height with corresponding temperatures.
[27] Spaceloft: Insulation material based on silica materials with a thermal conductivity of 0.013 W/mK (manufacture: Aerogel).

3.6 Grid operation and control

The electrical grid throughout the station is a three phase AC grid, the same as used in our homes. The grid control system is responsible for maintaining the instantaneous values of grid voltage and frequency within acceptable variations around the nominal (target) values. Table 27 shows the targets defined by the IEC 62257 standard[28]:

Table 27: Power quality voltage amplitude and frequency – low voltage networks (level 1)

	Voltage (V_{AC})	Frequency (Hz)
Nominal	230/400	51
Maximum	253/440	52
Minimum	207/360	43

A schematic presentation of the electrical system of the research base is shown in Figure 20. Components are sources, loads or balancing components (storage and dump loads). The grid has 2 operational modes. In the default mode, the battery converters will form and sustain the grid. Even when the generator is used, the battery converters still form the grid. Under the second mode, the generator will control the grid through its own governor and exciter, if the grid forming of the battery converter fails. The battery converters might still function to charge the batteries, but will follow the output values of the generator (slave mode).

[28] IEC 62257: Recommendations for small renewable energy and hybrid systems for rural electrification – power quality level 1

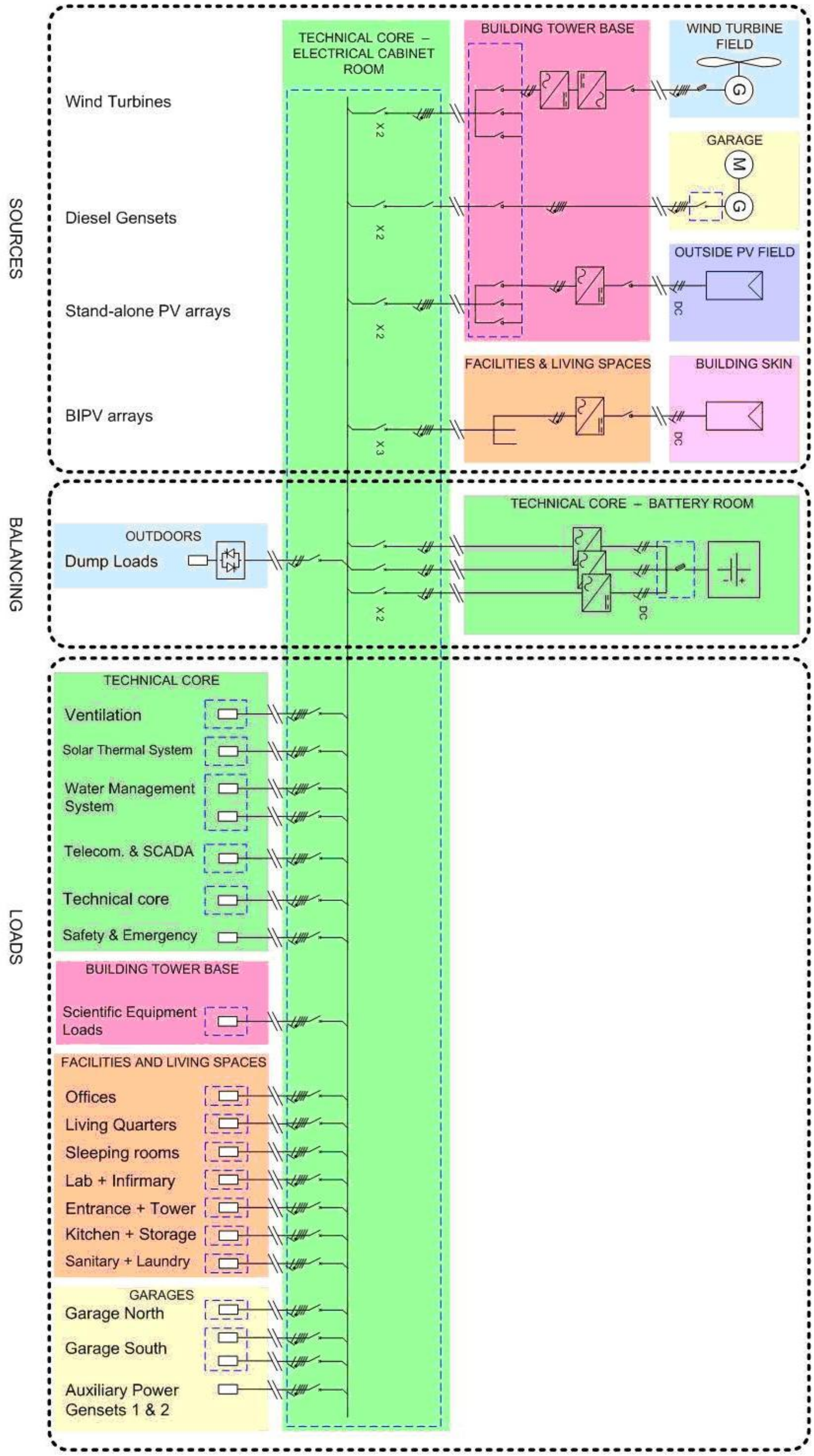

Figure 20: Principle schematic electrical systems [14]

To achieve the balance between power generated and power consumed, both need to be monitored and adjusted continuously. This holds true for both the active and the reactive power.

Active power balancing

Active power balancing is implemented by the various control algorithms in the power-electronic equipment interfacing the energy storage (batteries), the power sources and the loads. In primary mode, the battery converters constantly vary the active power output to ensure balance on the AC bus. In addition, the power converters on the renewable sources are capable of curtailing their power output. They automatically react on the grid frequency or can be triggered with a signal from the grid control system (battery converter). On the consumption side, "intelligent" dump loads are foreseen. They will react on the grid frequency and reduce/increase their load accordingly. Additionally load shedding can be applied to the non-critical loads. These loads can be temporarily turned off/on without compromising the functioning of the station.

Reactive power balancing

Just as active power balance is maintained to control the grid voltage frequency, the reactive power consumption and generation should be in balance to keep the grid voltage amplitude close to its nominal value. The power electronics interfacing the batteries and the renewable sources are force-commutated converters capable of delivering reactive power. By default however the converters of the renewable sources operate at a power factor equal to 1. The main reactive power is supplied by the battery converter, augmented with reactive power compensation using fixed capacitance.

3.7 Energy management (SCADA)

As grid control is responsible for the instantaneous balance in power, energy management handles on the medium- to long-term balance between consumption and generation. The goal is to supply all the loads with sufficient energy while optimizing the use of the generated energy. At the same time fuel consumption needs to be minimized and the battery lifetime maximized.

Obviously a lot of information on all the subsystems is needed to have an integrated energy management system. This energy management is therefore integrated in a SCADA (Supervisory Control And Data Acquisition) system.

3.7.1 SCADA functioning

The SCADA system integrates the numerous applications present in the station. These applications originate from the home environment (e.g. lighting), the office environment (e.g. communication networks) and even the industrial environment (e.g. water processing). The SCADA system covers the following functions [23]:

- Supervisory control: the SCADA governs all control algorithms from an upper hierarchy. This means most sub-systems have some type of local intelligence responsible for specific control (e.g. water treatment), but the SCADA system can always overrule this local control if needed.
- Data Acquisition: the SCADA gathers the data of all systems and makes them available for other subsystems, further processing and analysis. In most cases, sensors are part of the associated subsystem and the SCADA system gathers the information via the interface of the local control unit. Data compression and storage (archiving) is implemented to enable remote data transfers.
- HMI: the SCADA creates and provides an interface of all systems to different levels of users. There is a preference to standardize all interfaces and to have them running on international accepted browser applications based on a LAN environment. This enables each user to overview or control (depending on access rights) the SCADA with the existing hardware (such as laptops). In addition some portable terminals might be needed to access specific systems directly. Additional HMI hardware is used for event reporting and alarm signaling.

3.7.2 SCADA structure

The SCADA system is active on the subsystem level (field level) and the supervisory level. The complete system is closely linked to a communication level as remote control of the station is needed during the unmanned period. Figure 21 is a schematic overview of this structure.

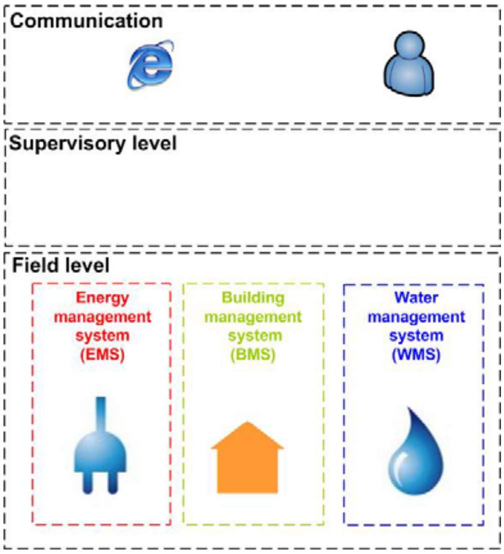

Figure 21: SCADA structure

All applications in the station are organized in 3 groups:

Water management systems (WMS)

The water management system consists of water production, water treatment, water storage, water distribution, solar thermal energy production and heat storage. The water treatment and the solar thermal system have their own local plc to control the pumps, valves, sensors, etc. This local intelligence will be coupled to the main SCADA plc to integrate all the other pumps, valves, temperature sensors, flow rate sensors, level indicators (storage tanks), electrical heaters (in the snowmelter and heat storage tank), quality indicators, etc. The SCADA governs the complete water cycle and generates accurate information to all users.

Building management systems (BMS)

Status monitoring of the building is an essential part of the BMS in order to guarantee safety and comfort. The following sensors are installed:

- Temperature sensors: temperature signals are used to trigger the decentralized heating units. Under normal operation conditions, the users can set the temperatures of each location with local thermostatic control. If sufficient renewable energy is available, the SCADA will supply the decentralized heaters on/off signals to keep the room at the requested temperature. If abundant energy is available, the SCADA can switch on specific heating units (conform a specific room temperature priority) to dump the energy (and consequently build up thermal reserve).
- CO_2 detection: coupled to the temperature sensors, CO_2 detection is used to control the ventilation rates.
- Smoke or fire detection sensors are installed throughout the base.
- Hydrogen detection: hydrogen release is possible due to malfunctioning of the battery charge controllers. Hydrogen concentration must stay below 4% (LEL: Lower Explosion Limit) to ensure there are no explosion risks [21]. Hydrogen sensors are installed in the battery room,

but also in the technical ventilation ducts. Additional to the hydrogen sensors, the battery temperature sensors need to be monitored very closely since a sudden rise in temperature of a battery cell often indicates a possible degassing of hydrogen.

- Methane detection: the black and grey water storage tanks and the WTU will house biological processes. In order to detect abundant degassing (process failure), methane detection sensors are installed in the specific locations and ventilation ducts.
- Presence detection: human presence is detected locally to ensure that lighting switches off automatically. The presence detection is however not integrated in the SCADA system.
- Door/hatch detection: the doors and hatches for access towards the outdoor or the garage are equipped with contact sensors to ensure no doors are left open.

In addition to the sensors, a closed circuit television (CCTV) system is installed to monitor the technical units, garage and the external environment. All the sensors and cameras enable the SCADA to visualize the complete building status and to trigger safety signs.

Energy management systems (EMS)

The power converters of the energy sources transmit the status of the source and its power output (both instantaneous value as well as average values). The battery converters transmit the status (SOC) and output/input power as well as all relevant variables of the battery clusters. At the consumption side, each feeder departure from the main cabinet has a contactor with current and voltage measurement. As discussed in previous section, the converters control the instantaneous voltage amplitude and frequency. The EMS rather controls the sources and loads to guarantee an optimized energy strategy in the medium- to long-term. This means the EMS senses the availability of energy (stored and generated) and based on this energy status, loads are authorized or shed.

If renewable energy is abundantly available, EMS creates a balance on the consumption by:

- Charging the batteries to the maximum allowed level.
- Melting snow electrically if snow is collected and additional storage is available for meltwater.
- Electrical heating of the heat storage if predefined maximum tank temperature is not yet reached.
- Starting household applications such as laundry and dish washing.
- Heating of certain zones in the building if predefined maximum is not yet reached.
- Increasing the ventilation flow rates.
- Increasing the humidification levels till the predefined maximum is reached.
- Additional electrical preheating on the fresh inlet air.
- Triggering dump loads.

If the energy supply is still higher than the demand, the power converters will curtail their power to create the balance.

If renewable energy is scarce and batteries are at low SOC, EMS warns the users to postpone non-priority loads. A visual sign will recommend to the users to avoid the use of electrical equipment such as the cloth- and dishwasher, mechanical power tools, intensive cooking and laptop charging. To ensure the balance, EMS interacts on consumption by:

- Reducing lighting, heating and ventilation loads according to a preplanned prioritization scheme during the critical timeframes.
- Prohibiting heavy non-priority loads such as welding and drilling.

If the maximum time of deferring the loads is reached and batteries are at minimum SOC level, EMS commands the generator to take over the grid forming. The batteries will be charged and the postponed loads will be executed. Once the batteries are again at a predefined SOC, the battery converters take over the grid forming and the generators are shut off.

For future optimization of the EMS system, additional data need to be integrated in the SCADA. For example weather data which can be used to predict short- and medium-term energy production; or historical data on the consumption side which can be used to analyze trends.

In Appendix K a more detailed overview of the EMS and the SCADA structure is presented.

3.8 Design summary

3.8.1 Loads and sources

The life supporting systems such as the water management, the ventilation, the heating and the complete station management, have the biggest stake (54%) in the complete annual energy consumption. The scientific equipment, which is turned on continuously, stands for 41% of the annual energy consumption. Only 5% of the energy consumption is used for household and office applications (Table 28).

Table 28: Summer station - loads - annual consumption

SUMMER STATION	Nov, Dec, Jan, Feb. (manned)		Mar, Apr, May, Jun, Jul, Aug, Sep, Okt (unmanned)		Total	
	Absolute	Relative	Absolute	Relative	Absolute	Relative
Household / office equipment	3.8 MWh	9.2%	0 MWh	0.0%	3.8 MWh	5.4%
Research equipment	9.6 MWh	23.3%	19.2 MWh	66.4%	28.8 MWh	41.1%
Workshop equipment	0.15 MWh	0.4%	0 MWh	0.0%	0.15 MWh	0.2%
Water management	15.5 MWh	37.6%	0 MWh	0.0%	15.5 MWh	22.1%
Ventilation	7.3 MWh	17.7%	3.9 MWh	13.5%	11.2 MWh	16.0%
Heating	1.4 MWh	3.4%	1.2 MWh	4.1%	2.6 MWh	3.7%
Station management	3.5 MWh	8.4%	4.6 MWh	16%	8.1 MWh	11.5%
Total	41.2 MWh	58.5%	28.9 MWh	41.5%	70.1 MWh	

Table 29 shows that the wind turbines generate 65% of the total electrical energy, even though their installed capacity only represents 30% of all the sources. The PV generates up to 32% of the electrical energy and the generators provide the final 3%. Figure 22 shows the monthly energy production potential for the different sources. The seasonal solar and wind variation can be clearly distinguished.

Table 29: Summer station - sources - annual production

SUMMER STATION	Nov, Dec, Jan, Feb. (manned)		Mar, Apr, May, Jun, Jul, Aug, Sep, Okt (unmanned)		Total	
	Absolute	Relative	Absolute	Relative	Absolute	Relative
Wind turbines	24.3 MWh	41.1%	68.5 MWh	81.5%	92.8 MWh	64.9%
Building integrated PV	7.4 MWh	12.5%	4.2 MWh	5.0%	11.6 MWh	8.1%
Stand-alone PV	25.8 MWh	43.7%	8.4 MWh	10.0%	34.2 MWh	23.9%
Generators	1.6 MWh	2.7%	2.9 MWh	3.5%	4.5 MWh	3.1%
Total	59.1 MWh	31%	84.0 MWh	59%	143.1 MWh	

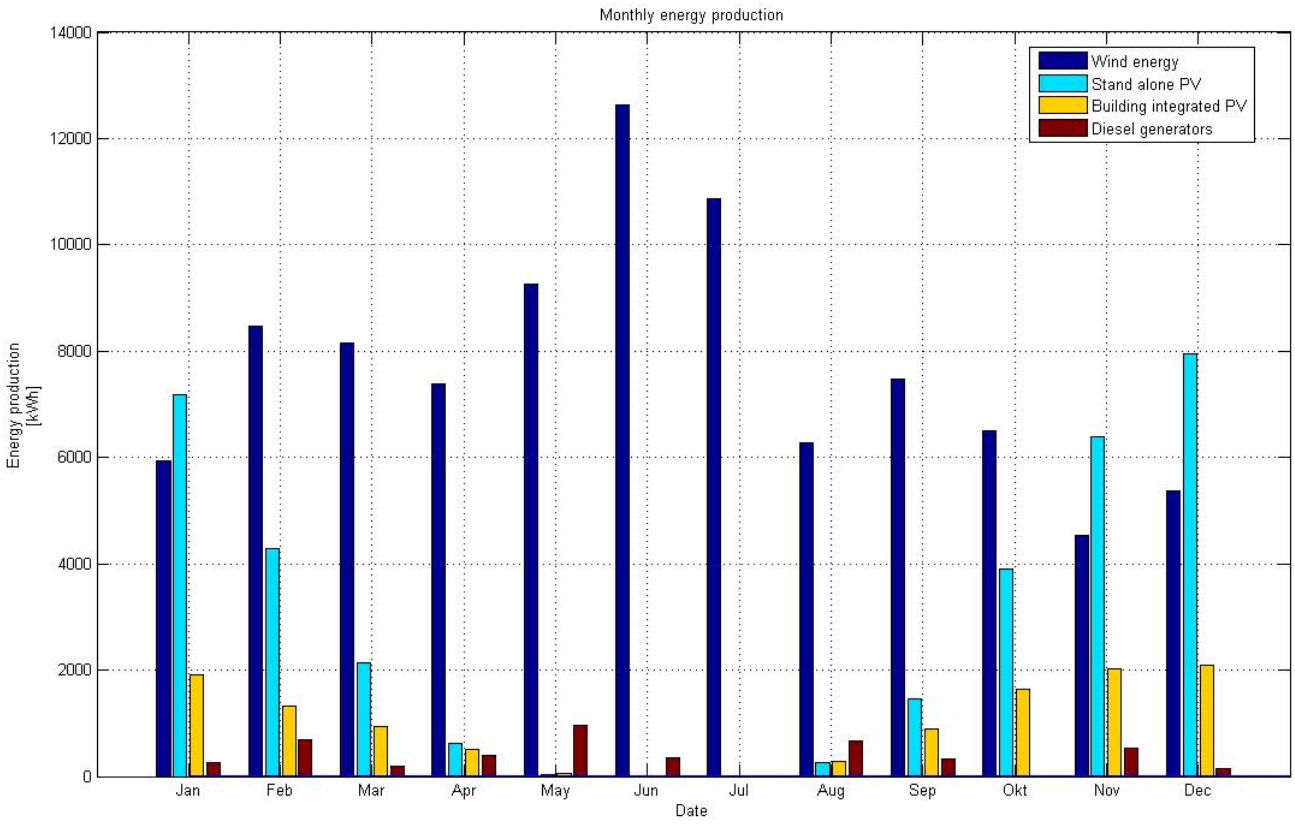

Figure 22: Summer station - sources - monthly production (potential)

It is important to notice the ratio between generated and effectively used energy. Only 49% of the total potential of energy that can be generated is used effectively. The rest of the energy (51%) needs to be dumped, or the sources need to be curtailed according to the energy demand. This result however needs an additional remark about the dynamical simulation model. Within the model, the maximum energy that can be generated (potential) is calculated and the excess of energy is dumped automatically. In reality however, the power electronics of the PV can curtail their power output and a braking mechanism might be installed on the wind turbines. Therefore the percentage of excess energy needs to be considered as a theoretical value. From Table 30 it is clear the current hybrid system is well sized for the manned period, but oversized for the unmanned period. This is mainly due to the stringent emission requirements for the manned period.

Table 30: Summer station - production versus consumption

Electricity production	Nov, Dec, Jan, Feb. (manned)		Mar, Apr, May, Jun, Jul, Aug, Sep, Okt (unmanned)		Total	
	Absolute	Relative	Absolute	Relative	Absolute	Relative
Total generation	59.1 MWh		84.0 MWh		143.1 MWh	
Total load	41.2 MWh	69.7%	28.9 MWh	34.4%	70.1 MWh	49%
Excess electricity	17.9 MWh	30.3%	55.1 MWh	65.6%	73.0 MWh	51%

Figure 23 shows that most of the energy excess (some months up to 70%) occurs during the unmanned winter period. Sufficient dump load (resistor banks) or a braking mechanism on the wind turbines need to be installed. It is also possible to lower 3 of the 6 wind turbines during the unmanned period.

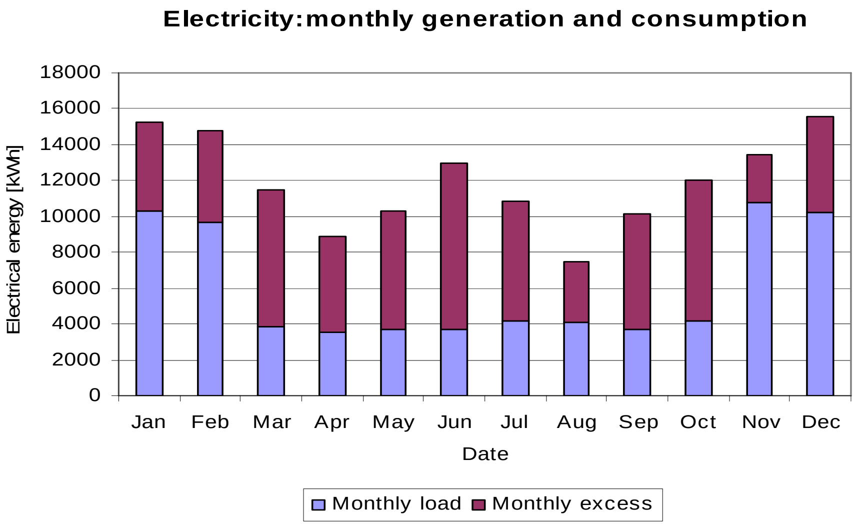

Figure 23: Summer station - electricity: monthly load and excess

3.8.2 Electrical storage and fuel consumption

Under the current design, 1370 litres of fuel is consumed each year to keep the station operational. The current battery bank will last for more than 7 years. Table 31 and Table 32 summarize the final performance of the station.

Table 31: Summer station – electrical storage - installed capacity and lifetime

Battery bank capacity	6000 Ah
Lifetime	7.2 years

Table 32: Summer station – annual fuel consumption and emissions[29]

Annual fuel consumption	1370 litres
Annual CO_2 emission	3.66 tons
Annual CO emission	9.04 kg
Annual unburned hydrocarbons emission	1.00 kg
Annual particulate matter emission	0.68 kg
Annual sulfur dioxide emission	7.35 kg
Annual nitrogen oxides emission	80.60 kg

Figure 24 represents the sensitivity analysis on the renewable sources (PV and wind turbines). Starting from the origin it is clear that adding additional wind turbines or PV modules decrease significantly the annual fuel consumption. At the current design however the marginal gain of adding extra wind turbines or PV modules is very limited. To decrease annual fuel consumption with approximately 400 litres, 2 extra wind turbines need to be installed or almost 10 kWp PV needs to be added to the existing stand-alone field. As the initial objective of the annual fuel consumption is reached and the marginal cost of further reduction is high, no additional effort is put in further fuel reduction.

[29] Emissions are a product of incomplete combustion and depend on the fuel type, the engine design, the operating conditions, etc. In the analysis however the emissions are assumed as constant fractions on the amount of fuel (carbon monoxide: 6.6 g/L; unburned hydrocarbons: 0.73 g/L; particulate matter: 0.49 g/L; sulfur dioxide: 5.4 g/L; nitrogen oxides: 59 g/L). A diesel fuel with density equal to 820 kg/m3, carbon content of 88% and sulfur content of 0.33 % is assumed.

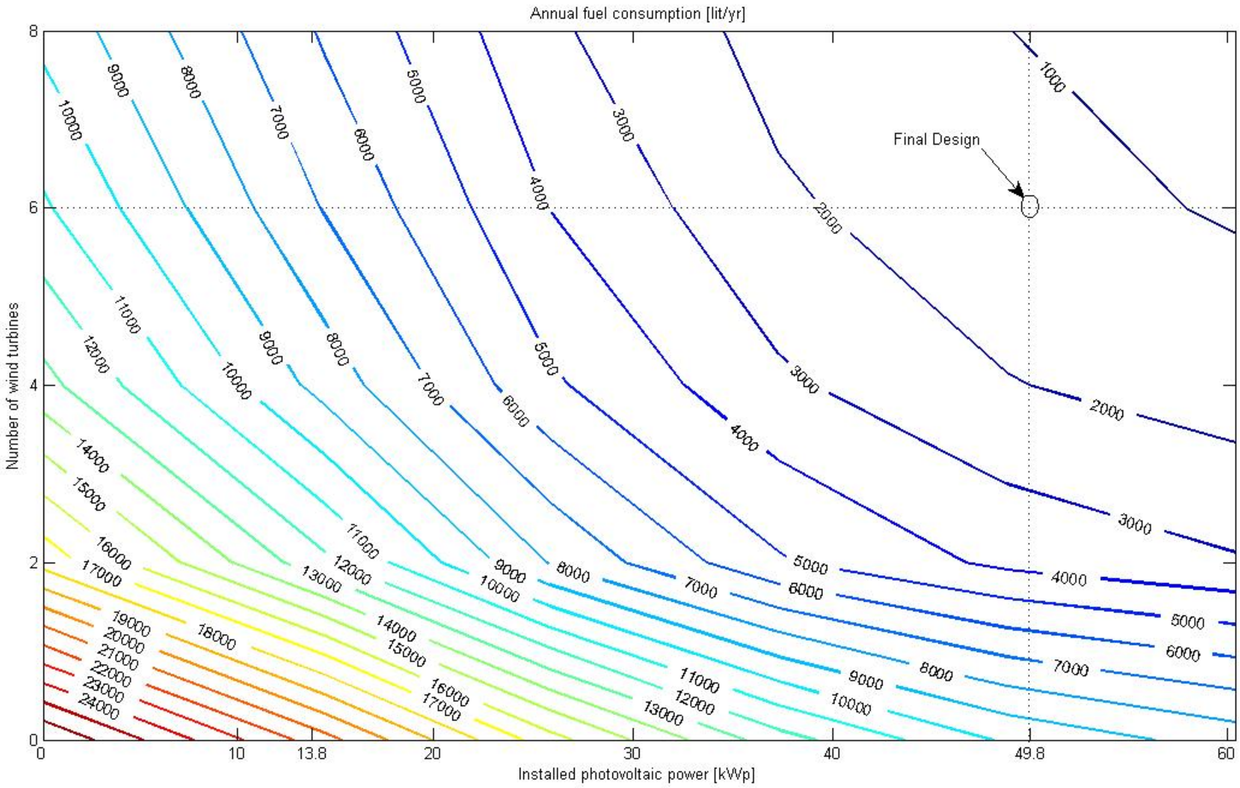

Figure 24: Summer station - sensitivity analysis sources (PV – Wind turbines)

3.8.3 Technology impact

To sketch a good overview of the complete design process, the impact of the different applied technologies is isolated. In the reference concept, none of the technologies described in previous sections are installed. Annual fuel consumption would be close to 45000 litres. If passive housing norms and a solar thermal system are integrated in the building, approximately 5000 litres of fuel can be saved each year. If a hybrid energy system (consisting of wind turbines, PV modules and a battery bank) is installed, an additional fuel reduction of almost 80% is achieved. Table 33 shows more details on the impact of each technology on the performance of the station.

Table 33: Fuel and CO_2 reduction due to optimized technology

Properties	Reference concept	Passive building	Solar thermal system	Photovoltaic	Wind	Hybrid
Insulation EPS	10 cm	40 cm	40 cm	40 cm	40 cm	40 cm
Ventilation (heat recovery)	50%	90%	90%	90%	90%	90%
Glazing (U-value)	1.8	0.5	0.5	0.5	0.5	0.5
Glazing (g-value)	0.8	0.5	0.5	0.5	0.5	0.5
Solar collector surface	0 m^2	0 m^2	21m^2	21 m^2	21 m^2	21 m^2
Heat storage tank	0 m^3	0 m^3	1.5 m^3	1.5 m^3	1.5 m^3	1.5 m^3
PV modules	0 kWp	0 kWp	0 kWp	49.8 kWp	49.8 kWp	49.8 kWp
Wind turbines	0 kW	0 kW	0 kW	0 kW	36 kW	36 kW
Electrical storage	0 Ah	0 Ah	0 Ah	0 Ah	0 Ah	6000 Ah

Properties	Reference concept	Passive building	Solar thermal system	Photovoltaic	Wind	Hybrid
Emission						
1 Year operation						
Fuel consumption [litres]	44121	40452	39462	29678	13820	1370
CO_2 equivalent [tons]	118	108	105	79	37	4
Design life						
Fuel consumption [litres]	1103025	1011300	986550	741950	345500	34250
CO_2 equivalent [tons]	2947	2702	2636	1982	923	92
Reduction		8%	2%	22%	36%	29%
Cumulative reduction		8%	10%	32%	68%	97%

It is clear that an optimized combination of different technologies is essential to reach the low emission aim. Having 97% of the energy from renewable sources is considered as a pioneering standard in the design of research stations on remote locations under extreme conditions.

3.9 Design validation

All the results from previous sections are based on the dynamical analysis of the TRNSYS model. An additional modeling tool is used to validate the design and to guarantee no errors are overlooked. The software HOMER[30] is a hybrid simulation tool to evaluate both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation (DG) applications. When applying the same design configuration and assumptions, an annual fuel consumption of 1973 litres is found. The difference of approximately 600 liters is possibly due to PV orientation and inclination. Multiple PV orientations and inclinations can not be simulated in HOMER. All PV is therefore simulated as being mounted horizontally. The positive effect of the building inclination and orientations can not be simulated in HOMER.

A huge difference in both models is the important ability of TRNSYS to couple meteorological inputs, geometrical building inputs, building orientation, etc. to generate the electrical loads. This feature is not available in HOMER. This means the electrical input file of HOMER needs to be regenerated with TRNSYS if some of the above variables change. Therefore TRNSYS is considered as a more broad design tool for integrated hybrid / building design. HOMER only covers the design and optimization of the hybrid system for a well known electrical demand.

[30] Property of NREL - National Renewable Energy Laboratory [42]

PART 2: DESIGN SENSITIVITY

Part 1 defined the final energy system. In part 2, this design is further investigated with regard to the meteorological input. In a first phase, the original meteorological data is validated and regenerated, as errors in the original data can have significant impact on the complete system design. In a second phase, the variation in the wind resources is investigated. Wind is not only the most variable meteorological parameter, but wind power also generates up to 2/3rd of the electrical energy. Finally the design is remodeled as a permanently manned station. This extension is a very likely scenario and can have huge impact on the performance of the station.

4 Princess Elisabeth: wind sensitivity

4.1 Temperature

The hourly temperatures are initially generated using a weather generator[31] based on monthly mean temperatures included in the dynamical TRNSYS model. This generator however mismatches the typical daily profile. To obtain the monthly mean temperature, it overestimated the day (positively) and night (negatively) temperatures. The real temperature however varies much less during the summer and winter season, as the sun is constantly present or absent.

In addition, no detailed information is known on the dew temperatures. The dew temperature is needed to calculate accurately the relative humidity. The humidity is an important parameter in the station as too low relative humidity decreases the living comfort and increases the risk for static electricity problems. The humidity is increased in the station using steam or ultrasonic humidifiers in the ventilation. This humidification process is however very energy demanding and therefore the impact on the electrical consumption is significant.

The temperature at the site is very analogous to temperature records at Asuka, a former station situated at 55 km further north-east at an elevation of 932 m [4]. At Asuka not only the ambient temperature, but also the dew temperature is registered in 3 hourly intervals. As the record of 1990 is best correlated with the site of Princess Elisabeth, it is used in further calculations. Table 34 compares the temperature properties of the site of Asuka and Princess Elisabeth. Figure 25 shows the temperatures of the original AWS data, the generation of TRNSYS and the AWS data of Asuka.

Table 34: Temperatures: Princess Elisabeth and Asuka [46]

	Princess Elisabeth - 2005	Asuka – 1990
Mean temperature	- 18 °C	- 18 °C
Max temperature	- 1 °C	- 1 °C
Min temperature	- 36 °C	- 44 °C
Lowest monthly mean	September: - 25 °C	September: - 28 °C
Highest monthly mean	December: - 8 °C	January: - 8 °C

31 TRNSYS - Type 54 generator [34]

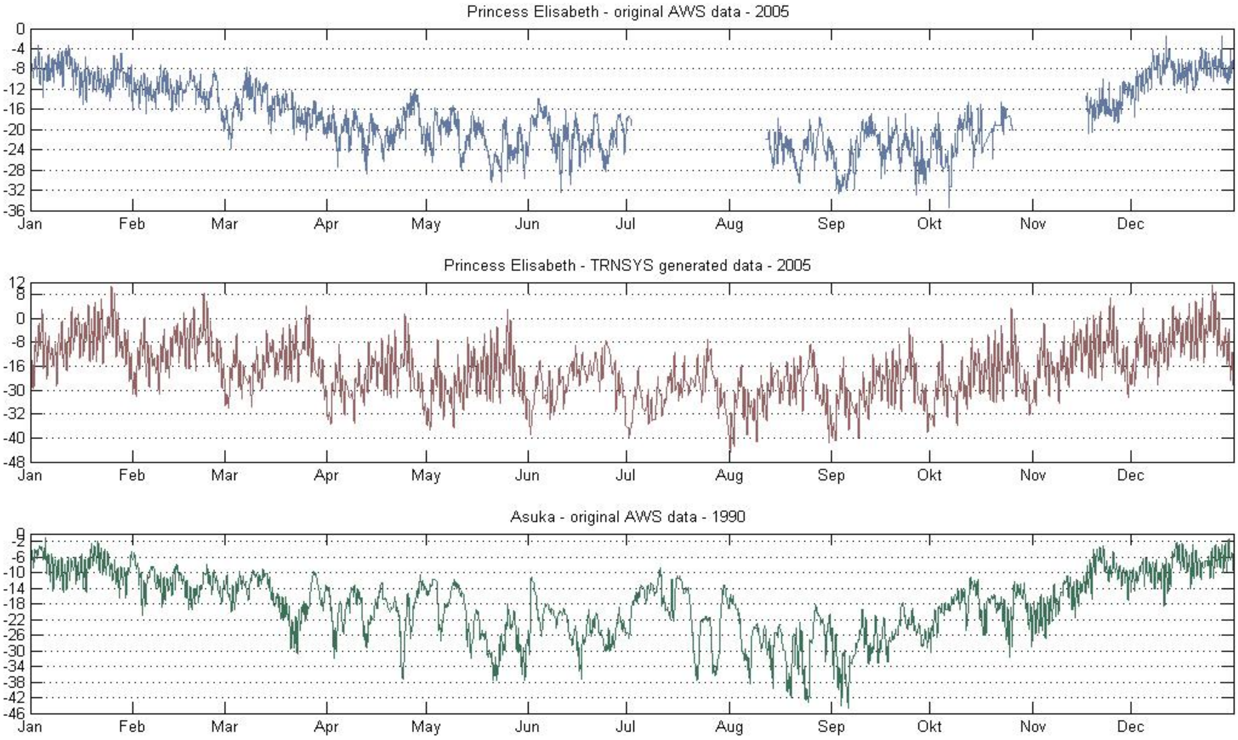

Figure 25: Comparison temperature data files

4.2 Radiation

The radiation calculated with TRNSYS is very similar to the theoretical results described in 2.2.1. Therefore the radiation does not need to be regenerated. Figure 26 shows the radiation at the surface modeled by TRNSYS.

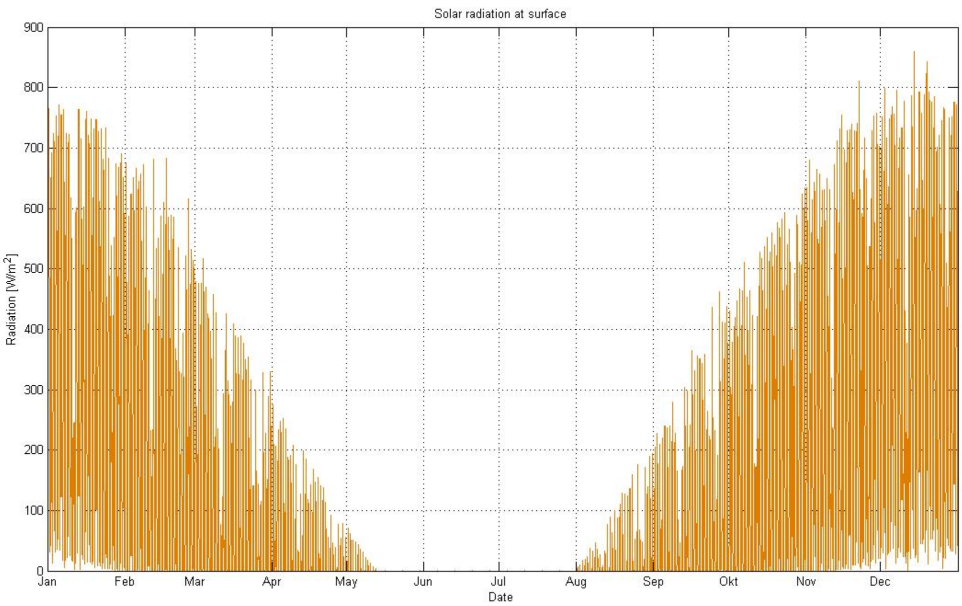

Figure 26: Solar surface radiation

4.3 Wind

4.3.1 Original AWS data

The original wind data from the AWS only covered a limited period, starting from the end of December 2004 till the end of September 2005. There is however a gap of data from the end of June till half August. For the period of September, the time interval of the logging had changed unexpectedly, resulting in data overflow. This failure can be observed in the scale of Figure 27. A second AWS is installed on the top of the ridge in November 2005.

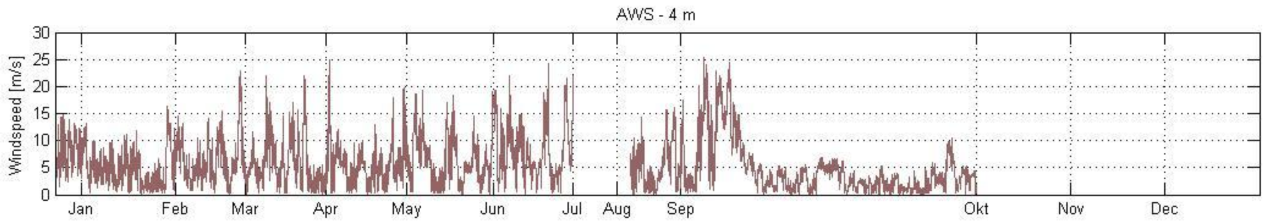

Figure 27: Princess Elisabeth AWS data (2005) - 4 m

4.3.2 Correlation other stations

To validate and to complete the wind data, records at other Antarctic locations are investigated. All the stations in the continent are mapped and the following stations (Table 35) are best suited for the correlation:

Table 35: AWS records for correlation analysis

Name	WMO / ARGOS number	Latitude	Longitude	Height [m]	Distance to Princess Elisabeth [km]	Range of data set [date]	Time interval of record [Hrs]
Princess Elisabeth		71°57′ S	23°20′ E	1400	NA	[2005]	Variable
Neumayer	890020	70°40′ S	8°15′ W	50	1115	[1981 - 2007]	3
Novolazarevskaya	895120	70°46′ S	11°50′ E	119	450	[1981 - 2007]	6
Asuka	895240	71°31′ S	24°07′ E	932	54	[1987 - 1991]	6
Syowa	895320	69°00′ S	39°35′ E	21	690	[1973 - 2007]	3
Mawson	895640	67°36′ S	65°52′ E	16	1570	[1985 - 2007]	3

Figure 28 shows the location of the selected stations. An overview of the weather stations in Antarctica can be found in Appendix L.

Figure 28: AWS locations for correlation analysis [53]

Table 36 gives an overview of the data availability for the stations under consideration. Two correlations are performed to investigate the potential use of AWS records from other locations to generate the data for our site.

Table 36: Data availability for correlation analysis

WMO / ARGOS number	1985	1986	**1987**	**1988**	**1989**	**1990**	**1991**	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	**2005**
Princess Elisabeth																					**x**
Neumayer	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Novolazarevskaya	x	x	**x**	**x**	**x**	**x**	**x**	x	x	x	x	x	x	x	x	x	x	x	x	x	**x**
Asuka			**x**	**x**	**x**	**x**	**x**														
Syowa	x	x	**x**	**x**	**x**	**x**	**x**	x	x	x	x	x	x	x	x	x	x	x	x	x	**x**
Mawson	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

A first correlation is performed over the period of March 1987 – November 1991 on the mean monthly wind speeds of Novolazarevskaya, Asuka and Syowa. Figure 29 shows there is a very similar pattern between the three stations but there is a significant difference in the amplitude of the mean speeds. Figure 30 gives an overview of the monthly variation on the mean wind speed. The same pattern similarity can be observed. Table 37 gives an overview of the correlation coefficients on the monthly mean wind speeds. Correlation coefficients indicate the strength of a linear relationship between two random variables. The Pearson product moment method is used, this means the covariance of the two variables is divided by the product of their standard deviations. The correlation coefficient between Novolazarevskaya and Asuka is 0.77, the correlation between Novolazarevskaya and Syowa is 0.70. Both are relatively well correlated if you take into account the stations are situated at relatively large distances from each other.

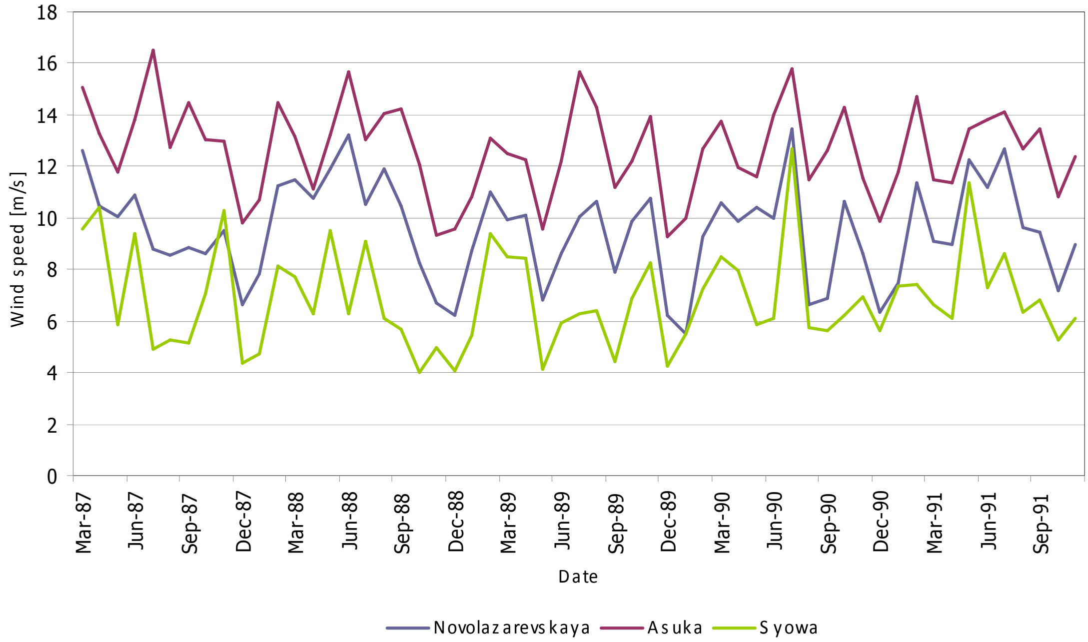

Figure 29: Monthly mean wind speeds (1987-1991) - correlation 1

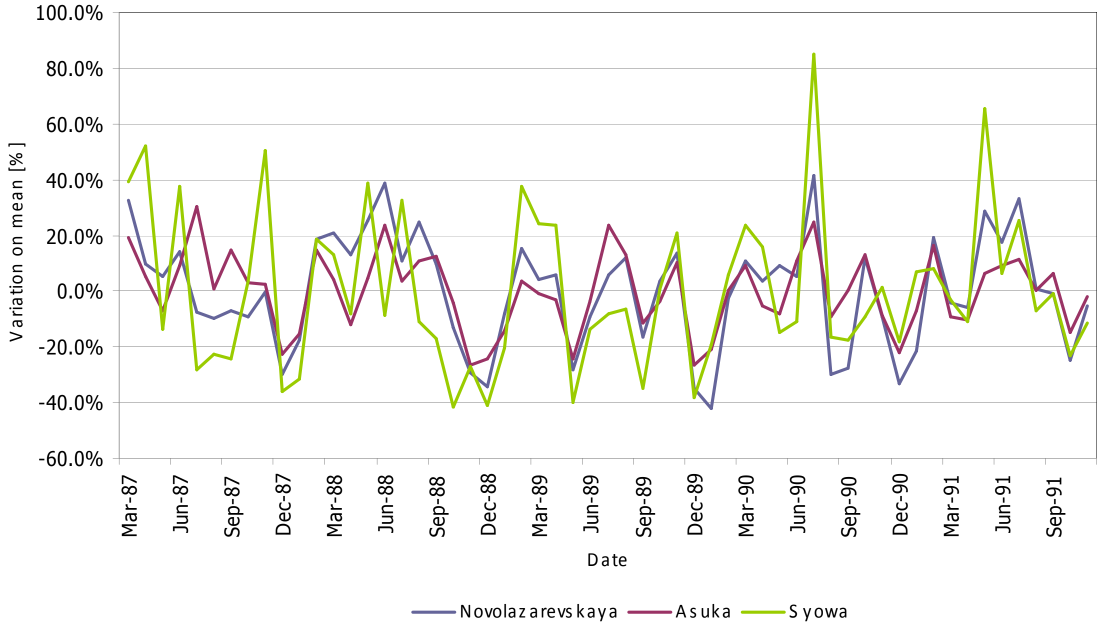

Figure 30: Variation on monthly mean wind speed (1987-1991) - correlation 1

Table 37: Correlation coefficients (1987 – 1991) – correlation 1

	Novolazarevskaya	Asuka	Syowa
Novolazarevskaya	1		
Asuka	0.769	1	
Syowa	0.698	0.500	1

A second correlation is performed on the monthly mean wind speeds over the period of 2005 for Novolazarevskaya, Princess Elisabeth and Syowa. Figure 31 shows that the wind pattern of

Novolazarevskaya is analogous to the one of the Princess Elisabeth site, even though the sites are located at great distance from each other and the amplitude of the mean wind differs. Figure 32 confirms the pattern analogy. Table 38 gives an overview of the correlation coefficient.The correlation coefficient between both stations is 0.87. Both sites are well correlated and therefore clearly dominated by the same katabatic winds.

Figure 31 and Figure 32 also reveal the seasonal wind pattern at the Princess Elisabeth site in 2005 is similar to the one of Novolazarevskaya in 2005 and even to the one averaged over 22 years (correlation coefficient equal to 0.7).

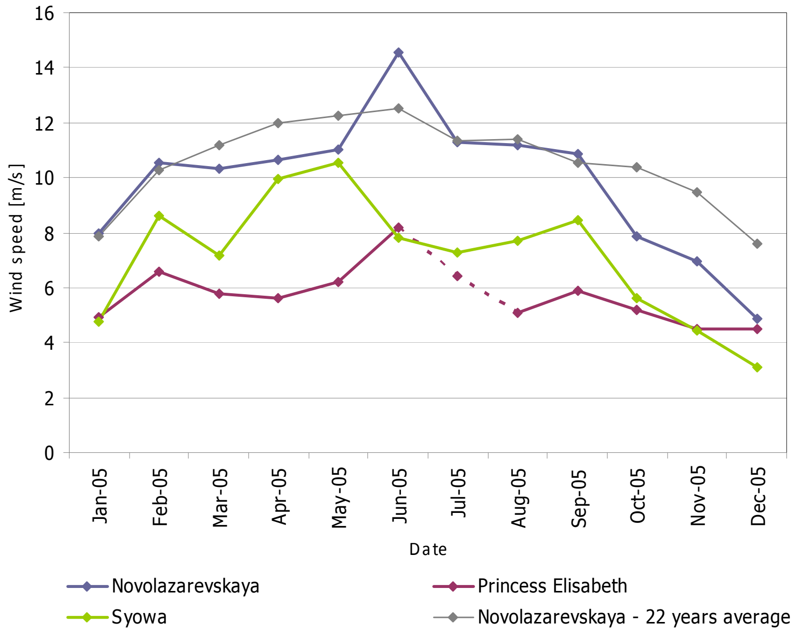

Figure 31: Monthly mean wind speeds (2005) - correlation 2

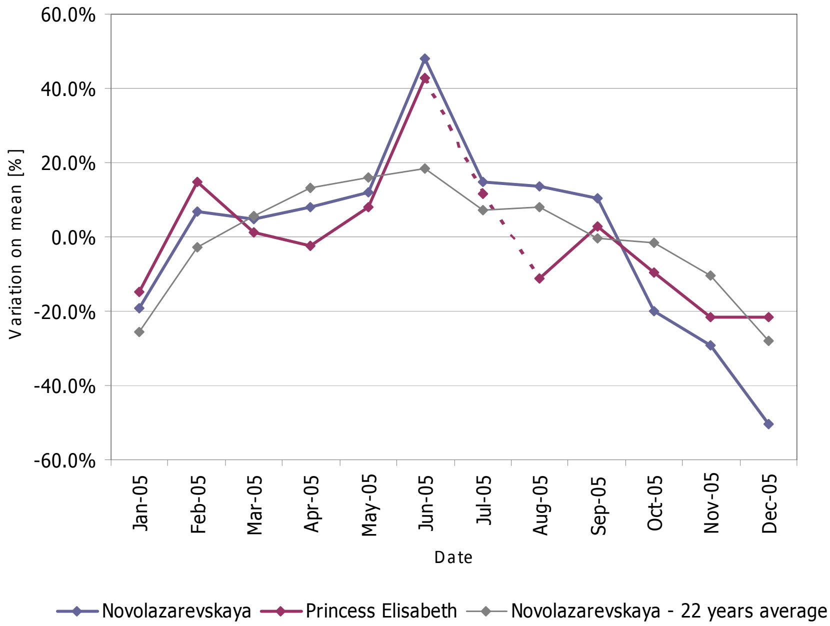

Figure 32: Variation on monthly mean wind speed (2005) - correlation 2

Table 38: Correlation coefficients (2005) – correlation 2

	Novolazarevskaya	Princess Elisabeth	Syowa
Novolazarevskaya	1		
Princess Elisabeth	0.873	1	
Syowa	0.766	0.590	1

The good correlation with the 45 years old station Novolazarevskaya is used by the Von Karmann Institute (VKI) to estimate the extreme velocity (for a 50 years recurrent period) at 54 m/s. The same correlation also allows estimating the possible future wind speed variation. Figure 33 shows the annual mean wind speed of Novolazarevskaya over 22 years (1985-2006). The annual mean wind speed ranged from 9.8 m/s to 11.6 m/s with a total mean of 10.5 m/s. The mean wind speed for the year 2005 is 10.25 m/s, approximately 2.5% below the long-term mean.

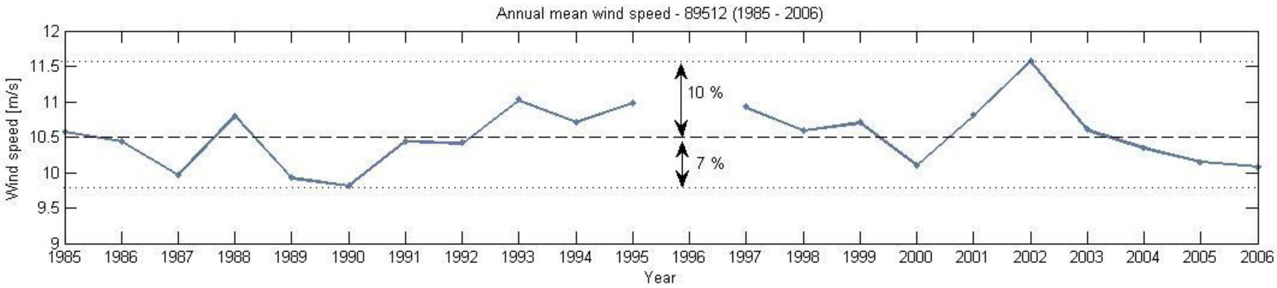

Figure 33: Annual mean wind speed - Novolazarevskaya(1985 - 2006)

4.3.3 Original model input file

Based on the original data file (of both AWS) and the correlation with Novolazarevskaya, a final AWS record for 2005 at a height of 4 m is generated. This data file has been transformed to 10 m and used for the simulations in previous sections. The gap filling applied is however incorrect as can be observed in Figure 34.

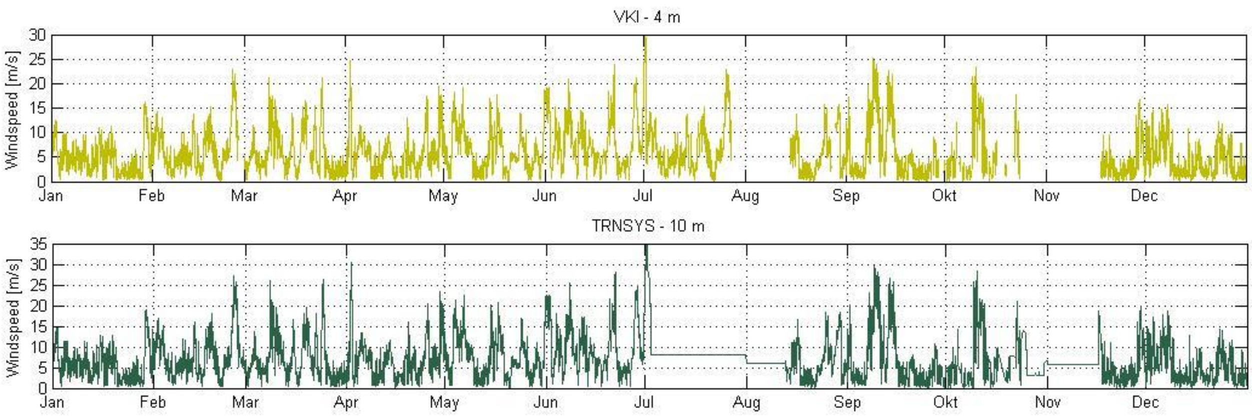

Figure 34: VKI AWS (4 m) and TRNSYS (10 m) wind data

4.3.4 Wind data regeneration

Based on the original AWS wind data for the year 2005, a complete new hourly wind series is generated using a first order Markov chain. This method uses the statistical properties of the original data to generate a new data series with similar statistical properties.

Methodology

In a Markov process, the probability of the given condition is deduced from information on the preceding condition(s). A Markov chain represents thus a system of elements moving from one state to another over time. Many natural processes are considered as Markov processes. The order of the process reflects the number of time steps in the past influencing the probability distribution of the present state. In other words, when using a first order Markov chain, the state of the current wind speed is defined depending on the previous state only [29].

In the first order Markov approach, the observed wind series is divided in a number of bins (states). Such a wind speed bin contains all the wind speeds between certain values. The number of bins, and thus the upper and lower wind speeds for the states, is subjectively chosen. Values ranging from 10 bins till 22 bins are found in other wind research [27, 28, 30, 31]. Some studies use the standard deviation as the width of an individual bin [29].

The likelihood that the wind has a particular value, given its previous state, is determined and summarized in a Transition Probability Matrix (TPM). This is done by counting the occurrence of a data point in a particular bin (j), given that the preceding point is present in some other bin (i) (or the same one). When this happens, a transition from state i to state j has occurred and the number of transitions n_{ij} is increased with 1. We also take into account the reverse signal and therefore increase n_{ji} with 1 to ensure detailed balance [27]. Detailed balance means that the process moves from wind speed interval i to j just as often as it moves from wind speed interval j to i [27].

Mathematically, the transition probability matrix of a first-order Markov chain with k states can be written as:

$$P = \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1k} \\ P_{21} & P_{22} & \dots & P_{2k} \\ \dots & \dots & P_{ij} & \dots \\ P_{k1} & P_{k2} & \dots & P_{kk} \end{bmatrix}$$

Where P_{ij} is the probability of transition from state i to state j. The state probabilities can be estimated from the relative frequencies of the k states.

$$P_{ij} = \frac{n_{ij}}{\sum_j n_{ij}} \quad \text{i, j} = 1,2,\dots,\text{k}$$

The probabilities are redistributed over the diagonal ($i \neq j$) to comply with the detailed balance described above [27]. After applying the detailed balance, the unity row sum needs to be restored. All row values are therefore normalized [30].

Once the TPM is defined, a synthetic wind series can be generated. A uniform random number generator generates the data series, based on an initial state vector and a given distribution vector (equal to the bin probabilities in the TPM) [29].

A higher order method can be applied to generate synthetic wind series, but further improvement on statistical similarity is however limited. A second order Markov model increases slightly the accurateness [30].

Data regeneration

For the Princess Elisabeth application, the original AWS data file is first transformed to the hub height of 10 m using the standard power law:

$$V = V_{AWS} \cdot \left(\frac{z}{z_{AWS}} \right)^{\alpha}$$

Where *V* is the wind speed in meters/second at height *z* (in meters), and V_{AWS} is the known wind speed at a reference height z_{AWS}. The exponent α is an empirically derived coefficient that varies dependent upon the stability of the atmosphere. For neutral stability conditions, α is approximately 0.143 [40].

The transformed data file is divided in monthly data intervals. This is done to ensure that the typical month profile is not lost when applying the Markov process. To start the first generation a random initial state is chosen and the original AWS data of the month January is analyzed by the Markov procedure to construct the TPM and subsequently the new synthetic data series. The final value of the newly generated synthetic data series (January) is used as initial state value of the following data generation (February). This process is repeated to complete a full synthetic year. Figure 35 compares the original AWS data file and the regenerated synthetic wind series.

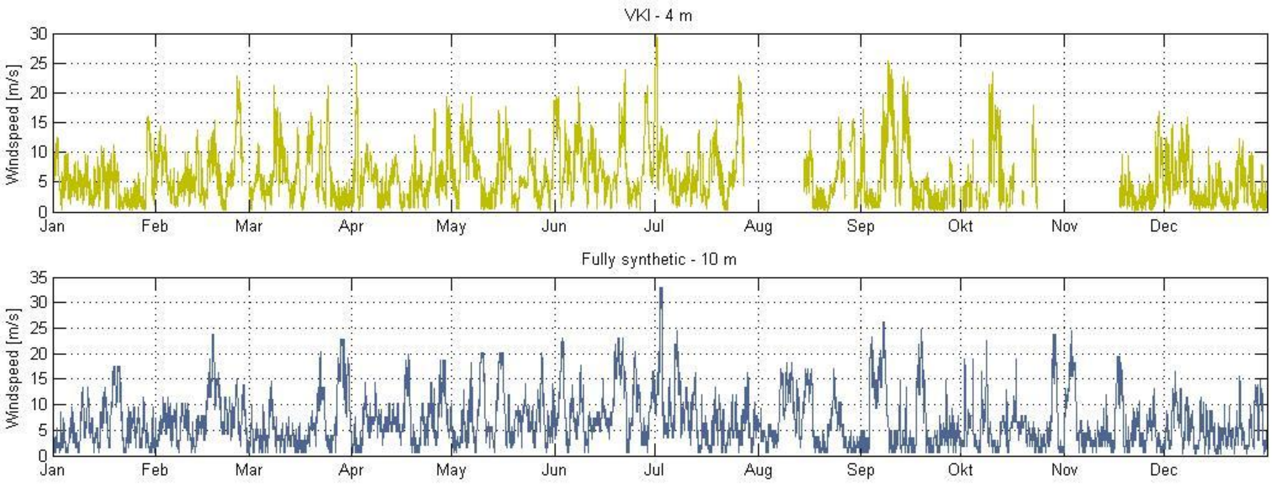

Figure 35: VKI AWS (4 m) and synthetic (10 m) wind data

Finally the data series are investigated on statistical similarity. The results are displayed in Table 39. The synthetic data profile differs 0.5% in mean value, 0.8% in standard deviation and less than 2% in Wiebull parameters from the transformed AWS data file. The previous data file from the TRNSYS model differs almost 5% in mean value, 2.5% in standard deviation and almost 9% in Weibull parameters compared to the transformed AWS data file. This means the synthetically generated wind series is statistical more relevant for further calculations.

Table 39: Statistics synthetic wind data

	Standard statistics				Weibull parameters			
	Mean		Standard deviation		Shape k		Scale c [m/s]	
TRNSYS – 10 m	6.98	4.4%	4.99	2.5%	1.47	8.7%	7.73	5.6%
VKI – 10 m	6.69	0%	5.11	0%	1.35	0%	7.32	0%
Synthetic – 10 m	6.72	0.5%	5.07	0.8%	1.37	1.6%	7.37	0.7%

In Appendix L more details can be found on the monthly observations and monthly synthetic generation. An example of a monthly TPM is also displayed.

4.4 Design summary

4.4.1 New meteorological input

The station has been simulated in TRNSYS using the new temperature data and the synthetic wind data. The configuration of loads, sources and storage did not change. When using the synthetic wind profile in stead of the original TRNSYS wind data, without changing the temperature profile, only 1% less of wind energy is produced each year. This results in an increased use of the generator (25%) and thus higher annual fuel consumption and shorter battery lifetime. The results can be found in Table 40.

Table 40: Design summary synthetic wind

	Original file		Synthetic wind	
	Absolute	Relative	Absolute	Relative
Wind turbines	92.8 MWh	65%	91.9 MWh	64%
Generators	4.5 MWh	3%	5.6 MWh	4%
Fuel consumption	1370 litre		1696 litre	
Battery life time	7.2 years		6.3 years	

Starting from the synthetic wind case, the temperature file is also substituted with the newly generated one. The use of the generator is 12.5% lower compared to the previous case, resulting in lower annual fuel consumption. This effect does not only originate of a changed heating load. Due to the passive house design, the heating load is limited anyway and this load is even higher in the new case as ambient temperatures vary less. The main temperature effect is found on the production of the PV arrays. The lower ambient temperatures during the day time create higher panel efficiency and thus a better energy production. Table 41 gives an overview of the results.

Table 41: Design summary new temperature profile

	Synthetic wind – original temperature		Synthetic wind – Asuka temperature	
	Absolute	Relative	Absolute	Relative
Annual heating load	2.6 MWh		3.0 MWh	
PV	45.8 MWh	32%	46.7 MWh	32.5%
Generators	5.6 MWh	4%	5.1 MWh	3.5%
Fuel consumption	1696 litre		1563 litre	
Battery life time	6.3 years		6.6 years	

It can be concluded that the impact on the design of the new meteorological inputs is limited. The new synthetic wind profile, which is statistical similar to the original AWS data, generates less wind power compared to the original model (TRNSYS). This result is expected as the mean values of both wind series also differ significantly (Table 39). When adding the new temperature input, the annual fuel consumption has decreased as the efficiency of the PV modules is increased. Figure 36 reveals that the marginal gain of adding wind turbines or PV is equal as in Figure 24. This means the final model configuration and its component sizing do not need to change when applying the validated meteorological inputs. The current design is therefore still valid to achieve the predefined objectives. For any further calculations, the newly generated meteorological data are used.

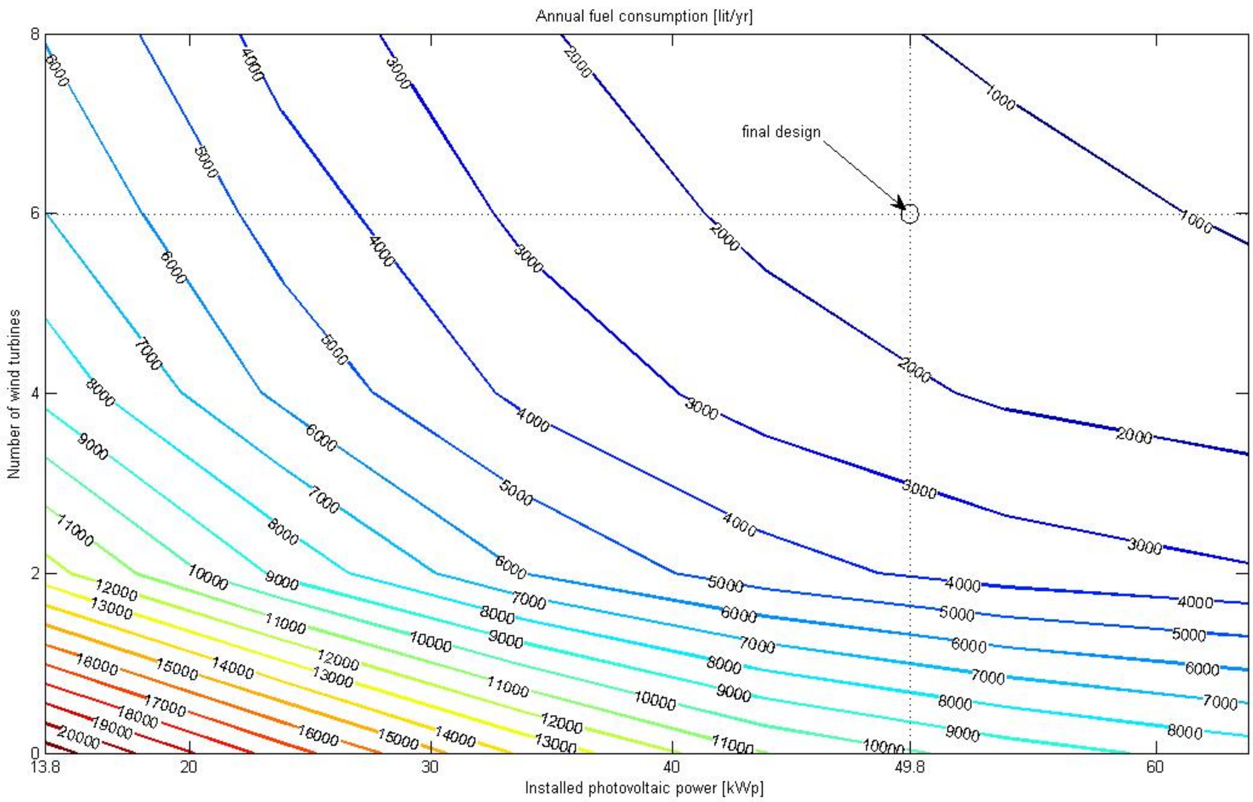

Figure 36: Summer station - sensitivity analysis sources (PV – Wind turbines) – synthetic input

4.4.2 Sensitivity on the wind data

The previous section (Figure 33) reveals that the annual wind speed at Novolazarevskaya only varies within a limited range. It also showed the wind speed of 2005 can be considered as rather "weak" compared to the average. As the data is highly correlated with the Princess Elisabeth site, the influence of a variation on the mean wind speed is investigated to determine the future performance variation. Table 42 gives an overview of the applied wind variation and the corresponding annual fuel consumption, battery lifetime and wind energy production.

Table 42: Summer station - wind sensitivity: data and performance results

	Statistics			Design performance		
	Mean wind speed [m/s]	Shape k	Scale c [m/s]	Annual fuel consumption	Battery lifetime	Wind energy produced
Case: + 25 %	8.40	1.37	9.21	951	8.6	121.1 MWh
Case: + 20 %	8.07	1.37	8.84	1040	8.2	115.7 MWh
Case: + 15 %	7.73	1.37	8.49	1165	8.0	109.8 MWh
Case: + 10 %	7.40	1.37	8.11	1339	7.5	104.1 MWh
Case: + 5 %	7.06	1.37	7.74	1442	7.0	98.1 MWh
Case: nominal	6.72	1.37	7.37	1563	6.6	91.9 MWh
Case: - 5 %	6.39	1.37	7.00	1762	6.2	85.6 MWh
Case: - 10 %	6.05	1.37	6.63	1990	5.8	79.1 MWh
Case: - 15 %	5.72	1.37	6.27	2230	5.4	72.5 MWh

Case: - 20 %	5.38	1.37	5.90	2460	5.1	65.7 MWh
Case: - 25 %	5.04	1.37	5.53	2741	4.7	58.5 MWh

Figure 37 shows the same performance variation in percentages. Both the wind energy produced and the battery lifetime are slightly more variable than the applied wind variation. The fuel consumption is much more variable, especially when the mean wind is significantly decreased.

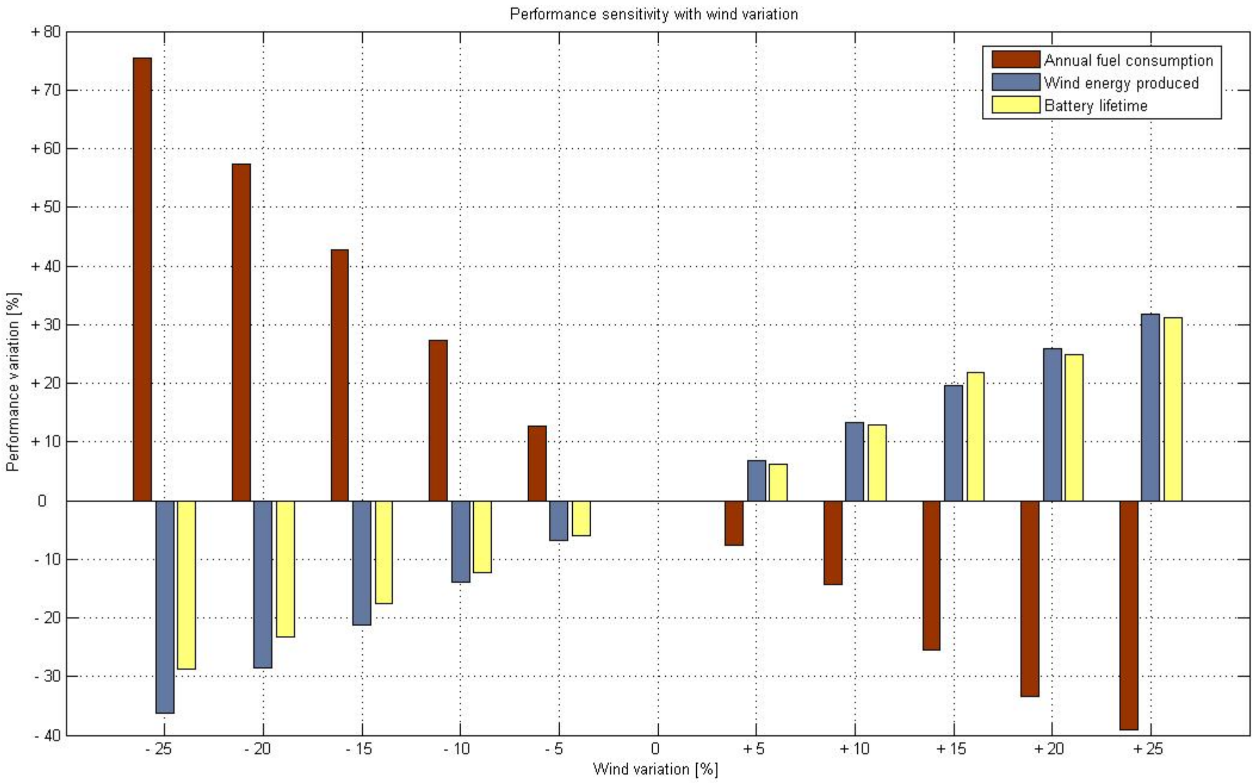

Figure 37: Summer station - performance sensitivity for wind variation

Based on the wind climate correlation, it is assumed that the wind at the Princess Elisabeth site varies in a similar way as at Novolazarevskaya. Therefore the future annual fuel consumption will vary between 1250 and 1750 litres under normal operations. Table 43 shows some more details on the effect of the statistical expected variation of wind speeds on wind energy production, fuel consumption and battery lifetime.

Table 43: Summer station - Long term performance estimation due to wind variation

	Difference with wind year 2005	Mean wind speed [m/s]	Annual fuel consumption	Battery lifetime	Wind energy produced
Best wind year	+ 12.5%	7.56	1252	7.75	107 MWh
Average wind year	+ 2.5%	6.89	1503	6.8	95.0 MWh
Wind year 2005	0%	6.72	1563	6.6	91.9 MWh
Worst wind year	- 4.5%	6.42	1742	5.76	86.2 MWh

5 Princess Elisabeth: permanent station

One of the design objectives of the station is the possibility to upgrade easily to a permanently manned station. This section investigates the possibilities and needs on the energy systems for this upgrade. Firstly the user profiles are redefined for the winter period and consequently the loads (energy and water) are modified. Secondly the station is simulated with the new input profiles and specific attention is paid to the annual performance and possible future design adaptations.

5.1 User profiles

Table 44 shows the station occupation under the permanently manned configuration. During the winter, the spring and the fall (including the former start-up and closing down periods), 6 crew members will hibernate on the station. No long-term field excursions are planned during this period.

Table 44: Crew members - permanent station

Scenario	Start date	End date	Max crew	Avg crew	Main activity
Winter	03/02	07/11	6	6	Crew hibernation
High season 1	08/11	30/11	20	14.3	Science
High season 2	01/02	22/02	20	14.1	Science
Low season	01/12	31/01	12	8.6	Science

5.2 Electrical loads

During the winter all electrical equipment related to household and office activities stay available and operational. The comfort temperatures (Table 9) are guaranteed in each zone as electrical heating is applied. The lighting comfort is slightly reduced (since natural light is no longer available), but still sufficient for the activities of the reduced crew. The water production treatment is maintained continuously.

5.3 Design summary

5.3.1 Loads and sources

If the station is permanently manned, the life supporting systems represent 73% of the complete annual energy consumption (compared to 54% for a summer station). The scientific equipment stands for 20% of the consumption and the household and office applications for the remaining 7%. A comparison on the annual energy consumption for the summer and permanent station can be found in Table 45. Table 46 gives a more detailed view of the annual consumption of the permanent station over the different periods. Figure 38 shows the monthly electrical energy consumption for the permanent station.

Table 45: Summer versus permanent station - loads - annual consumption

Electricity consumption	Summer station		Permanent station		Permanent/Summer
	Absolute	Relative	Absolute	Relative	
Household and office equipment	3.8 MWh	5.4%	9.9 MWh	6.9%	2.63
Research equipment	28.8 MWh	41.1%	28.8 MWh	20.0%	0
Workshop equipment	0.15 MWh	0.2%	0.36 MWh	0.2%	2.40
Water management	15.5 MWh	22.1%	47.9 MWh	33.3%	3.09
Ventilation	11.2 MWh	16.0%	28.4 MWh	19.7%	2.54
Heating	2.6 MWh	3.7%	18.0 MWh	12.5%	6.92
Station management	8.1 MWh	11.5%	10.6 MWh	7.4%	1.31
Total	70.1 MWh		143.9 MWh		2.05

Table 46: Permanent station - loads - annual consumption

PERMANENT STATION	Nov, Dec, Jan, Feb. (manned)		Mar, Apr, May, Jun, Jul, Aug, Sep, Okt (manned)		Total	
	Absolute	Relative	Absolute	Relative	Absolute	Relative
Household / office equipment	3.8 MWh	9.2%	6.1 MWh	5.9%	9.9 MWh	6.9%
Research equipment	9.6 MWh	23.3%	19.2 MWh	18.7%	28.8 MWh	20.0%
Workshop equipment	0.15 MWh	0.4%	0.21 MWh	0.2%	0.36 MWh	0.2%
Water management	15.5 MWh	37.6%	32.0 MWh	31.1%	47.9 MWh	33.3%
Ventilation	7.3 MWh	17.7%	21.4 MWh	20.8%	28.4 MWh	19.7%
Heating	1.4 MWh	3.4%	16.8 MWh	16.4%	18.0 MWh	12.5%
Station management	3.5 MWh	8.4%	7.1 MWh	6.9%	10.6 MWh	7.4%
Total	41.2 MWh	28.6%	102.7 MWh	71.4%	143.9 MWh	

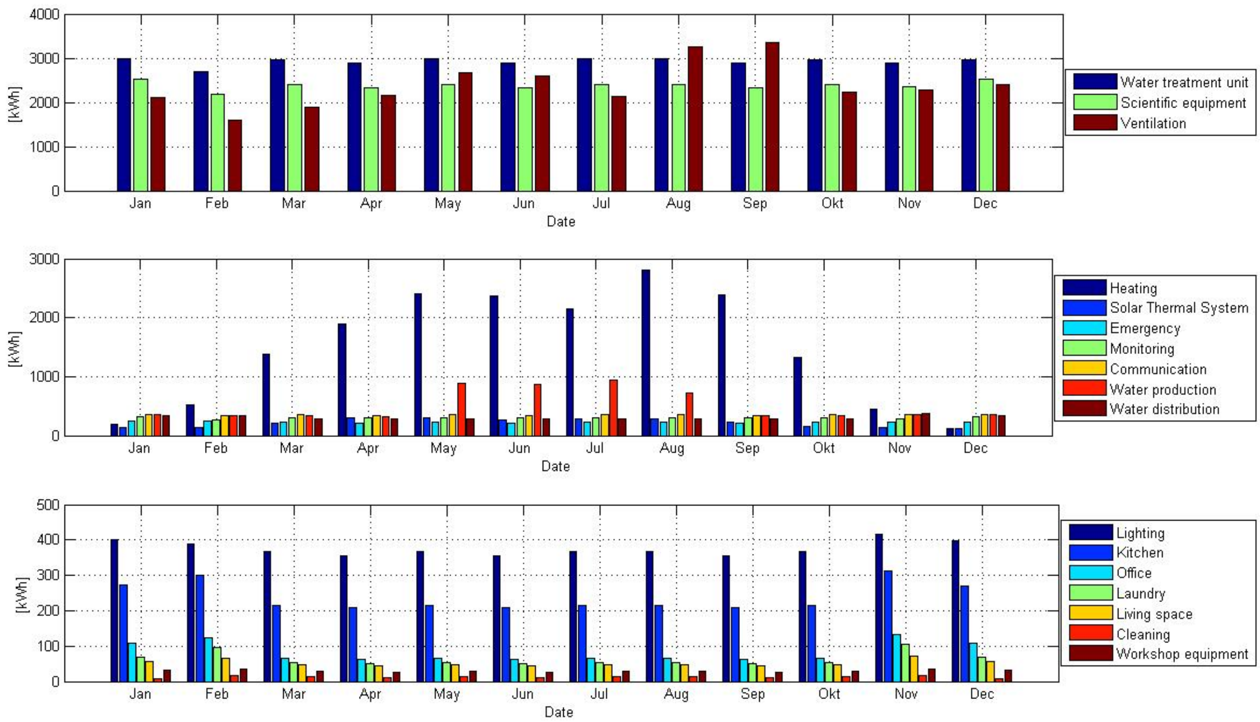

Figure 38: Permanent station - sources - monthly production (potential)

When considering the energy sources in the permanent station and the summer station, the electricity generated by wind and sun are approximately the same. The small differences are due to the meteorological data generated in the previous section. The generator however needs to operate almost 11 times more than in the summer station and thereby generates 28% of the total electricity. Table 47 compares the electricity generation between the summer and the permanent station. Table 48 gives a more detailed overview for the permanent station. Figure 39 gives an overview of the monthly electricity production. It shows the additional generator time is mainly needed during the manned spring, autumn and winter period.

Table 47: Summer versus permanent station - sources - annual production

Electricity production	Summer station		Permanent station		Permanent/Summer
	Absolute	Relative	Absolute	Relative	
Wind turbines	92.8 MWh	65%	91.9 MWh	48.0%	0.99
Building integrated PV	11.6 MWh	8%	12.0 MWh	6.3%	1.03
Stand-alone PV	34.2 MWh	24%	34.7 MWh	18.1%	1.01
Generators	4.5 MWh	3%	52.8 MWh	27.6%	11.7
Total	143.1 MWh		191.4 MWh		1.34

Table 48: Permanent station - sources - annual production

PERMANENT STATION	Nov, Dec, Jan, Feb. (manned)		Mar, Apr, May, Jun, Jul, Aug, Sep, Okt (unmanned)		Total	
	Absolute	Relative	Absolute	Relative	Absolute	Relative
Wind turbines	25.1 MWh	41.8%	66.8 MWh	50.9%	91.9 MWh	48.0%
Building integrated PV	7.6 MWh	12.6%	4.4 MWh	3.4%	12.0 MWh	6.3%
Stand-alone PV	26.0 MWh	43.3%	8.7 MWh	6.6%	34.7 MWh	18.1%
Generators	1.4 MWh	2.3%	51.4 MWh	39.1%	52.8 MWh	27.6%
Total	60.1 MWh	31.4%	131.3 MWh	68.6%	191.4 MWh	

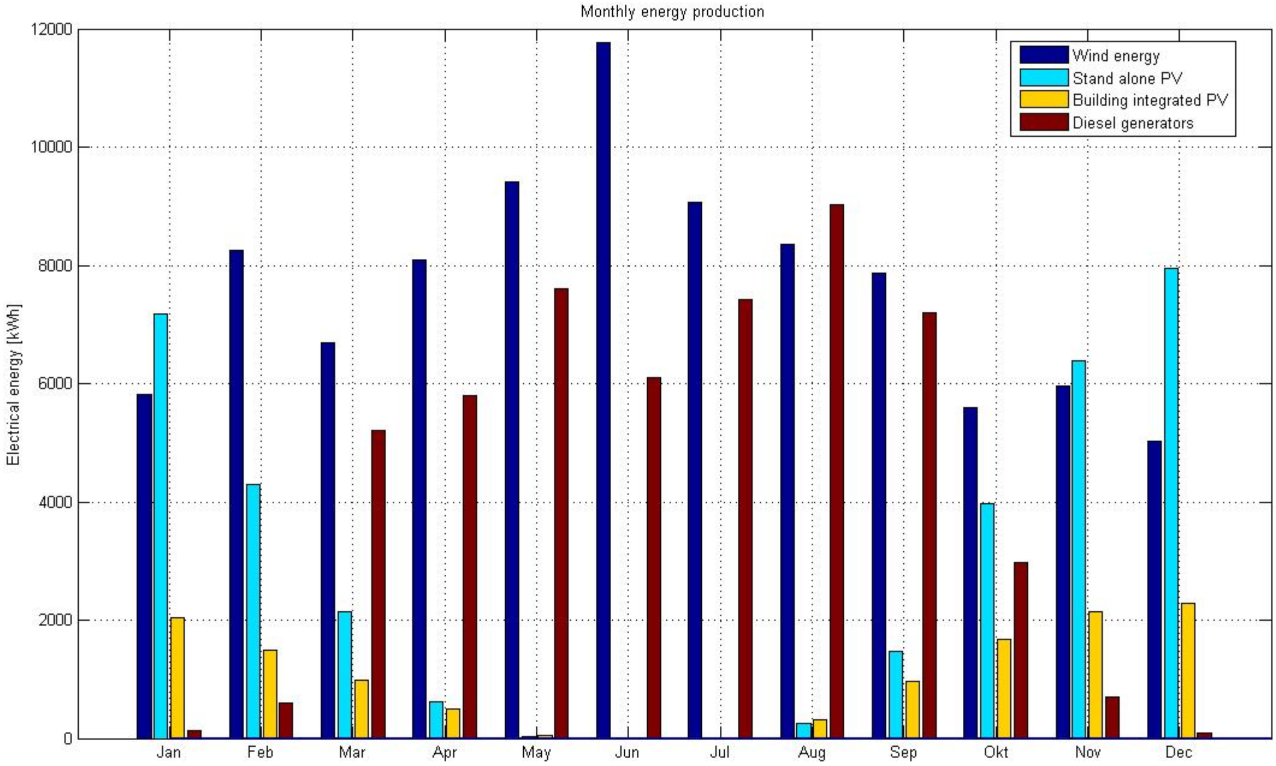

Figure 39: Permanent station - sources - monthly production (potential)

Table 49 shows 75% of the potential generated energy is used effectively. As can be observed in Figure 40 and in Table 50, the excess energy is much more limited in the winter period compared to the summer station.

Table 49: Summer versus permanent station - production versus consumption

	Summer station		Permanent station	
	Absolute	Relative	Absolute	Relative
Total generation	143 MWh		191.4 MWh	
Total load	70 MWh	49%	143.7 MWh	75%
Excess electricity	73 MWh	51%	47.7 MWh	25%

Table 50: Permanent station - production versus consumption

PERMANENT STATION	Nov, Dec, Jan, Feb. (manned)		Mar, Apr, May, Jun, Jul, Aug, Sep, Okt (unmanned)		Total	
	Absolute	Relative	Absolute	Relative	Absolute	Relative
Total generation	60.1 MWh		131.3 MWh		191.4 MWh	
Total load	41.2 MWh	68.5%	102.7 MWh	78.2%	143.9 MWh	75.2%
Excess electricity	18.9 MWh	31.5%	28.6 MWh	21.8%	47.5 MWh	24.8%

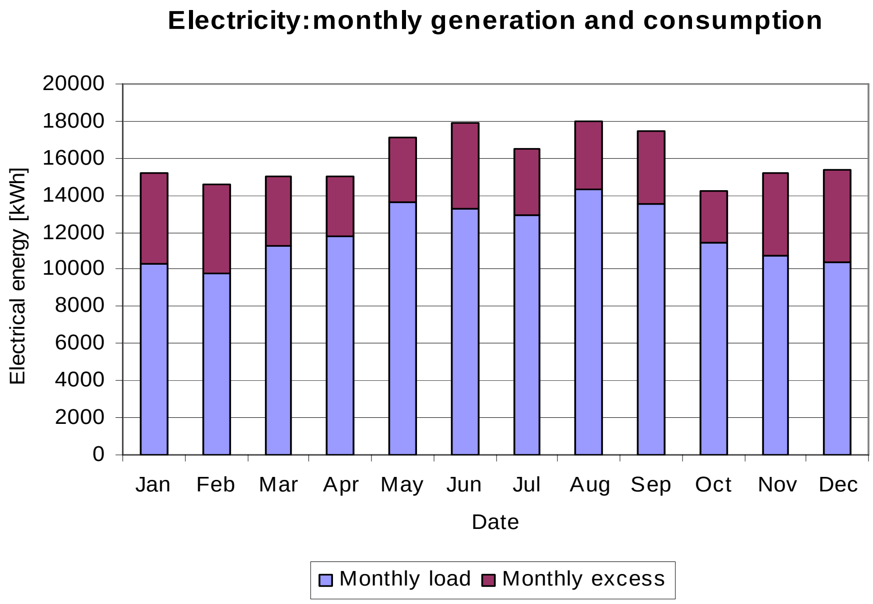

Figure 40: Permanent station - Electricity: monthly load and excess

5.3.2 Electrical storage and fuel consumption

The permanent station uses each year 16000 litres of fuel, which is almost 12 times more than for the summer station. The current battery bank will last only for 2.3 years if the same battery control algorithm is applied as for the summer station. It is clear both the annual fuel consumption and the battery lifetime are no longer within the initial objectives. Table 51 and Table 52 compare the performances for the summer and the permanent station.

Table 51: Summer versus permanent station - electrical storage - installed capacity and lifetime

	Summer station	Permanent station
Battery bank capacity	6000 Ah	6000 Ah
Lifetime	7.2 years	2.3 years

Table 52: Summer versus permanent station - annual fuel consumption and emissions[32]

	Summer station	Permanent station
Annual fuel consumption	1370 litres	16060 litres
Annual CO_2 emission	3.66 tons	42.7 tons
Annual CO emission	9.04 kg	105.5 kg
Annual unburned hydrocarbons emission	1.00 kg	11.7 kg
Annual particulate matter emission	0.68 kg	7.9 kg
Annual sulfur dioxide emission	7.35 kg	85.7 kg
Annual nitrogen oxides emission	80.60 kg	940.4 kg

5.3.3 Design sensitivity

When performing sensitivity analysis on the renewable sources, the annual consumption can be reduced mainly by installing more wind turbines. This is logical as the PV modules do not deliver any energy during the winter period. Doubling the wind power capacity (by adding 6 additional turbines or

[32] Emission for diesel fuel with density equal to 820 kg/m3, carbon content of 88% and sulfur content of 0.33 %

installing larger wind turbines) would result in an annual fuel reduction of approximately 4500 litres. Tripling this capacity would result in an annual reduction of 6500 litres (Figure 41).

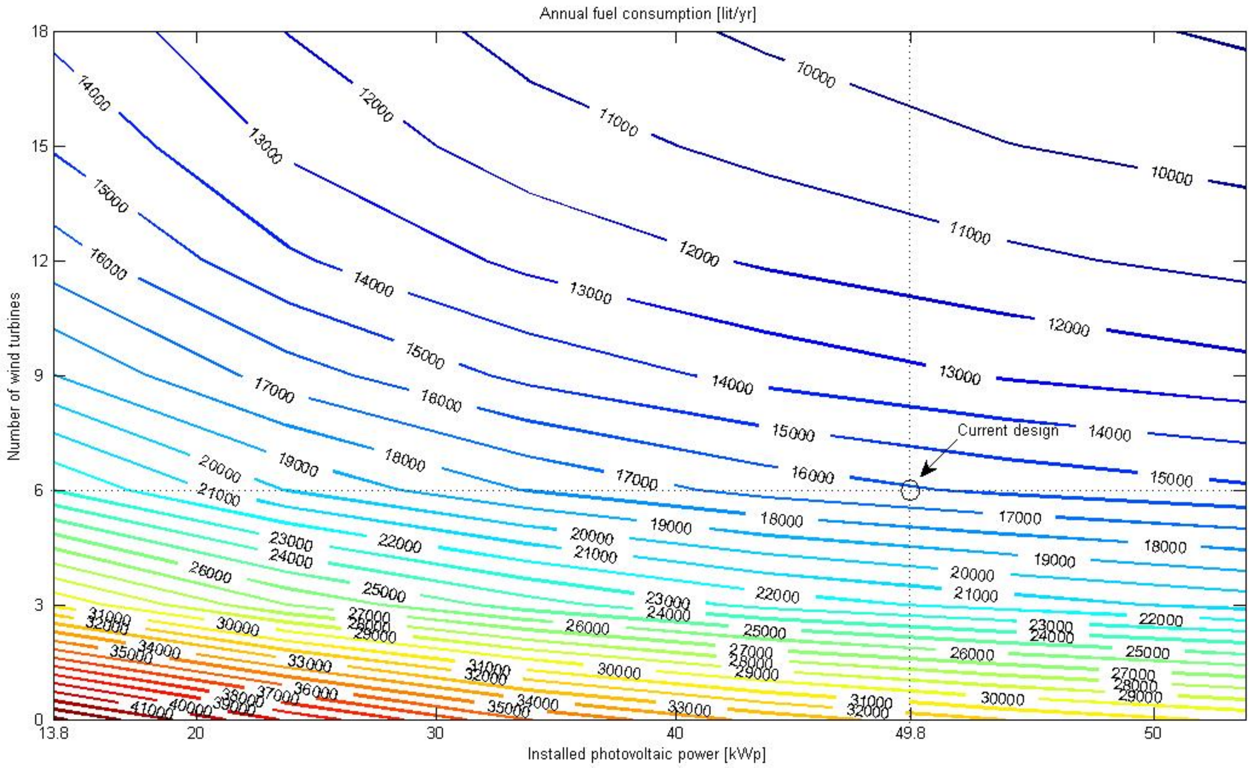

Figure 41: Permanent station - sensitivity analysis sources (PV - Wind turbines)

If extension of the electrical storage capacity is under consideration, the possible annual fuel reduction stays limited. Doubling the storage capacity would result in an additional annual fuel reduction of approximately 1500 litres (Figure 42). Due to limited geometrical constraints in the stations' battery room, a different battery technology needs to be chosen if storage capacity has to increase. Other technology also means different cycling depths (lifetime), different charging algorithms, etc. These calculations are beyond the scope of this research.

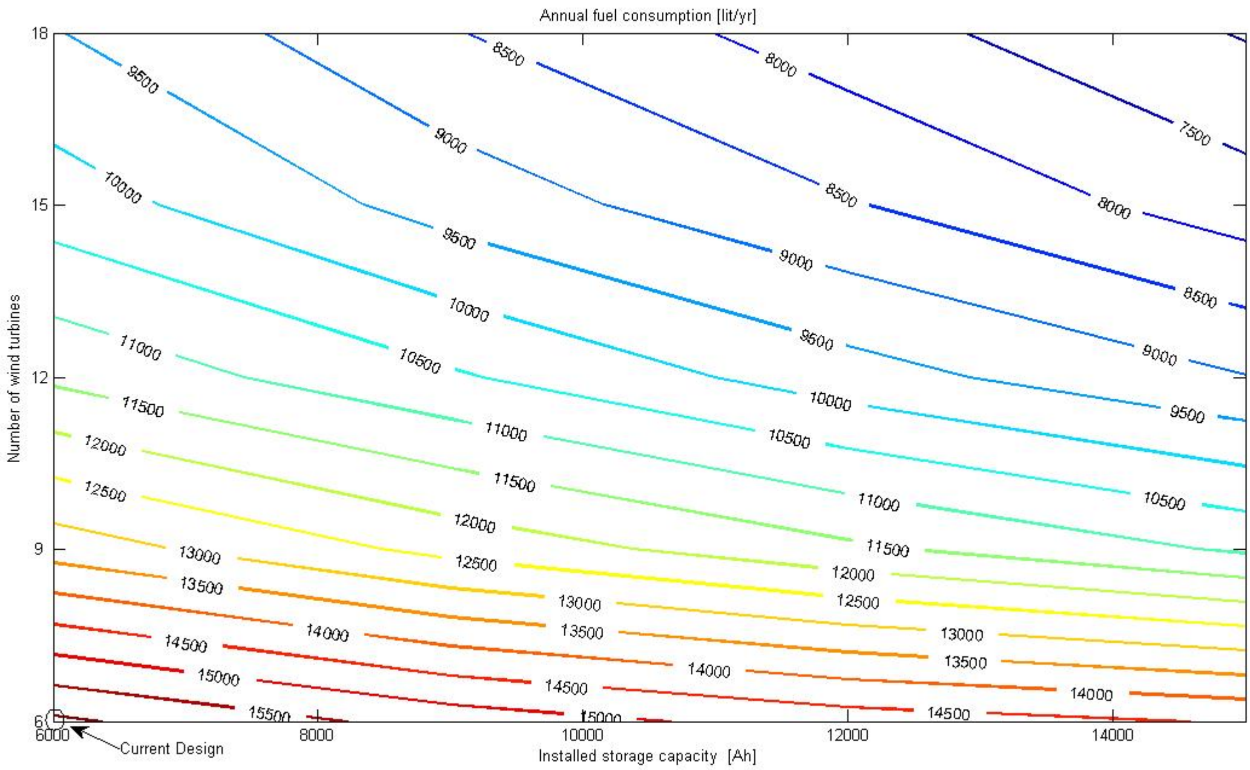

Figure 42: Permanent station - sensitivity analysis (Electrical storage - Wind turbines)

Based on the simulations, it can be concluded that the low emission aim is no longer reached when the station is being upgraded to a permanent station. The calculations also that show the low emission cannot easily be reached by adding more renewable sources or battery capacity. In addition, within the current design, the generator is not qualified to cope with the hibernating period and the battery charging control needs to be adapted as the battery cycles too much.

In order to reach the low emission objective, the loads during the autumn, spring and winter need to be reduced. The following items need some further research:

- Due to the reduced crew occupation, the base might be only partly operational. If heating, ventilation and lighting can further be reduced, this will have significant impact on the annual fuel consumption. This will however influence the structural design of the building and is therefore not preferred.
- The water treatment unit currently runs on full capacity during the whole complete year. A reduced water treatment program for the hibernating period can reduce the loads significantly. The possibility of periodic water treatment with extended water storage also needs to be further investigated.

If the low emission objective is abandoned for the permanent station, the installation of a small continuous generator is recommended. This small generator, with a minimum prime power rating of 10 kW, can supply sufficient energy for the continuous loads such as the water treatment and the science equipment. This would not only re-establish the balance in generated and consumed energy, but limit the number of cycles on the battery bank (and thus the lifetime).

5.3.4 Wind sensitivity – permanent station

The same wind variation as in the previous section is applied to the permanent station. Table 53 summarizes the results.

Table 53: Permanent station - wind sensitivity: data and performance results

	Statistics			Design performance		
	Mean wind speed [m/s]	Shape k	Scale c [m/s]	Annual fuel consumption	Battery lifetime	Wind energy produced
Case: + 25 %	8.40	1.37	9.21	12073	2.8	121.1 MWh
Case: + 20 %	8.07	1.37	8.84	12879	2.7	115.7 MWh
Case: + 15 %	7.73	1.37	8.49	13648	2.5	109.8 MWh
Case: + 10 %	7.40	1.37	8.11	14394	2.5	104.1 MWh
Case: + 5 %	7.06	1.37	7.74	15353	2.4	98.1 MWh
Case: nominal	6.72	1.37	7.37	16060	2.3	91.9 MWh
Case: - 5 %	6.39	1.37	7.00	17073	2.3	85.6 MWh
Case: - 10 %	6.05	1.37	6.63	18017	2.2	79.1 MWh
Case: - 15 %	5.72	1.37	6.27	18907	2.1	72.5 MWh
Case: - 20 %	5.38	1.37	5.90	20064	2.0	65.7 MWh
Case: - 25 %	5.04	1.37	5.53	21129	1.9	58.5 MWh

The variation on the annual fuel consumption and battery lifetime is more reduced in the permanent station compared to the summer station. This is logic as the total energy generation has increased. Figure 43 gives an overview of this variation.

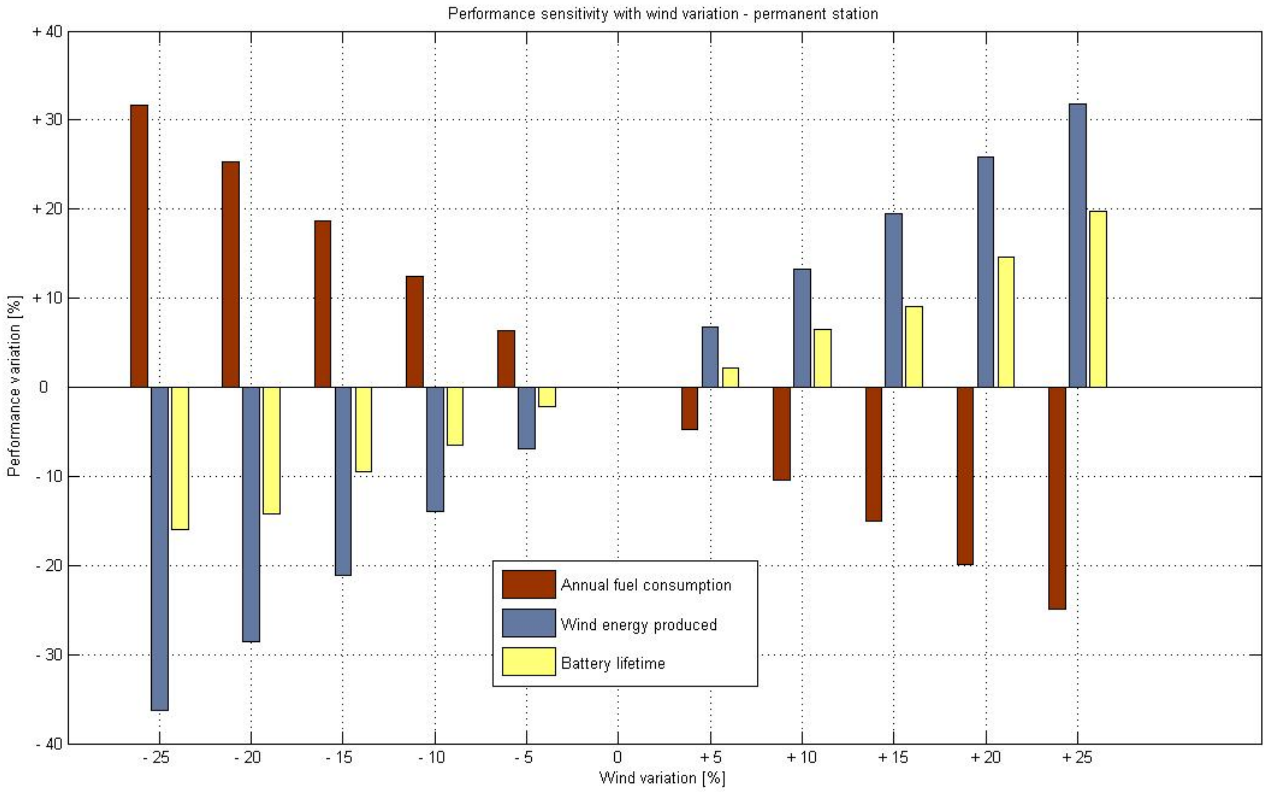

Figure 43: Permanent station - performance sensitivity for wind variation

When applying the wind margins of Novolazarevskaya, the annual fuel consumption ranges from 14000 litres to 17000 litres. The corresponding battery life is limited to 2.3 / 2.5 years. Both parameters are obviously not within the initial objectives. Table 54 shows some more details on the performance margins.

Table 54: Permanent station - long term performance variation due to wind variation

	Difference with wind year 2005	Mean wind speed [m/s]	Annual fuel consumption	Battery lifetime	Wind energy produced
Best wind year	+ 12.5%	7.56	14021	2.5	107 MWh
Average wind year	+ 2.5%	6.89	15706	2.35	95.0 MWh
Wind year 2005	0%	6.72	16060	2.3	91.9 MWh
Worst wind year	- 4.5%	6.42	16972	2.3	86.2 MWh

6 Conclusions and recommendations

The site of the Princess Elisabeth station is very suited for renewable energy. The low temperatures, snow reflection and sun abundance during the austral summer provide optimal conditions to use solar power. In addition the unidirectional high-energy wind makes the site perfectly suited for wind power all year round.

The station itself and its implementation on site are optimized to limit the energy demands. An iterative design process is used to optimize the thermal and electrical energy system. A total of 36 kW wind turbines is installed on site. Six small wind turbines, each of 6 kW, are preferred for handling, logistics and system redundancy. Next to the wind turbines, a 50 kWp photovoltaic system is required. One third of the PV modules is mounted on the different orientations of the building to stretch out the daily energy availability. The rest is installed on the field in the vicinity of the station. To complete the hybrid system, a VRLA AGM battery bank is needed with a capacity of 6000 Ah. Finally, two back-up generators of 35 kW are foreseen. For thermal energy, 21 m^2 solar thermal collectors and 1.5 m^3 heat storage is installed.

The hybrid energy system supplies sufficient energy for the operations at the polar station. Fuel and emission reduction are achieved due to the optimized combination of different technologies. As a result, the renewable energy fraction is 97% (65% wind power, 32% solar power), making the Princess Elisabeth station the most environmental friendly polar research station. To keep the station up and running, only 1370 litres of diesel is needed each year. The hybrid system configuration is mainly based on the stringent requirements during the manned period, as during the unmanned period approximately 65% of the potential generated energy needs to be dumped. Additional measures such as adding dump loads or lowering 3 of the 6 wind turbines during the unmanned period should be considered.

As the meteorological observations at the site are limited in time, they are validated with other polar stations. To investigate the impact of wind, a synthetic wind series is generated with a first order Markov chain process with similar statistical properties as the original observations. Using the validated meteorological inputs, the annual fuel consumption has increased with 14% to 1563 litres. It is clear the impact is limited and the low emission objective is still reached.

As two third of the energy is generated by wind, the possible wind variation is investigated based on the well correlated 45 years old station Novolazarevskaya. This wind variation defines the performance margins that can be expected in the future operations of the Princess Elisabeth station. The annual fuel consumption will range from 1250 litres in a best case scenario to 1750 litres in a worst case. This margin is still within the low emission objective.

Starting from the initial design objective (summer station), the low emission objective is clearly achieved. It is however very likely that the station will be manned permanently. Even though the initial energy system is not optimized for this additional requirement, the impact of this change is evaluated. If the Princess Elisabeth station is upgraded for permanent use, the total electrical load will double. The main contributors are ventilation, water treatment and heating which are almost independent of the amount of crew members. Under current system design, the renewable energy fraction is reduced to 72% (48% wind power, 24% solar power) with a corresponding annual fuel consumption of approximately 16000 litres. When considering the possible wind variation, the annual fuel consumption ranges from 14000 to 17000 litres. Sensitivity analysis show further fuel reduction is possible by adding wind turbines and storage capacity, but the marginal gain is limited. Attaining the low emission objective cannot be realized by extension of the energy generation and storage capacity. Significant reduction of the loads is needed to achieve this objective.

If the low emission objective is weakened, the Princess Elisabeth station can be permanently manned without major changes in the design. However attention is needed on the battery charge control and generator selection. The current battery bank will only last for 2 years due to elevated cycling. A possible solution is having a small generator (10 – 15 kW) which runs continuously from March till November to cope with the base load.

For further activities, the following items are recommended:

- The on-site installation of the stand-alone photovoltaic field needs to be investigated. Issues such as aerodynamic forces, anchoring, structural support, possible orientation and tilt angle are still undefined.
- Research needs to be done on the SCADA, more specific on the integrated energy management system. The impact of local control algorithms is significant and the hierarchic control system needs to be further defined. Real testing or emulation might be needed.
- Detailed research on optimal sizing of the dump loads, lowering part of the wind turbines or additional electrical storage is preferred to cope with the excess of energy.
- If the Princess Elisabeth station is upgraded to a permanent station more detailed research is needed on several aspects:
    - The user profiles and load correlations need to be redefined as they are currently based on summer assumptions.
    - The on-site possibilities of anchoring additional wind turbines or installing larger wind turbines need to be mapped.
    - In order to extent the electrical storage capacity, different technologies need to be investigated.
    - The water treatment unit needs to be further investigated on a possible load reduction due to a limited crew occupation. Other possibilities such as periodic water treatment coupled with extended water storage can also be considered.
- The installation of an additional automatic weather station to ensure higher reliability in the observed meteorological data. By preference this should be done at a different height.
- The implementation of a framework to register the actual energy generation and consumption in the station. Observations on the electrical load are needed to adapt or validate the current load assumptions and crew correlations. Additionally, observations on the generation are needed to estimate the operating frequency and reliability of all the systems.
- Research is needed on weather prediction in Antarctica. To optimize the energy management, historical trends and short-term weather predictions can help to fine tune the load prioritization schemes for load shedding.
- Additional research can be performed on the system design (and component selection) including economical decision variables. These parameters were omitted deliberately in this research as insufficient information is available on the cost of logistics, sponsorship contracts and rebates. An important item for further research might be the economical trade-off in the low emission objective for the permanent station. The current engineering optimum certainly differs from the economical optimum.

- A framework for knowledge and experience sharing is needed to promote the design of sustainable research stations on remote locations and to extend the general awareness in the possibilities and functionalities of hybrid energy systems.

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Appendix A Location description

Figure 44 shows the ridge observed from the Nunatak nearby. Figure 45 is a more detailed close up on the ridge and the view from the living room of the station. Figure 46 shows the beginning of the ridge and the installation of the second AWS.

Figure 44: Utsteinen ridge from Nunatak [Source: IPF]

Figure 45: Utsteinen ridge and Nunatak [Source: IPF]

Figure 46: Utsteinen ridge and AWS [Source: IPF]

Appendix B Meteorological data

Figure 47 is a more detailed view of the AWS at the beginning of the ridge. Table 55 represents the meteorological observations on the site.

Figure 47: AWS on the site [Source: IPF]

Table 55: Meteorological observations [Source: IPF]

Date	Atmospheric pressure [hPa]	Mean temp [C]	Maximum temp [C]	Minimum temp [C]	Mean wind speed [m/s]	Maximum gust [m/s]	Wind Direction [degrees]	Wind sector
Jan	834.7	-8.7	-3	-16.8	4.9	19.2	99.5	E
Feb	825	-12.3	-7	-20.2	6.6	28.6	105.9	ESE
Mar	827.1	-15.5	-7.2	-24.1	5.8	26.7	123.1	ESE
Apr	824.4	-19.7	-11.8	-29.1	5.6	31.1	134.9	SE
May	824.2	-22	-15.2	-31.4	6.2	23.2	125.3	SE
Jun	831	-21	-13.9	-32.4	8.2	28.9	118.3	ESE
Jul	823.5	-23.2	-15.8	-30.8		32.9		
Aug	821	-23.3	-15.4	-34	5.1	18.8	122.5	ESE
Sep	818.2	-24.4	-16.8	-33	5.9	30.7	113.2	ESE
Oct	823.1	-21	-14.5	-35.5	5.2	26.5	124.3	SE
Nov	832.9	-15	-9.9	-20.9	4.8	20.9	99.4	E
Dec	842.1	-8.4	-1.4	-17.5	4.8	18.3	98.1	E
year	827.3	-17.9	-1.4	-35.5	5.9	32.9	116.2	ESE

Figure 48 shows the theoretical day length, the maximum solar elevation (north at noon) and the solar elevation at East and West. Figure 49 is the result from the theoretical radiation calculations based on the daily presence of the sun.

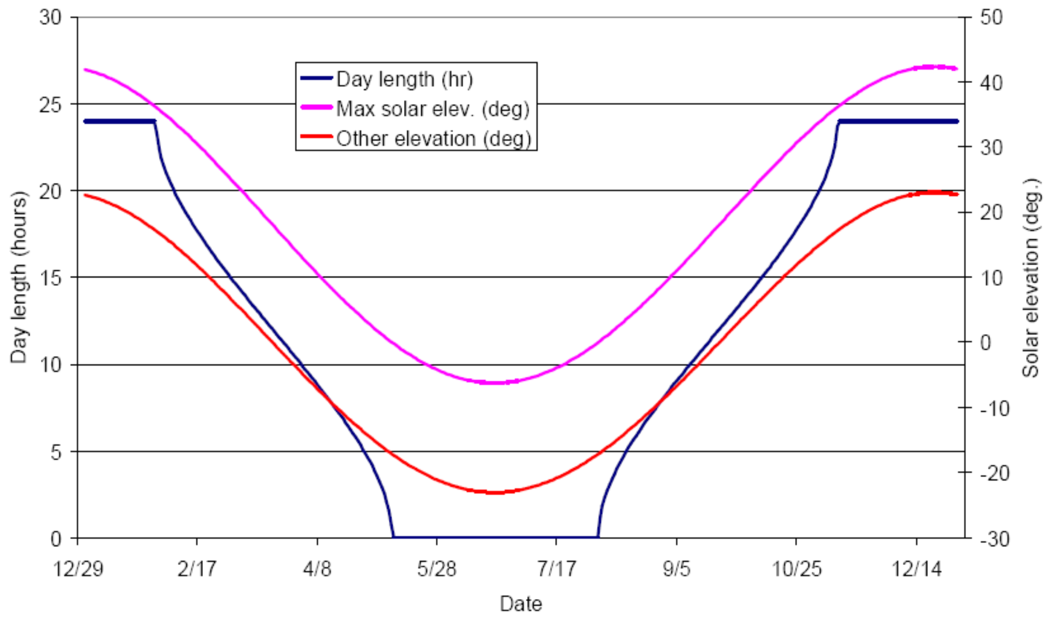


Figure 48: Theoretical day length and solar elevation [Source: IPF]

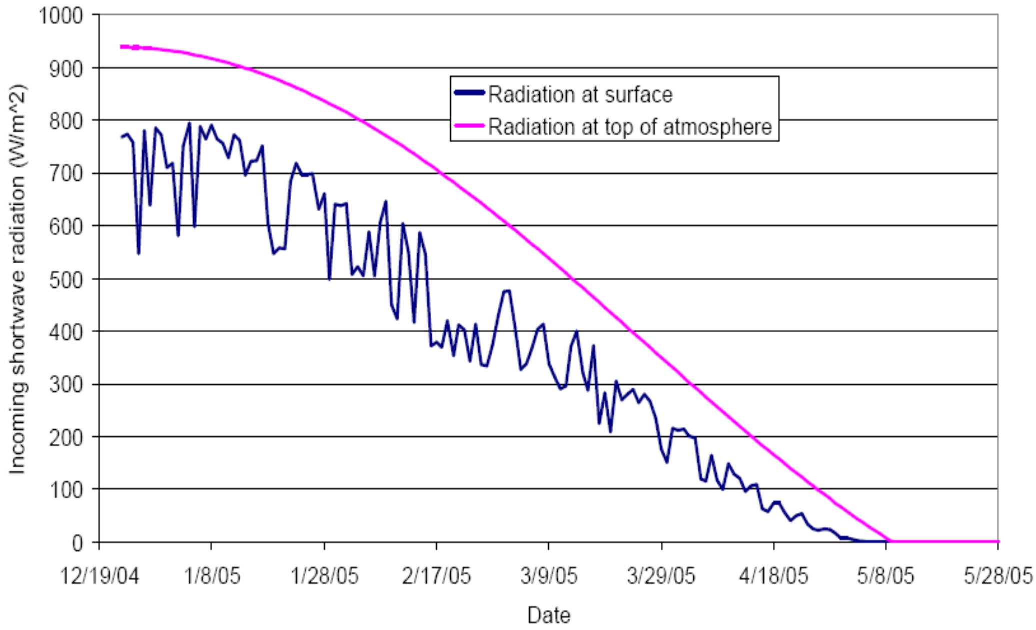


Figure 49: Surface and atmosphere radiation (sun at its highest elevation) [Source: IPF]

Appendix C Building concept, design and construction

Concept validation by VKI

Figure 50 shows the different stages for the building type selection. Based on 3D differential gps measurements, a snow boundary is simulated in a wind tunnel and a CFD model. Different building configurations are tested for different orientations to end up with the final building design. Figure 51 shows the hybrid design where the garage is under the snow surface and the main building mounted on struts on the ridge. Figure 52 shows the estimated wind speed up due to the building orientation.

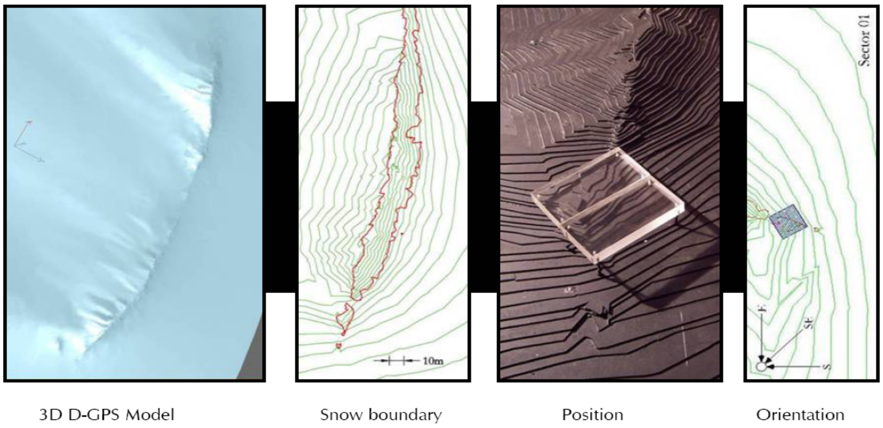


Figure 50: Development of building type [Source: IPF]

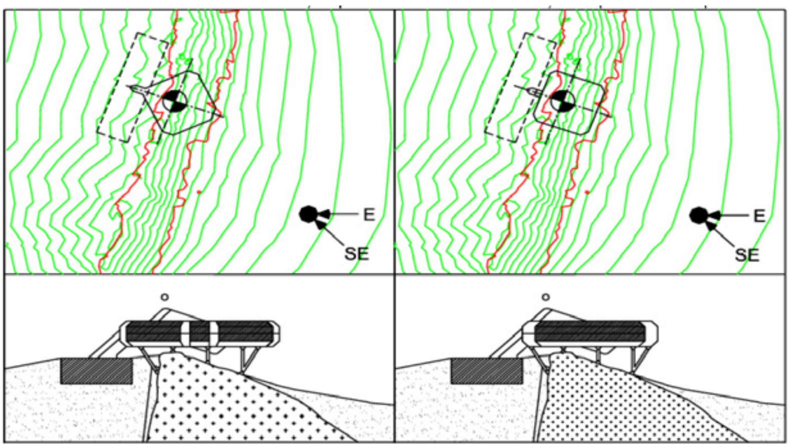


Figure 51: Hybrid building concept for different orientations [Source: IPF]

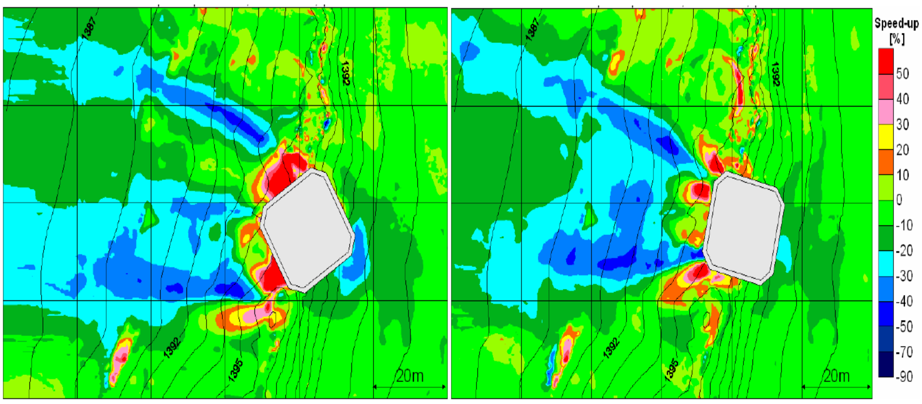


Figure 52: Wind speed up map (%) [Source: VKI]

Figure 53 shows the wind tunnel tests on snow accumulation / erosion and the building. Figure 54 is an illustration of the final chosen building design.

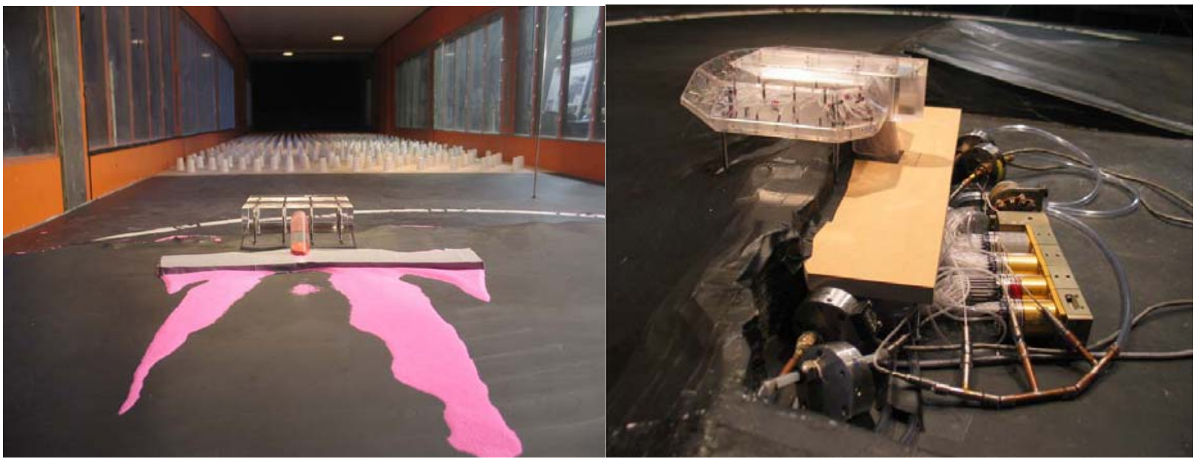


Figure 53: Sand erosion and building wind tunnel tests [Source: VKI]

Final building design

Figure 54: Building design [Source: IPF - www.detrols.com]

Preconstruction at Tour & Taxis (Brussels) – August 2007

Figure 55 shows the manual construction of a wooden building element. The black material is the 40 cm insulation that is cut tailor-made for each section. Figure 56 shows some different building modules that are used to construct the station. All the unique building modules fit as construction blocks in a wooden/steel frame. This concept is applied to facilitate construction (and disassembly) at Antarctica.

Figure 55: Construction of building elements [Source: Prefalux - IPF]

Figure 56: Final building modules [Source: IPF]

In September 2007, the main building of the station is assembled in Brussels to test the structural integrity. This assembly was also the general repetition for the building team. Figure 57 shows the unfinished living room of the station and the complete building pre-mounted.

Figure 57: Official presentation at Brussels (September 2007)

Construction at Antarctica

Figure 58: Construction on site (December 2007) [Source: IPF]

Appendix D TRNSYS modeling tool

Figure 59 is a visual presentation of the TRNSYS working environment.

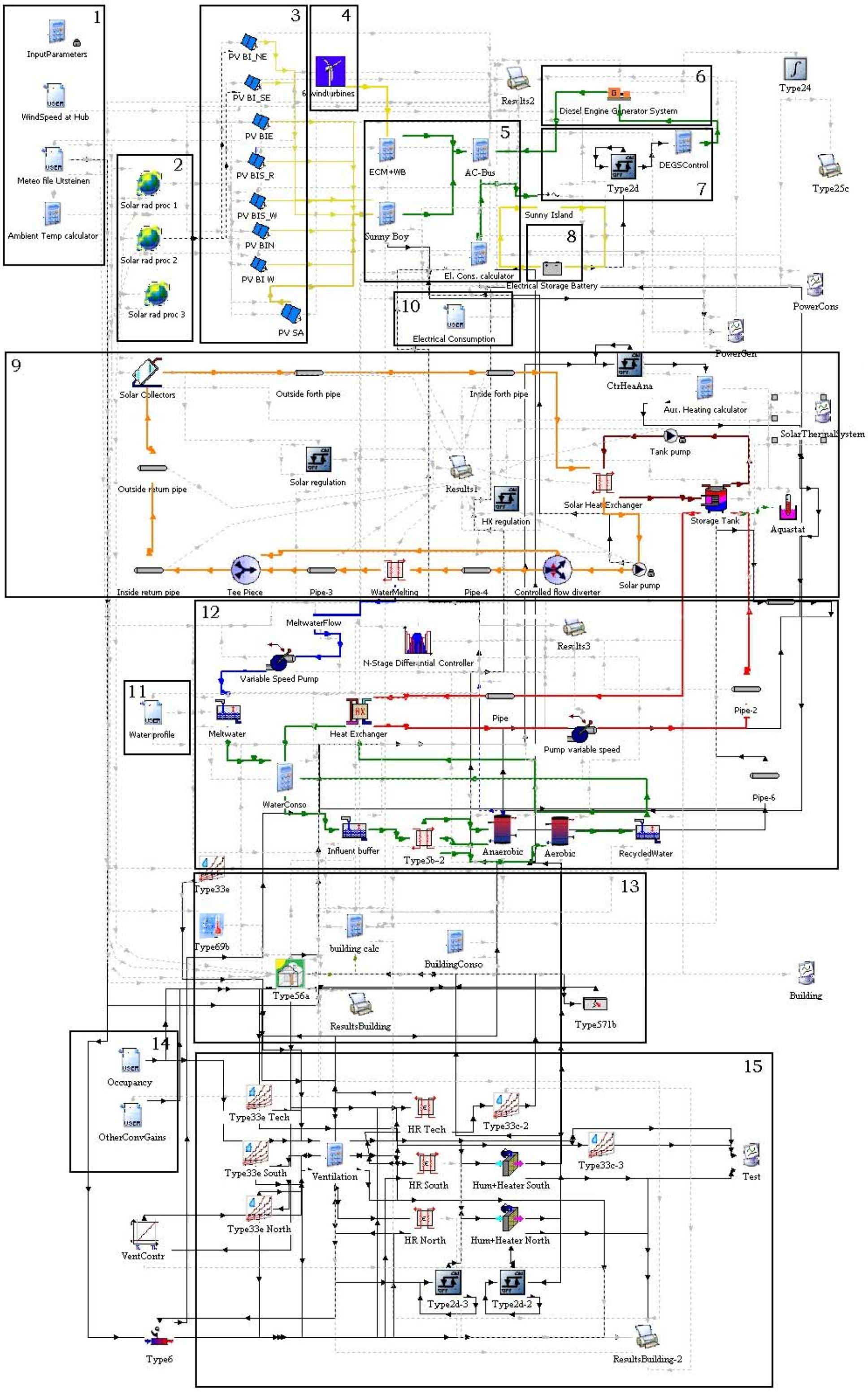


Figure 59: TRNSYS model representation

The following elements can be distinguished in the visual presentation of the TRNSYS model

- 1: Meteo input files (txt,dat: 1hr readings for 1 year)
- 2: Solar irradiation files (adapted to albedo effect, inclination and orientation)
- 3: PV simulation (module referenced)
- 4: Wind turbine simulation (manufacturer referenced)
- 5: Wind, solar, grid electronics
- 6: Diesel generators
- 7: Charge controller
- 8: Battery banks
- 9: Solar thermal systems (with simulation of pipes, pumps, etc.)
- 10: Electrical input file (electrical consumption related to base occupancy)
- 11: Water input file (water consumption related to base occupancy)
- 12: Water distribution and treatment
- 13: Complete building simulation (physical layout, insulation, windows, ventilation profiles, solar gains, wall properties, etc)
- 14: Thermal internal gains of electrical equipment and crew occupation
- 15: HVAC simulation (with heat and moisture recovery)

Appendix E User profiles

Figure 60 shows the base occupation during the summer months (for the summer station). It also shows the estimated amount of crew members on expedition. Figure 61 reveals the corresponding water demand. Figure 62 shows the typical day profile for the water consumption.

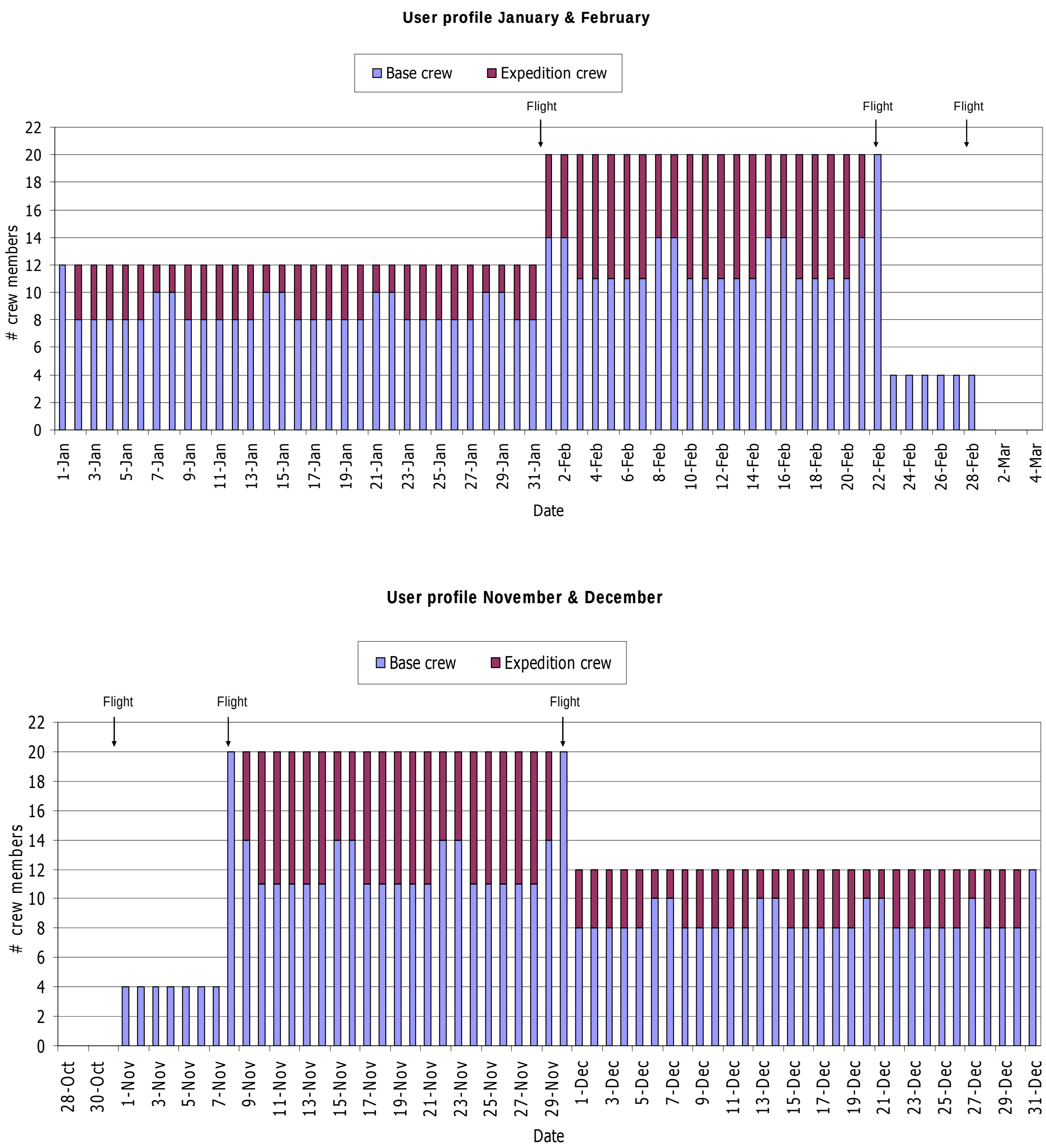
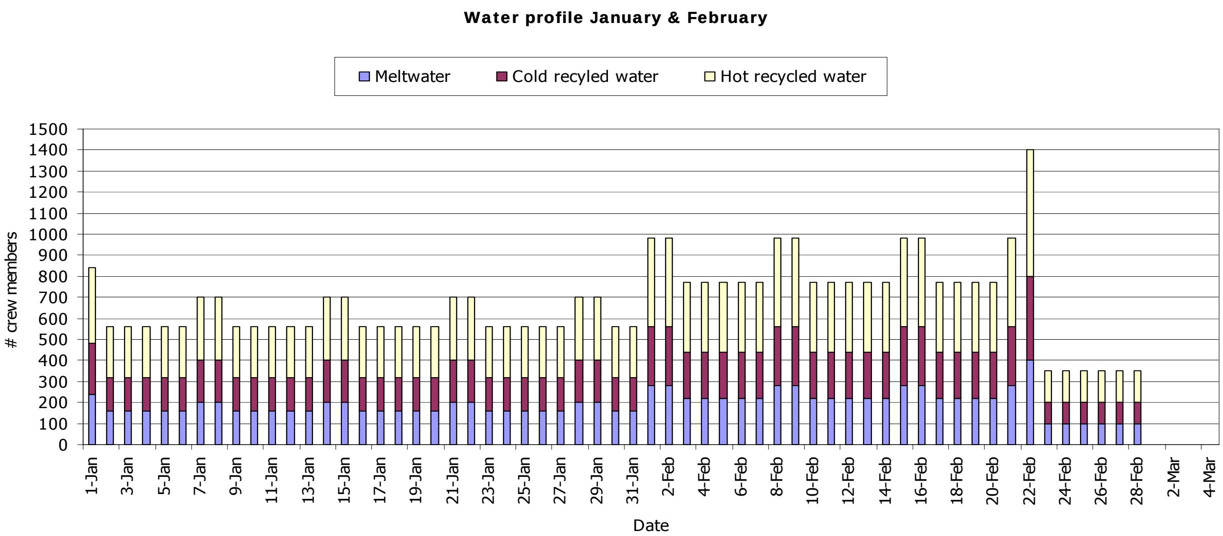


Figure 60: Station occupation during manned period



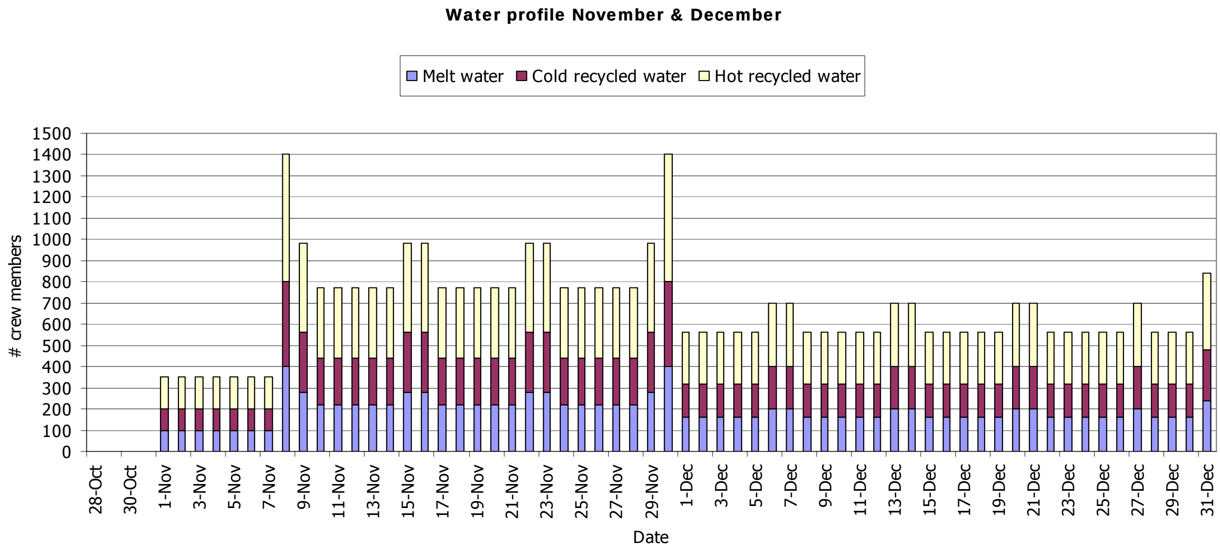


Figure 61: Water profiles manned season

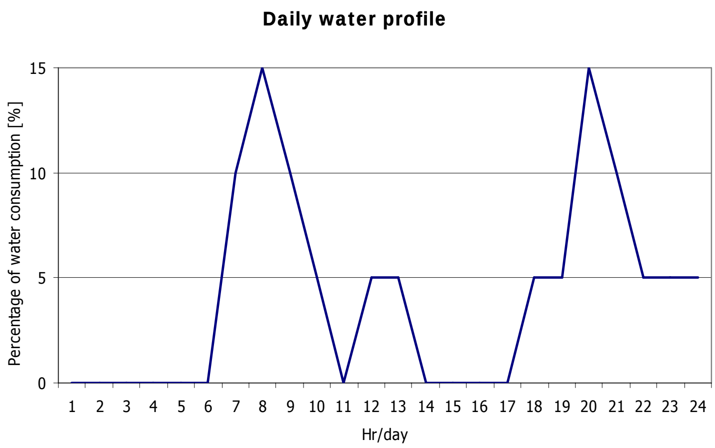


Figure 62: Daily water consumption profile

Appendix F Electrical equipment

Household and office equipment

Table 56 lists all the electrical equipment installed for household and office applications. The correlation with number of people reflects the additional consumption that is expected for an additional user on the station.

Table 56: Electrical equipment for living accommodations

Household and office equipment						
1.1. Kitchen						
User Controlled Loads	*Number*	*Power pu*	Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Coffee Machine	2	1000	2000	50%	1	1
Oven	1	2500	2500	20%	1	1
Cooking plates	4	2,000	8,000	60%	1	1
Cooking hood	1	300	300	60%	1	1
Micro-Wave	2	1300	2600	100%	1	1
Dishwasher	1	2200	2200	30%	1	1
Food grinder	1	500	500	20%	1	1
Food / juice mixer	1	600	600	100%	1	1
Electric kettle (water boiler)	1	1800	1800	80%	1	1
Continuous Loads						Duty Cycle
Freezer	2	120	240	0%		0.239726027
Fridge	2	120	240	0%		0.139
1.2. Offices						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Desktop PCs + LCD screen	2	120	240	20%	1	1
Portable PCs	10	60	600	20%	1	1
Printers	1	200	200	30%	1	1
Projector (LCD)	1	220	220	30%	1	1
Continuous Loads						Duty Cycle
Standby office			10	0%		1
1.3. Laundry						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Washing machine	2	2200	4400	30%	1	1
Drying machine	1	2400	2400	30%	1	1
1.5. Living						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Music Installation	1	65	65	0%	1	1
Television	1	100	100	20%	1	1
DVD-player	1	60	60	0%	1	1
Projector (LCD)	1	220	220	0%	1	1
Continuous Loads						Duty Cycle
MP3-players, other personnel appliances	1	20	20	100%		0.166666667
1.6. Cleaning						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Vacuum Cleaner (manual)	1	1000	1000	20%	1	1

Table 57 is an overview of the properties of different lighting technology, used for the selection. Figure 63 is a more detailed overview of the different lighting units throughout the building.

Table 57: Lighting - technology tradeoff

	Incandescent light bulb	Halogen	Compact fluorescent	TL5	LED
Efficiency	Bad	Average	Good	Very good	Good
Track record	Very good	Very good	Very good	Very good	New technology
Maintenance and lifetime	1000 hours	3000 hours	10000 hours	20000 hours	100000 hours
Working conditions	OK	Not checked	Bad below 0°C	Bad below 0°C	OK
Total harmonic distortion	None	Not checked	Critical	Critical	Critical
Cost	Low	Low	Low	Average	High

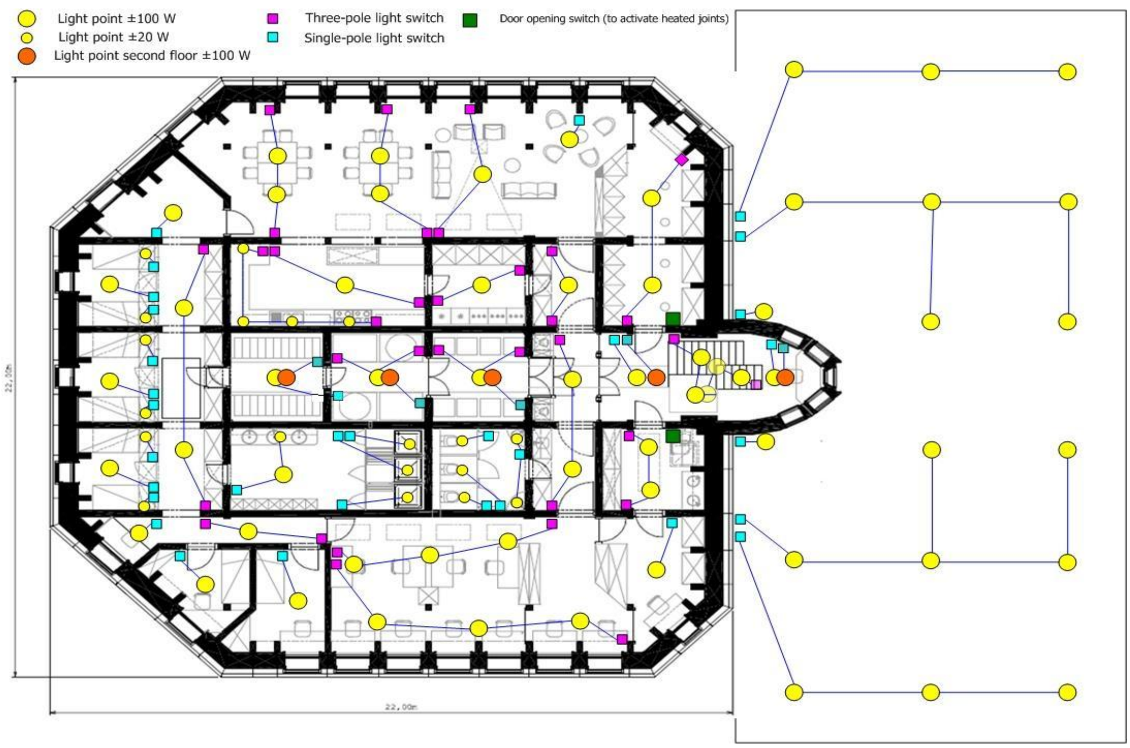


Figure 63: Lighting layout

Scientific equipment

Table 58 lists all the equipment currently accepted for the scientific programs.

Table 58: Scientific and working equipment

Research equipment						
3.1. Scientific equipment						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Exhaust Hood	1	300	300	0%	1	1
Seisometer	1	25	25	0%	1	1
Seisometer- gps antenna	1	50	50	0%	1	1
Absolute gravity measurements	1	700	700	0%	1	1
GPS measurements	0	0	0	0%	1	1
Variometer LAMA	0	0	0	0%	1	1
DIFlux	0	0	0	0%	1	1
CPC3772	1	210	210	0%	1	1

TEOM	1	720	720	0%	1	1
Aethalometer	1	60	60	0%	1	1
CIMEL	1	850	850	0%	1	1
Nephelometer	1	100	100	0%	1	1
CPC 3776 (a)	1	335	335	0%	1	1
SMPS (b)	1	300	300	0%	1	1
Brewer	0	750	0	0%	1	1
MaxDOAS	0	1200	0	0%	1	1
Pyranometers	1	570	570	0%	1	1
Ozone sounding	1	70	70	0%	1	1
RM antenna	1	3	3	0%	1	1
Oscilloscope	0	15	0	0%	1	1
generql equipment	0	400	0	15%	1	1
servers	1	90	90	0%	1	1
cameras	1	20	20	0%	1	1
Air Flow Bench			0	0%	1	1
Microscope			0	0%	1	1
3.2. Mechanical Workshop Equipment						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Electric Lifting Equipment	1	5000	5000	0%	1	1
Drilling Machine	1	3000	3000	10%	1	1

Life support equipment

Table 59 lists all the electrical equipment related to life support systems. Not all equipment installed in the station is listed in these tables as part of the equipment is directly modeled in the TRNSYS model. The ventilation, heating and lighting are examples of equipment directly modeled in TRNSYS.

Table 59: Electrical equipment for support systems

Life support equipment						
2.1 Water production						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Pump production recycled water	1	500	500	20%	1	1
Heating meltwater ducts tower	1	600	600	0%	1	1
Heating meltwater ducts garage	1	600	600	0%	1	1
2.2. Water distribution						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
pump meltwater	1	1000	1000	80%	1	1
Pump recylced	1	1000	1000	80%	1	1
Heating water circuits tower	2	600	1200	80%	1	1
Recycled water UV filter	1	100	100	0%	1	1
Meltwater UV filter	1	100	100	0%	1	1
2.3. Safety/emergency						
emergency LEDS	30	8	240	0%		1
sensors/monitoring	150	2	300	0%		1
2.6. Communication						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Satelite phone	3	40	120	100%	1	1
VHF Phone	3	160	480	10%	1	1
Intercom	1	40	40	0%	1	1
Satelite data -link	2	375	750	0%	1	1
Continuous Loads						Duty Cycle

Satelite data-link (permanent)	1	200	200	0%		0
Cameras	8	60	480	0%		0
2.7. Sanitary Equipments						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Toilets: mixing	3	150	450	100%	1	1
Shower filters	3	50	150	50%	1	1
Washbasins - grinders	5	50	250	50%	1	1
2.9. Waste Treatment						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Solid Waste Compactor			0	100%	1	1
Acid pump	1	70	70	0%	1	1
Base pump	1	70	70	0%	1	1
Filtrate pump	1	180	180	0%	1	1
Filtrate pump	1	180	180	0%	1	1
Cleaning pump	1	250	250	0%	1	1
Air pump for tank aeration	1	380	380	0%	1	1
Feeding pump to anaerobic reactor	1	650	650	0%	1	1
Feeding pump to anaerobic reactor	1	650	650	0%	1	1
Blender aerobic tank	1	500	500	0%	1	1
Grinding immersed pump in I-Tnk-01	1	900	900	0%	1	1
Retentate pump	1	2500	2500	0%	1	1
Spare retentate pump	1	2500	2500	0%	1	1
Waste water pump	1	300	300	100%	1	1
2.10. Monitoring						
User Controlled Loads			Rated Power(W)	Correlation with # people	Variable Load	Number of Units
Control server	1	180	180	0%	1	1
Continuous Loads						Duty Cycle
AWS	1	100	100	0%		1
Building Monitoring / sensors	1	50	50	0%		1
Building Monitoring / applications	1	30	30	0%		1
Management server	2	80	160	0%		1

Water management

Figure 64 represents the temperature variation in the anaerobic reactor during the austral summer. The temperature at 4 different levels in the reactor is shown and the mean temperature is plotted with a dashed line. A huge temperature variation is noticed at the inlet of the cold untreated black water and a better division of the inlet is needed to avoid stratification. Table 60 shows the mean temperature is within the accepted margins of biological water treatment.

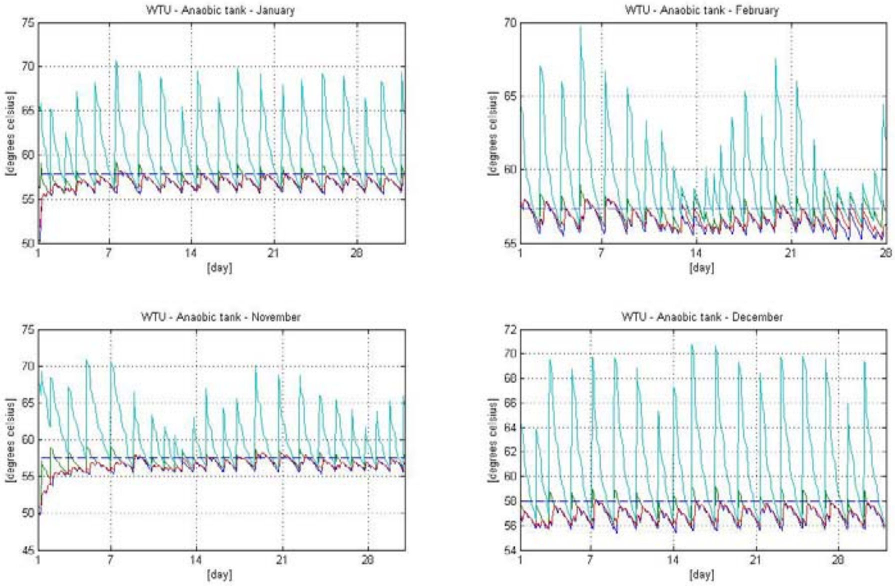


Figure 64: Anaerobic tank - temperature

Table 60: Monthly mean temperatures anaerobic reactor

Anaerobic	January	February	November	December
Mean T [º C]	57.8	57	57.2	57.7

The same calculations are performed on the aerobic reactor. The results are shown in Figure 65. Especially in the start-up period in November, the temperature of the reactor is insufficient during the first 10 days. The reactor should be preheated earlier in the season.

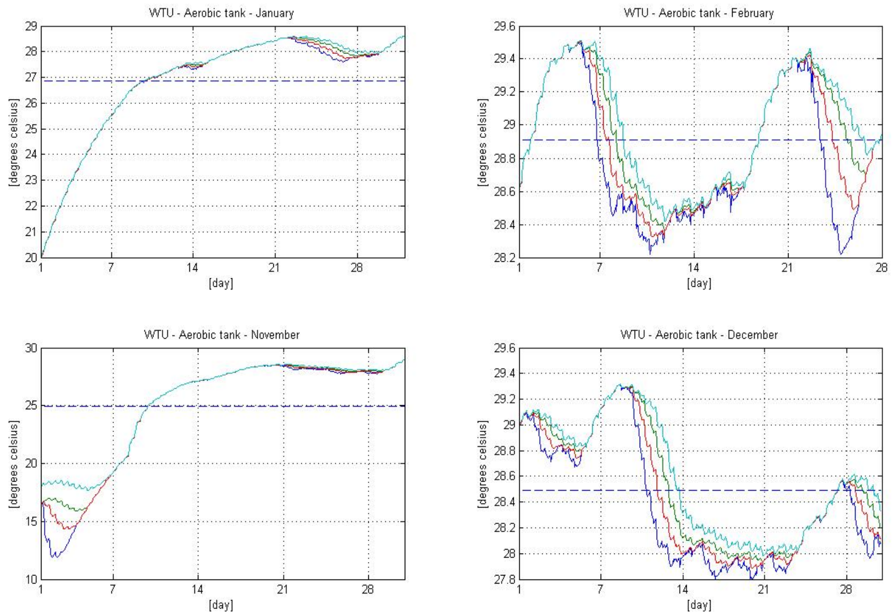


Figure 65: Aerobic tank - temperature

Table 61: Monthly mean temperatures aerobic reactor

Aerobic	January	February	November	December
Mean T [º C]	24.4	26.3	21.2	25.7

Table 61 shows the temperature variation for the aerobic reactor. The variation is still acceptable. Figure 66 represents the daily meltwater production, storage and use during the austral summer.

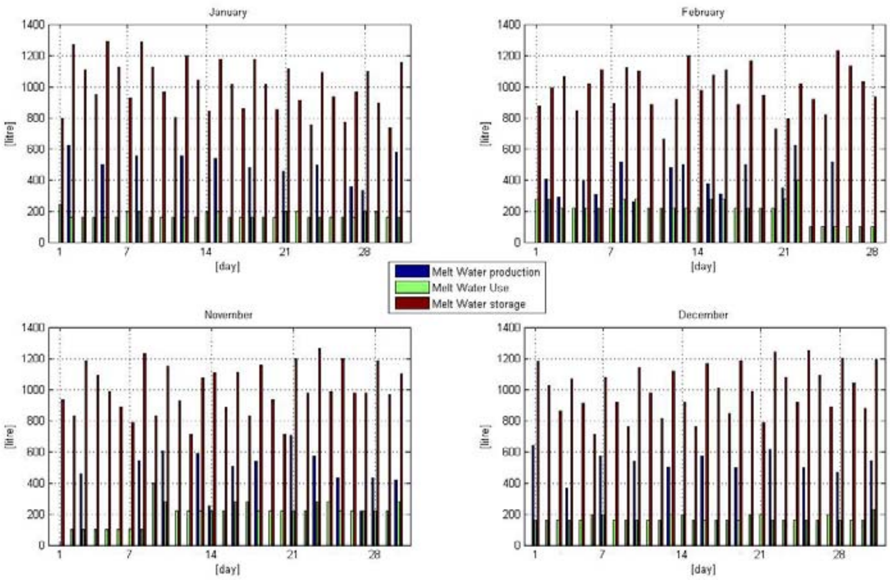


Figure 66: Meltwater produtcion, storage & use

Heating

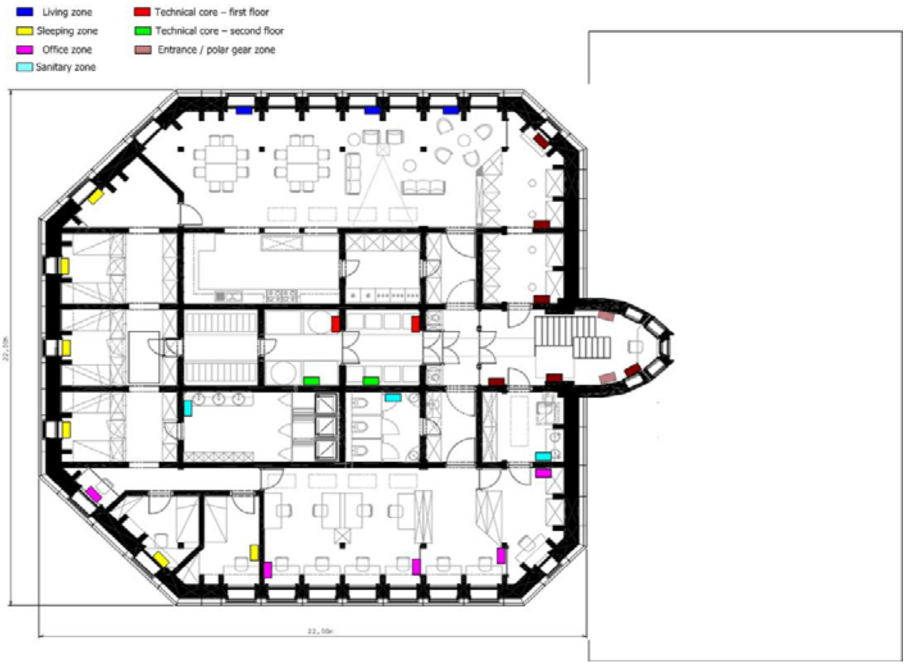


Figure 67: Layout of decentralised heating elements

Figure 67 is a more detailed view of the locations of the decentralized heating elements. All different building zones are simulated and coupled to the solar radiation, the internal gains (human presence and machines), ventilation rates and heating control algorithms. Table 62 gives an overview of the temperatures throughout the building, in which the red values are considered as unwanted.

Table 62: Temperatures for different building zones

	Summer season			Unmanned winter season		
Location	Max T [º C]	Min T [º C]	Mean T [º C]	Max T [º C]	Min T [º C]	Mean T [º C]
Ambient	11.0	-28.5	-9.4	4.0	-44.6	-21.2
Garage	6.2	-19.1	-6.5	-3.3	-37.6	-20.4
Entrance	17.9	16.0	16.1	16.0	-16.0	-6.5
Control room	32.0	20.0	26.7	21.1	-14.3	-7.0
Tower	62.4	2.5	19.1	50.7	-19.6	8.7
Living	22.8	20.0	20.8	21.1	-14.3	-7.0
Office	21.9	20.0	20.7	20.1	-18.2	-8.5
Hall	26.2	17.1	21.7	19.2	-11.0	-4.0
Sleeping rooms	17.8	16.0	16.4	16.0	-19.1	-10.8
Polyvalent room	17.7	16.0	16.4	16.0	-19.4	-10.3
Kitchen storage	22.2	16.0	19.5	17.3	-11.8	-5.2
Sanitary	29.5	23.0	23.5	23.0	-10.9	-4.3
Technical core	44.1	10.9	19.9	38.8	1.4	4.2
Technical roof	32.9	11.1	18.8	20.5	1.4	2.9

Figure 68 shows the temperature profile for each location during a representative week in the manned summer season. One can notice a clear day cycle, or a cycle depending on the crew occupation, or a cycle depending on the wind or solar energy.

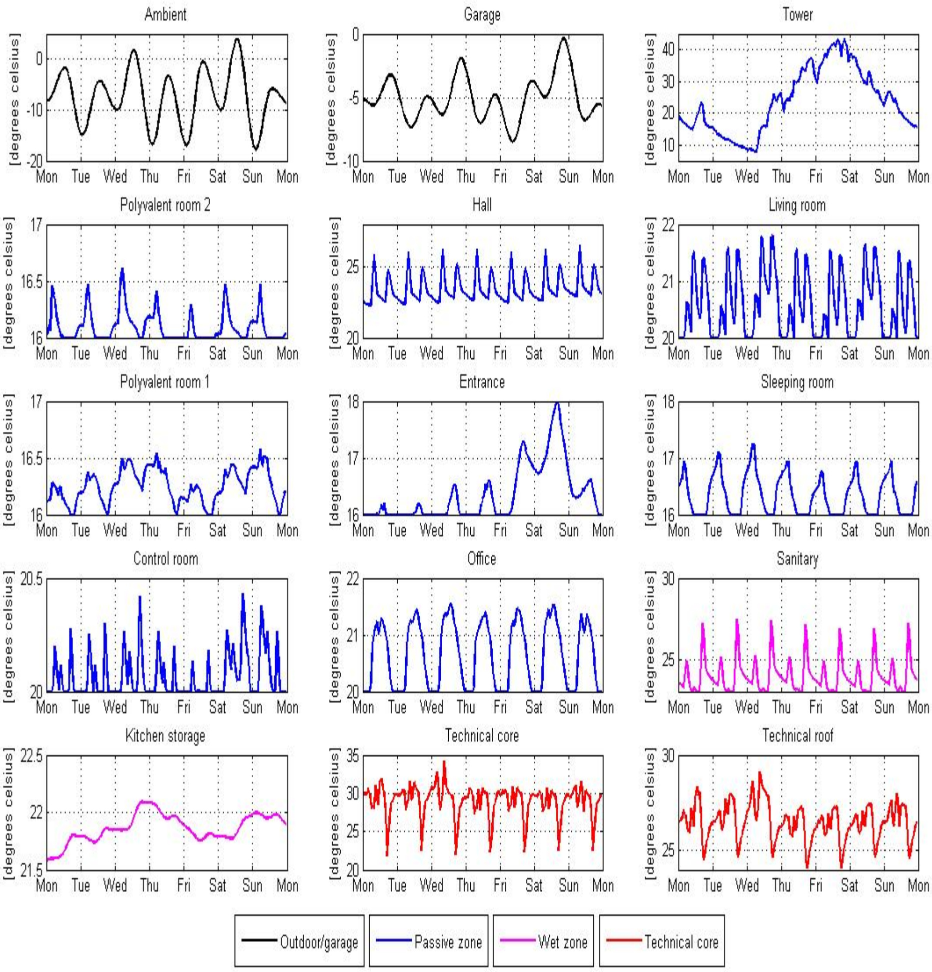


Figure 68: Weekly temperature overview - summer

Ventilation

Figure 69 is a schematic overview of the ventilation in the technical core. Figure 70 shows a layout of the ventilation ducts in the wet zone and passive core. The red ducts are used for pulsion, the blue ones for the extraction.

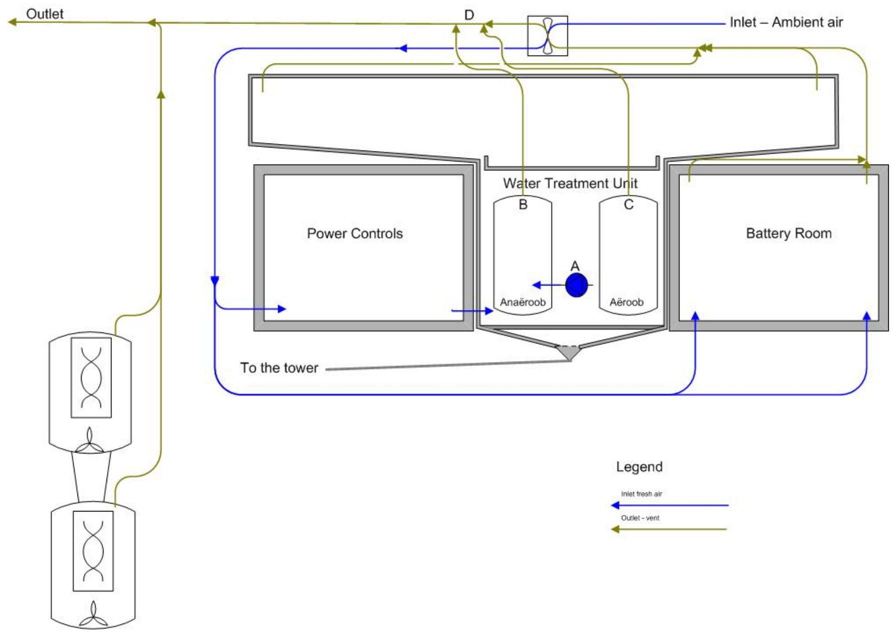


Figure 69: Layout ventilation – technical core

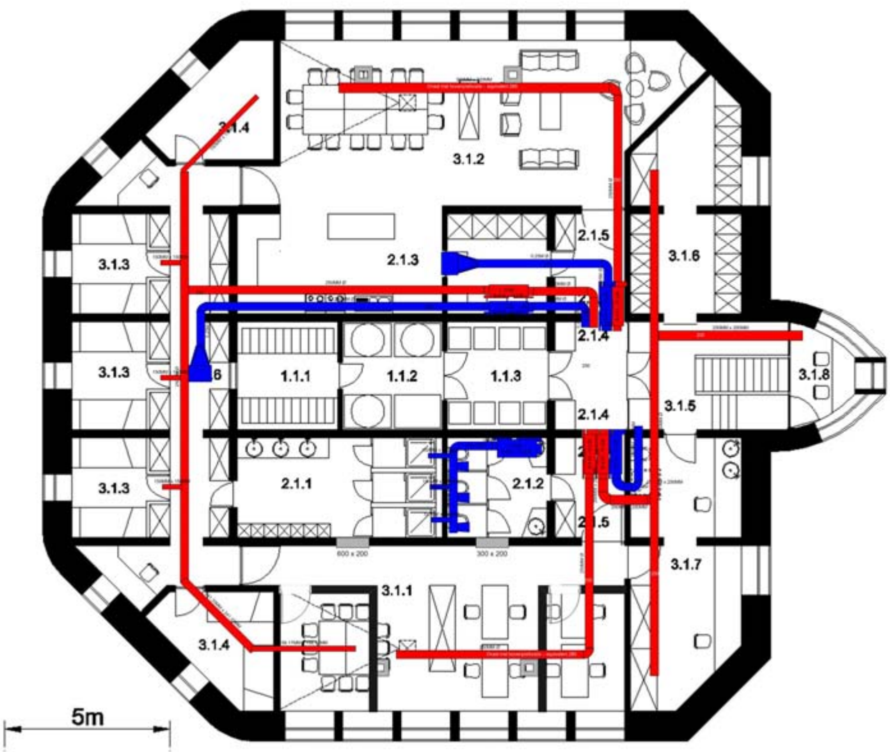


Figure 70: Layout ventilation – wet core and passive zone

Load summary

Figure 71 represents the total electrical power consumption during a year. Figure 72 and Figure 73 are more detailed overviews of the daily load profiles for the different electrical equipment.

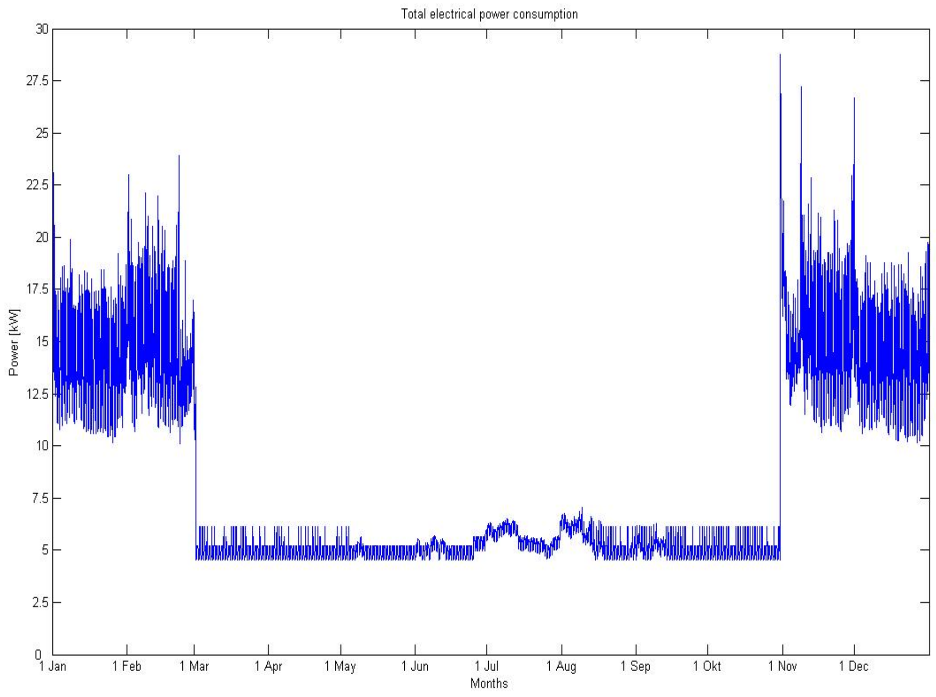


Figure 71: Total electrical load [kW]

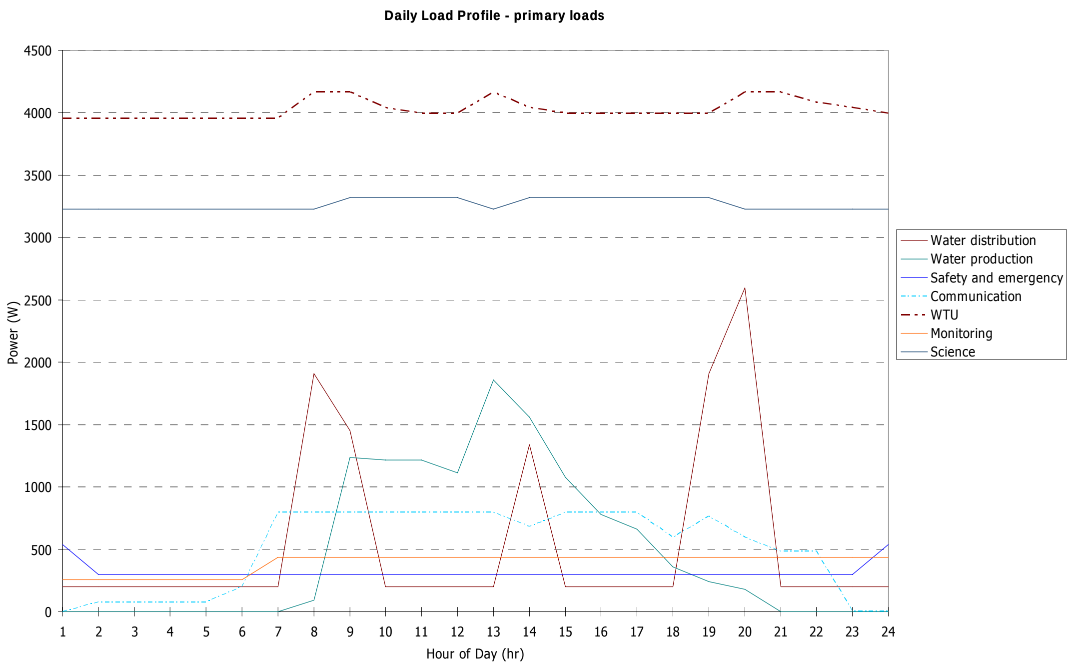


Figure 72: Daily load profile primary loads (21 November)

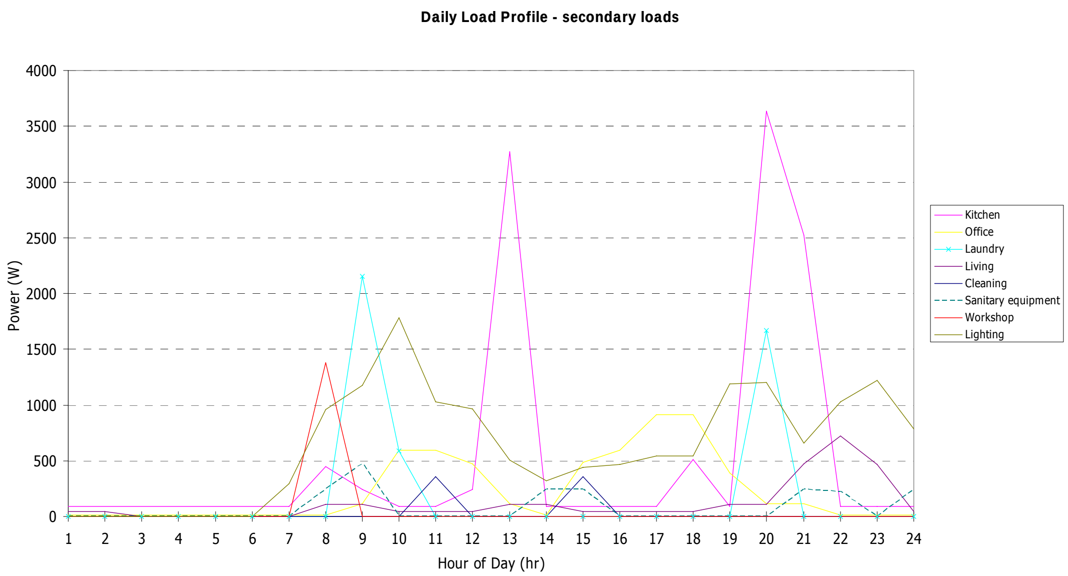


Figure 73: Daily load profile secondary loads (21 November)

Appendix G Wind turbine specifications

Figure 74 shows the first turbine mounted on site in 2007. Figure 75 is a more detailed specification sheet for the selected turbine.

Figure 74: Proven WT6000 mounted on site (2007) [Source: IPF]

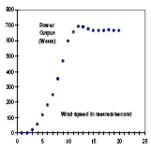
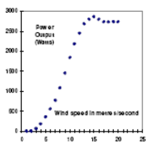
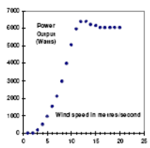
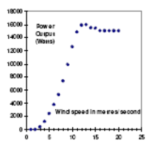
Proven Wind Turbines - Technical Specification Sheet				
Rotor Speed Control Above 12m/s or 25mph) blades twist to limit power in response to high rpm ***Low Speed Equals Durability***				
Marine Build Quality All machines ***galvanised*** steel, ***stainless*** steel & ***plastic*** components				
WT MODEL	**WT600 (0.6kW)**	**WT2500 (2.5kW)**	**WT6000 (6kW)**	**WT15000 (15kW)**
Cut In (metres/sec)*	2.5			
Cut Out (metres/sec)	None!			
Survival (metres/sec)	65			
Rated (metres/sec)	12			
Rotor Type	Downwind, Self Regulating			
No. of Blades	3			
Blade Material	Polypropylene	Polypropylene	Wood/Epoxy	Glass Epoxy
Rotor Diameter(m)	2.55	3.5	5.5	9
Generator Type	Brushless, Direct Drive, Permanent Magnet			
Battery charging	12 , 24 ***or*** 48V DC	24 ***or*** 48V DC	48V DC	48V DC
Grid connect with *Windy Boy Inverter*	n/a	230Vac 50Hz ***or*** 240 Vac 60Hz	230Vac 50Hz ***or*** 240 Vac 60Hz	230Vac 50Hz ***or*** 240 Vac 60Hz
Direct Heating	n/a	120Vac ***or*** 240Vac	120Vac ***or*** 240Vac	120Vac ***or*** 240Vac
Rated RPM	500	300	200	160
Annual Output†	900-2,300 kWh	3,300-7,400 kWh	9,000-19,400 kWh	23,000-48,500 kWh
Head Weight (kg)	70	190	500	1100
Mast Type	Tilt-up, tapered, self-supporting, no guy wires (Taller guyed towers also available on request)			
Hub Height (m)	5.5 ***or*** 12	6.5 ***or*** 11	9 ***or*** 15	15
WT Found (m)	1x1x1 ***or*** 1.6x1.6x1	1.6x1.6x1 ***or*** 2.5x2.5x1	2.5x2.5x1 ***or*** 3x3x1.2	3.7x3.7x1.2
Winch Found (m)	0.65x0.65x0.65	0.65x0.65x0.65 ***or*** 1x1x1	1x1x1 ***or*** 1.5x1.5x1	1.5x1.5x1.2
Tower Weight (kg)	120 ***or*** 350	241 ***or*** 445	360 ***or*** 656	1200
Mechanical Brake	No	Yes	Yes	Yes
Noise‡ @ 5m/s	35 dBA	40 dBA	45 dBA	48 dBA
Noise @ 20m/)	55 dBA	60 dBA	65 dBA	65 dBA
Rotor Thrust (kN)	2.5	5	10	26
Sample of UK commercial customers	British Telecom Scottish | Youth Hostel Association | British Rail | Irish Lighthouse Authority UK Lighthouse Authority | T-mobile |Orange			

Figure 75: Specification wind turbine Proven - WT6000 [Source: Proven Energy]

Appendix H Photovoltaic arrays

Radiation from TRNSYS simulations

Figure 76 is the graphical result of the solar assessment to investigate the effect of orientation and inclination. Figure 77 shows the radiation profile over the different orientations of the building.

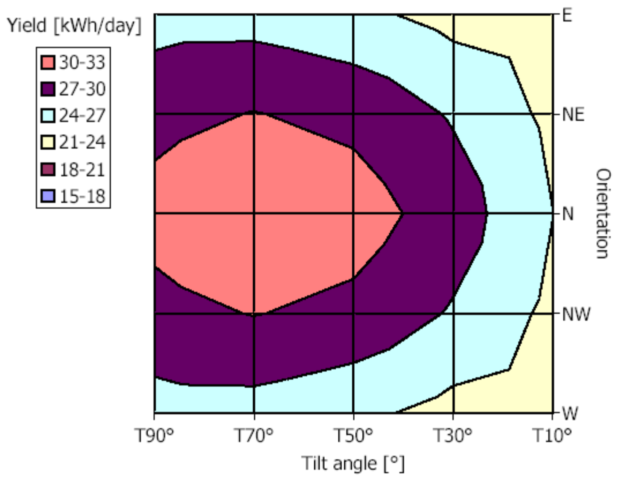


Figure 76: Influence of orientation and tilt angle for a 10 kWp PV system [Source: 3E]

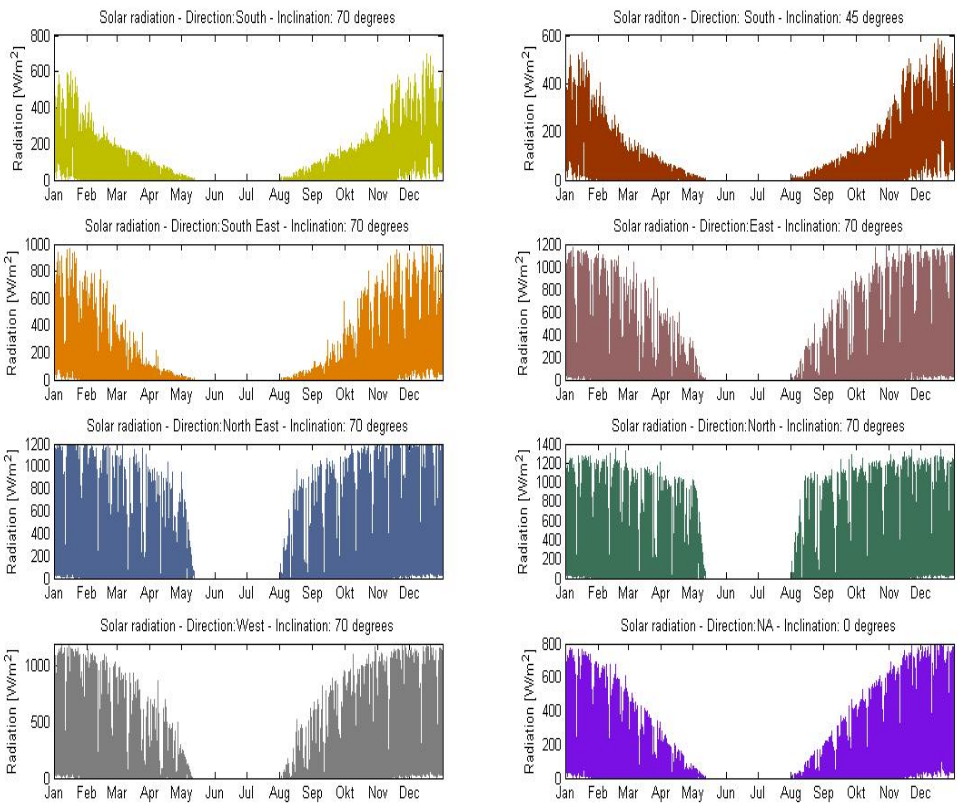


Figure 77: Solar radiation on building (TRNSYS)

Figure 78 shows the daily radiation profile at the different orientations of the building (all under 70 degrees inclination)

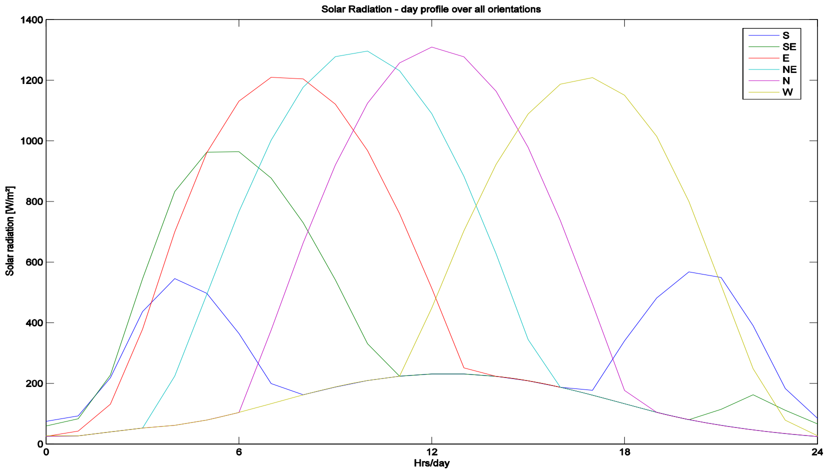


Figure 78: Radiation day profile BIPV (21 November)

Mechanical interface and module configuration - BIPV

The BIPV modules are mounted onto the building envelope:

- Directly mounted by means of protruding bolts sticking out of the skin at regular interval. The skin concept allows a flexible layout of fixation points and can meet the module requirement.
- Indirectly mounted on brackets that will be specifically designed to meet the modules and skin requirements. Note that the design of the mounting brackets may differ from standard solutions to meet the specific requirements of the environment.

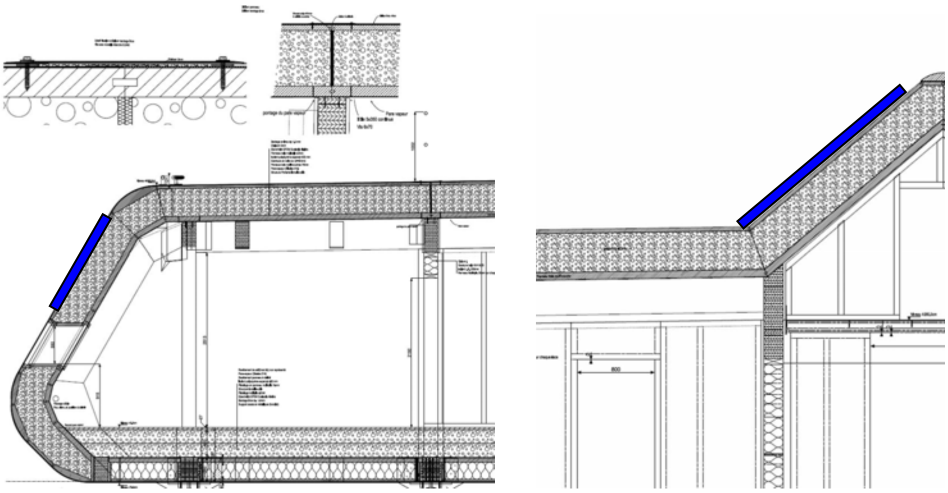


Figure 79: Integration of PV on the building skin

Figure 79 shows the integration of PV modules on the building skin. Figure 80 and Figure 81 are the detailed module layout for the two reference modules. The indicated areas are the available building surfaces and the blue blocks represent the reference modules.

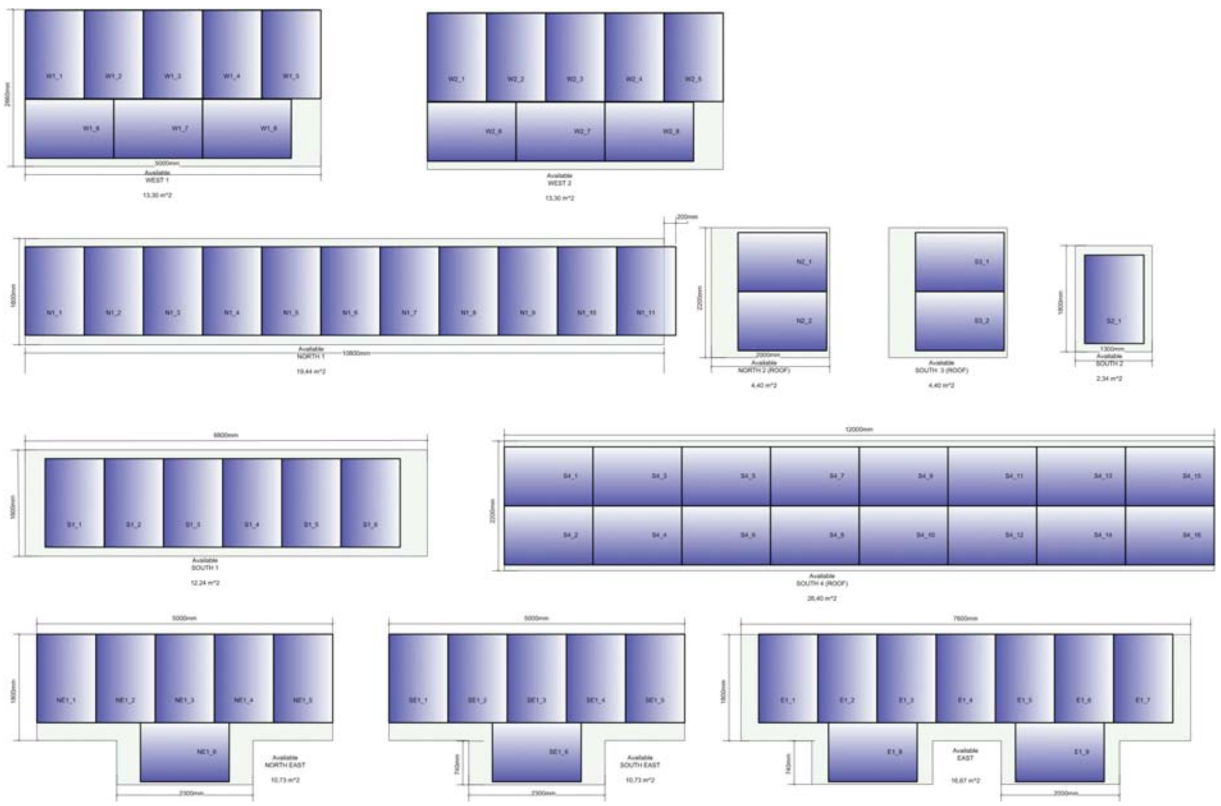


Figure 80: PV module configuration - reference module 1

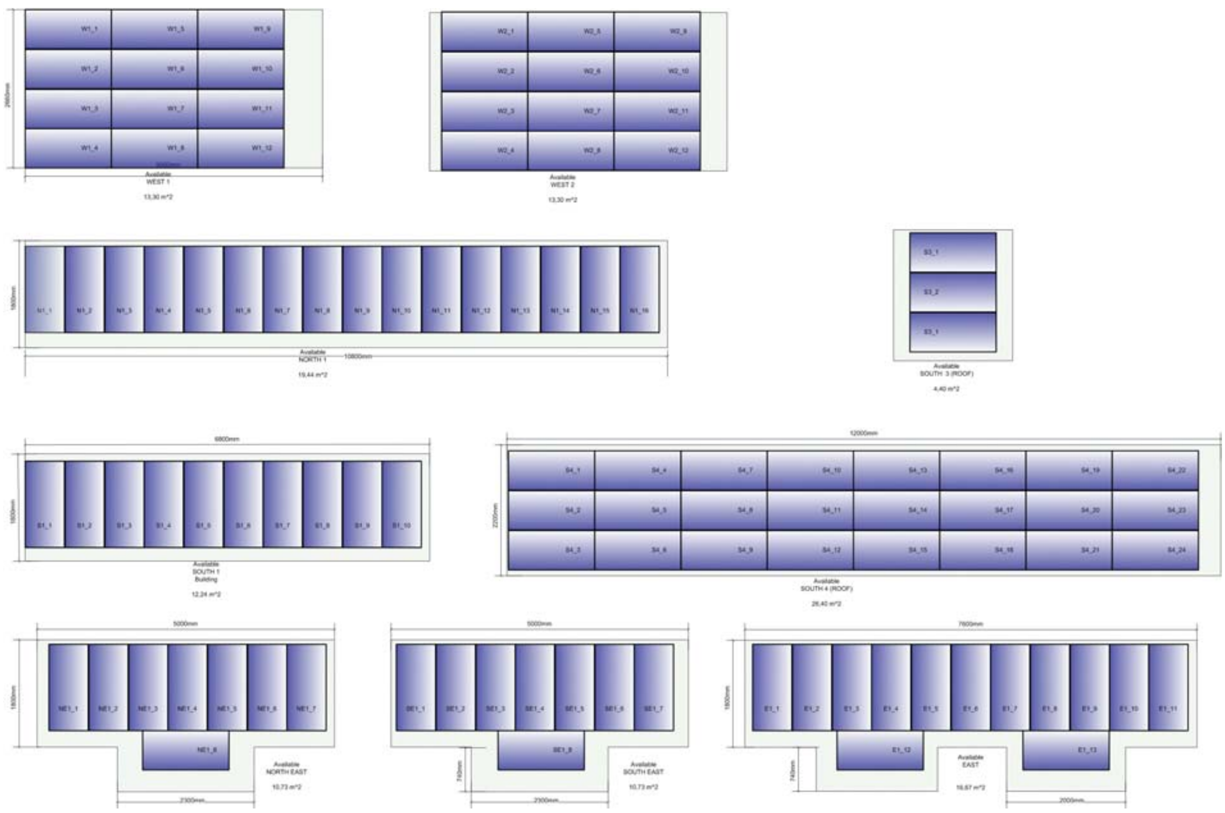


Figure 81: PV module configuration - reference module 2

Optimized array configuration - BIPV

Figure 82 explains how the different arrays are organized on the building skin. Each color represents a PV array consisting of 1 or 2 PV strings and a dedicated converter. Each rectangular block represents a single string of PV modules connected in series.

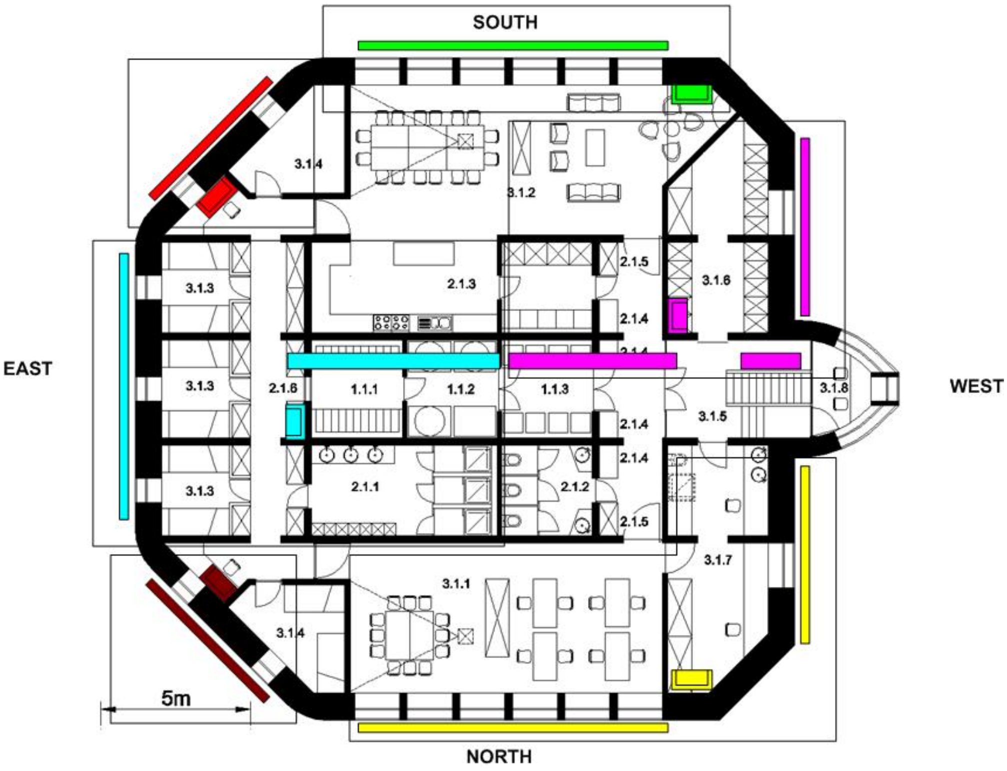


Figure 82: Array configuration BIPV

Appendix I Solar thermal system

Figure 83 shows more details on the integration of the flat plate collectors in the roof section of the main building.

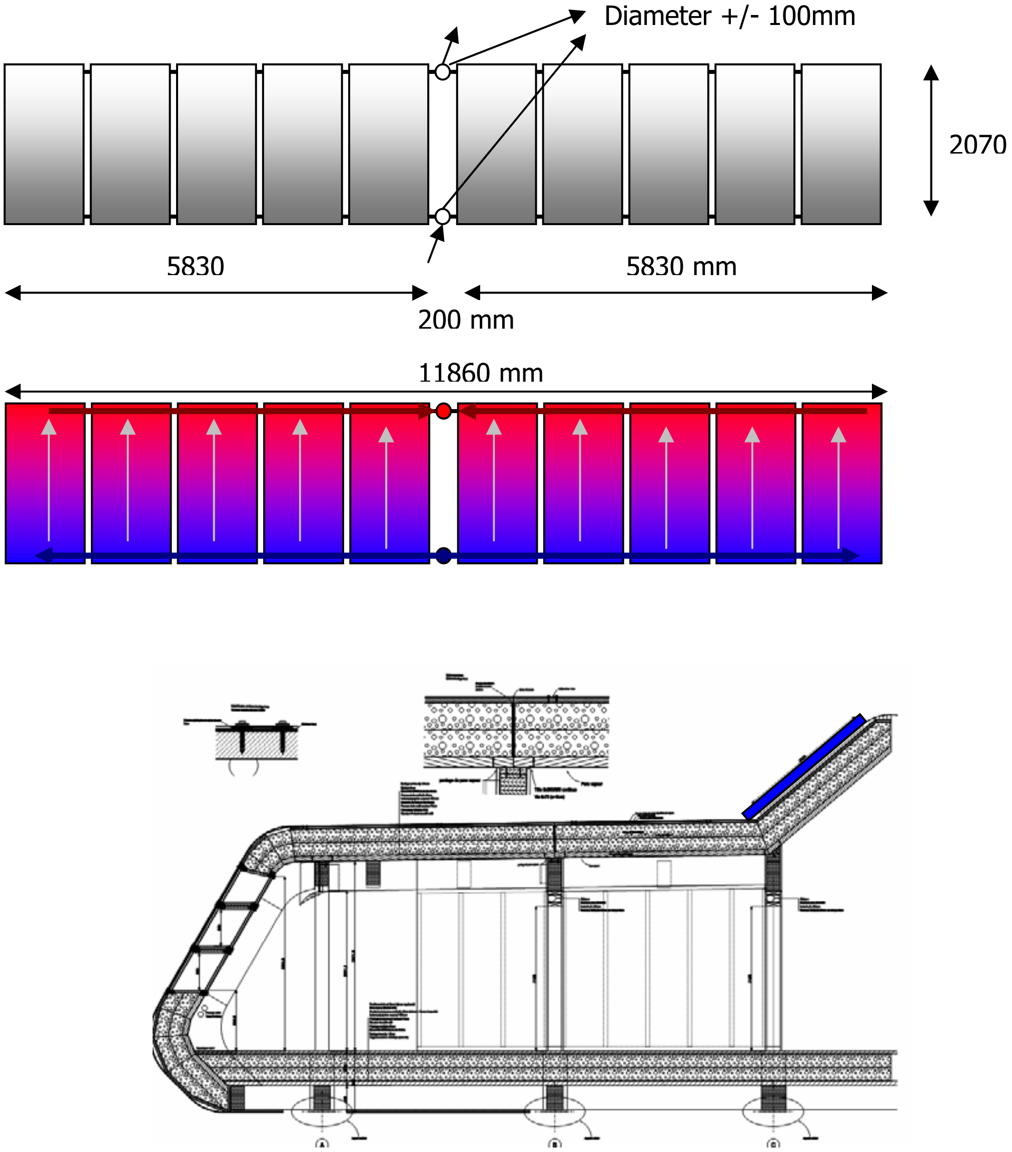


Figure 83: Integration of solar collector on the building skin

Appendix J Electrical energy storage

Explosion risk: ventilation and electrical equipment

Figure 84 shows a cross-section of the ventilation for the technical core and a detailed ventilation scheme for the battery room. Especially in the battery room, the explosion risk (due to possible hydrogen release) is of main importance. A natural ventilation path to the external environment is foreseen in the case of failure of the technical core ventilation or hydrogen accumulation.

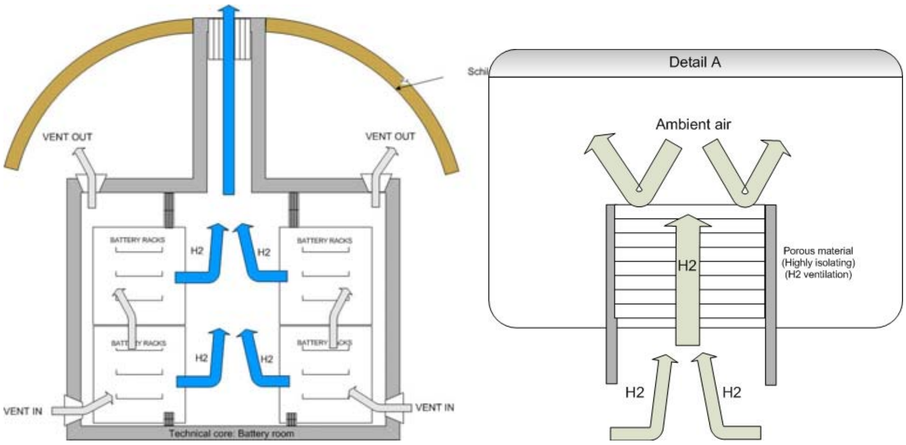


Figure 84: Cross section of ventilation - technical core

Ventilation requirements

The dimensions of the natural ventilation shaft are calculated as stated by the European norm: EN 50272-2.

Minimum air flow rate: $$Q = 0.05 \cdot n \cdot I_{gas} \cdot C_{rt} \cdot 10^{-3} \left[m^3 / h\right]$$

With: n = number of cells

I_{gas} = current producing gas in mA per Ah rated capacity for the float charge current or boost charge current.

C_{rt} = Capacity C10 for lead-acid cells.

$$Q = 0.05 \cdot 144 \cdot 8 \cdot 1000 \cdot 10^{-3} = 57.6\left[m^3 / h\right]$$

The minimum required opening for inlet and outlet is described by the standard as:

$$A = 28 \cdot Q = 28 \cdot 57.6 = 1613\left[cm^2\right]$$

This area is approximately a square of 40 by 40 cm.

Presence of electronics based

The same European norm is used to investigate if electronic equipment is allowed in the battery room. The following distance should be respected for any sparking or glowing devices

$$d = 28.2 \cdot \sqrt[3]{N} \cdot \sqrt[3]{I_{gas}} \cdot \sqrt[3]{C_{rt}} = \left[mm\right]$$

$$d = 28.2 \cdot \sqrt[3]{144} \cdot \sqrt[3]{8} \cdot \sqrt[3]{1000} = 3019\left[mm\right]$$

This means no electronics can be installed in the battery room.

The lighting system should respect a IP54 protection level. Hand lamps are only allowed with switches and protective glass according to protection class II and protection class IP54.

Trade-off 1: Charging efficiency and depth of discharge (DOD).

The objective of the first trade-off is to investigate the sensitivity (expressed in fuel consumption) of battery technology (Gel and AGM) and corresponding charging efficiency and allowed depth of discharge of the battery bank.

Assumptions for the simulations:

- All loads are defined as in section 3.3.
- All sources are defined as in section 3.4.
- Battery bank charging algorithm (Table 63).

Table 63: Battery trade-off 1: charging algorithm

Depth of discharge (DOD)	Variable
Charging efficiency	Variable
Charging range (When reaching DOD, diesel generator is powered on till SOC is 20 % above the DOD value)	20 %
Maximal discharging current	200 A

Gel technology

Table 64 and Figure 85 show the battery bank configuration assumed for the gel technology

Table 64: Battery trade-off 1: Gel - battery bank / cluster / cell specification

Type	VRLA Gel
# battery clusters	2
# strings / cluster (parallel)	2
# cells / string (series)	24
Nominal output voltage	48 V_{DC}
Nominal capacity / cluster	3160 Ah

Single cell						
Type	Capacity [Ah]	Nominal Voltage [V]	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
12OPvZ1500	1580	2	210	275	845	120

Single cluster						
Type	#Cells horizontal	#Cells vertical	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
12OPvZ1500	8	6	1760	1880	945	5760

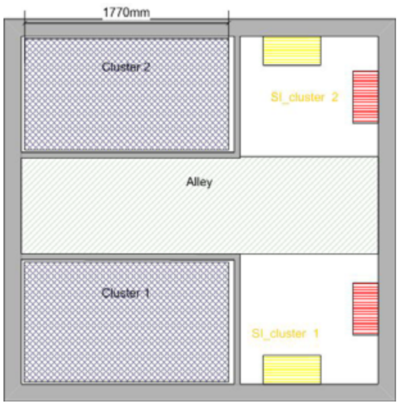


Figure 85: Battery trade-off 1: Gel - layout battery room

Table 65 shows the impact of the charging efficiency and depth of discharge based on the previous configuration. The green results are still within the initial low emission objective.

Table 65: Battery trade-off 1: Gel - sensitivity analysis

Charging efficiency [%]	Depth of discharge [%]	Fuel consumption [litre]
90	40	2185
90	50	1837
90	60	1563
80	40	2475
80	50	2069
80	60	1819

AGM technology

Table 66 and Figure 86 show the battery bank configuration assumed for the AGM technology

Table 66: Battery trade-off 1: AGM - battery bank / cluster / cell specification

Type	VRLA AGM
# battery clusters	2
# strings / cluster (parallel)	2
# cells / string (series)	24
Nominal output voltage	48 V_{DC}
Nominal capacity / cluster	2600 Ah

Single cell						
Type	Capacity [Ah]	Nominal Voltage [V]	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
DDM100-27	1300	2	271	165	624	92

Single cluster						
Type	#Cells horizontal	#Cells vertical	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
DDM100-27	6	8	1874	2060	666.8	5230

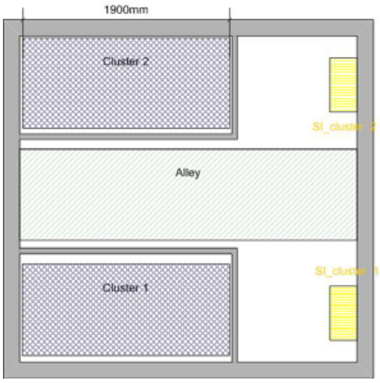


Figure 86: Battery trade-off 1: AGM - layout battery room

Table 67 shows the corresponding results.

Table 67: Battery trade-off 1: AGM - sensitivity analysis

Charging efficiency [%]	Depth of discharge [%]	Fuel consumption [litre]
95	40	2266
95	50	1976
95	60	1681
90	40	2478
90	50	2046
90	60	1736
80	40	2726
80	50	2320
80	60	2021

From the first trade-off can be concluded both technologies can handle the design constraints. There is a slight preference for the gel technology due to better performance under current assumptions. Charging efficiency and depth of discharge have a significant impact on the performance. Based on literature and expert communication, the following assumption hold true for further analysis:

Table 68: Charging efficiency AGM and gel technology

Type	VRLA Gel	VRLA AGM
Charging efficiency	80%	90%

Trade-off 2: Lifetime

Objective: sensitivity (expressed in lifetime and annual fuel consumption) of different AGM and gel type configurations

Assumptions for the simulations:

- All loads are defined as in section 3.3.
- All sources are defined as in section 3.4.
- The available surface in the battery room is maximized and completely used for housing the batteries as no additional electrical equipment can be installed in the room

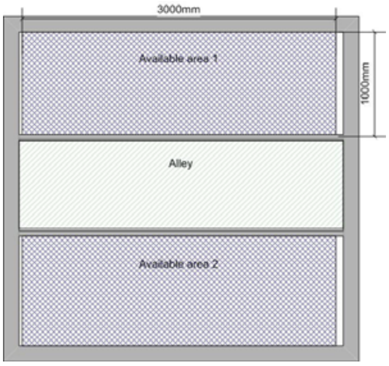


Figure 87: Battery trade-off 2 – final layout battery room

- Battery bank charging algorithm (Table 69).

Table 69: Battery trade-off 2: charging algorithm

Depth of discharge (DOD)	60%
Charging efficiency	Gel: 80%, AGM: 90%
Charging range	20%
Maximal discharging current	200 A

- Battery lifetime needs to exceed 7 years. A peak counting algorithms is implemented to deduct the lifetime of the battery bank. Figure 88 shows the relation between depth of discharge (DOD) and the number of cycles a GEL or AGM battery can withstand before reaching 80% of its nominal capacity (end of life).

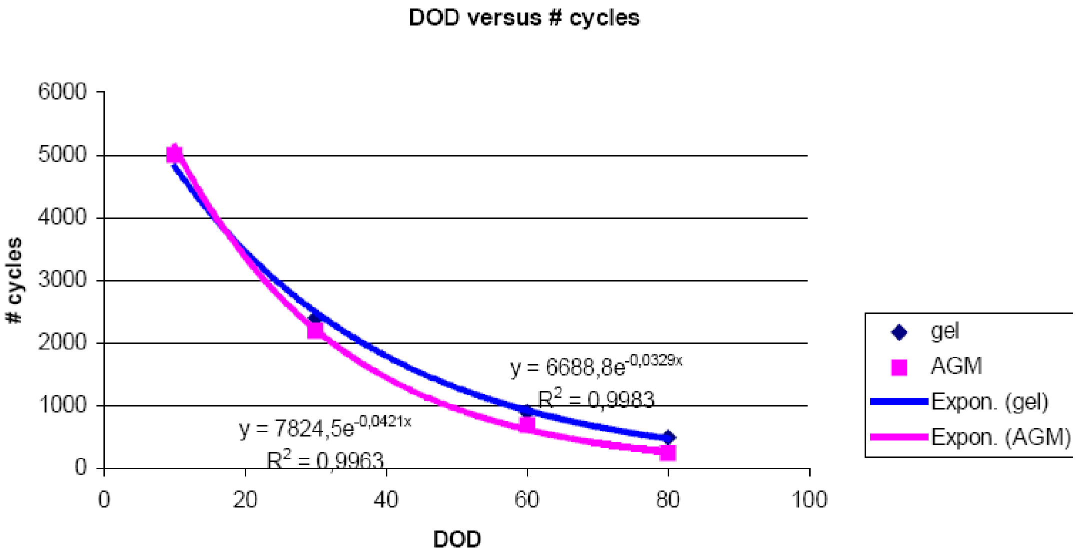


Figure 88: Lifetime estimation curve AGM / Gel

Peak analyses are applied to the SOC profile to count the cycles within a specified range. A rainflow[33] counting algorithm is used to determine the occurrence of cycles in a specified range. Based on peak occurrences, the partial damage to an individual cell for one year is calculated. This number (partial use / year) is used to approximate the lifetime of the battery bank.

33 Rainflow counting is often applied for structural analysis (fatigue calculations).

Figure 89 represents a typical SOC profile over a year on which the counting algorithm is applied.

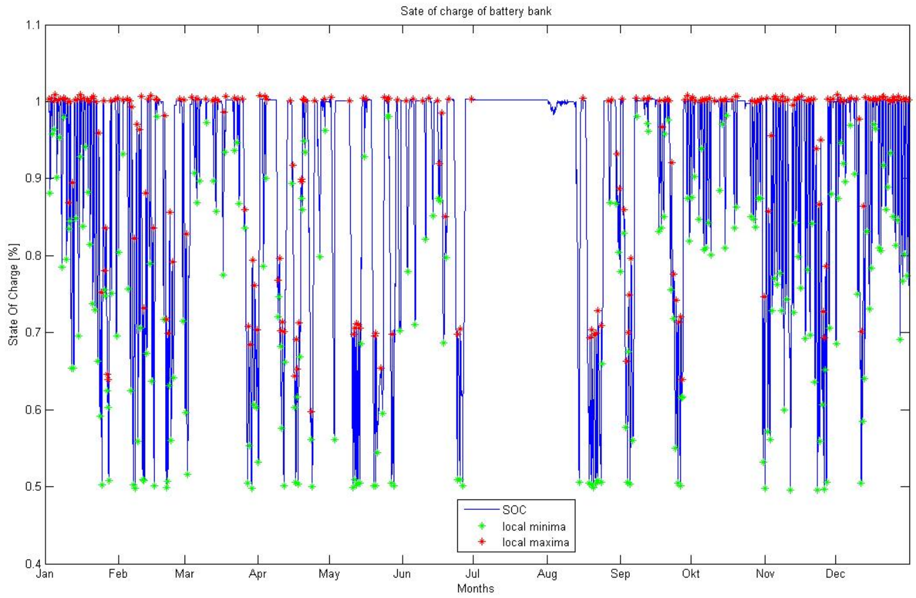


Figure 89: Battery SOC - counting algorithm

Gel technology

Table 70 and Table 71 show the battery bank configuration and performance results for the first scenario of the gel technology.

Table 70: Battery trade-off 2: Gel – scenario 1 - battery bank / cluster / cell specification

Type	VRLA Gel
# battery clusters	2
# strings / cluster (parallel)	3
# cells / string (series)	24
Nominal output voltage	48 V_{DC}
Nominal capacity / cluster	2820 Ah

Single cell						
Type	Capacity [Ah]	Nominal Voltage [V]	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
8OPvZ800	940	2	210	191	695	68

Single cluster						
Type	#Cells horizontal	#Cells vertical	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
8OpvZ800	12	6	2700	1860	822	4896

Table 71: Battery trade-off 2: Gel – scenario 1 - sensitivity analysis

Allowed DOD [%]	Fuel consumption / year [litres]	Partial use / year [%]	Estimated lifetime [years]
80 %	1128	19.3	5.19
60 %	1582	13.6	7.36
50 %	1969	11.4	8.80
40 %	2257	9.4	10.59

Table 72 and Table 73 show the configuration and results for the second scenario of the gel technology. The main difference between both scenarios is the individual cell weight and therefore the total amount of cells.

Table 72: Battery trade-off 2: Gel – scenario 2 - battery bank / cluster / cell specification

Type	VRLA Gel
# battery clusters	2
# strings / cluster (parallel)	2
# cells / string (series)	24
Nominal output voltage	48 V_{DC}
Nominal capacity / cluster	2820 Ah

Single cell						
Type	Capacity [Ah]	Nominal Voltage [V]	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
12OPvZ1200	1410	2	210	275	695	97

Single cluster						
Type	#Cells horizontal	#Cells vertical	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
12OPvZ1200	8	6	2400	1860	822	4656

Table 73: Battery trade-off 2: Gel – scenario 2 - sensitivity analysis

Allowed DOD [%]	Fuel consumption / year [litres]	Partial use / year [%]	Estimated lifetime [years]
80 %	1204	19.8	5.04
60 %	1658	13.8	7.27
50 %	1977	11.4	8.79
40 %	2264	9.5	10.57

AGM technology

Table 74 and Table 75 show the configuration and results for the first scenario with the AGM technology.

Table 74: Battery trade-off 2: AGM – scenario 1 - battery bank / cluster / cell specification

Type	VRLA Gel
# battery clusters	2
# strings / cluster (parallel)	3
# cells / string (series)	24
Nominal output voltage	48 V_{DC}
Nominal capacity / cluster	3000 Ah

Single cell						
Type	Capacity [Ah]	Nominal Voltage [V]	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
DDM100-21	1000	2	214	165	590	73.5

Single cluster						
Type	#Cells horizontal	#Cells vertical	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
DDM100-21	12	6	2946	1620	720	5292

Table 75: Battery trade-off 2: AGM – scenario 1 - sensitivity analysis

Allowed DOD [%]	Fuel consumption / year [litres]	Partial use / year [%]	Estimated lifetime [years]
60 %	1302	16.9	5.93
50 %	1370	13.9	7.20
40 %	1886	10.8	9.25
60 %	1302	16.9	5.93

Table 76 and Table 77 show the configuration and results of the second scenario with the AGM technology. Again the difference between both scenarios is the weight of the individual cell and thus the total number of cells.

Table 76: Battery trade-off 2: AGM – scenario 2 - battery bank / cluster / cell specification

Type	VRLA Gel
# battery clusters	2
# strings / cluster (parallel)	2
# cells / string (series)	24
Nominal output voltage	48 V_{DC}
Nominal capacity / cluster	2600 Ah

Single cell						
Type	Capacity [Ah]	Nominal Voltage [V]	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
DDM100-27	1300	2	271	165	590	92

Single cluster						
Type	#Cells horizontal	#Cells vertical	Length [mm]	Height [mm]	Depth [mm]	Weight [kg]
DDM100-27	8	6	2420	1620	720	4416

Table 77: Battery trade-off 2: AGM – scenario 2 - sensitivity analysis

Allowed DOD [%]	Fuel consumption / year [litres]	Partial use / year [%]	Estimated lifetime [years]
60 %	1515	19.9	5.03
50 %	1704	16.2	6.19
40 %	1977	12.1	8.25

Heat dissipation

Table 78 represents the estimates maximum heat dissipation based on the internal resistances of the chosen cells.

Table 78: Batteries: heat dissipation

	CELL			BATTERY BANK	
Scenario	Internal resistance [Ω]	Max charging current [I]	Max heat dissipated [W]	Number of cells	Max heat dissipated [W]
GEL - 1	0.4 e^{-3}	97 (C10)	3.76	144	541.44
GEL - 2	0.27 e^{-3}	141 (C10)	5.37	96	515.52
AGM - 1	0.2 e^{-3}	105	2.21	144	318.24
AGM – 2	0.14 e^{-3}	156	3.41	96	327.08

Final trade-off

Table 79 gives an overview of the different criteria used in the trade off. The scoring is based on:

- Weight factor: Less important: 1 - important: 2 - very important: 3
- Score Bad: 1 - acceptable: 2 - moderate: 3 - good: 4 - very good: 5

Table 79: Battery final trade-off

		AGM	GEL
criteria	Weight factor		
Safety and explosion risk	3	5	5
Robustness cold conditions	2	4	5
Robustness charging errors	2	5	2
Complexity charging algorithm	2	5	2
Heat dissipation	2	5	4
Charging efficiency	2	4	3
Robustness handling and installation	2	5	4
Price	3	4	3
Lifetime	3	3	5
Deep discharging capability	2	3	5
Power/weight density	1	4	3
Power/space density	1	4	3
Limit on charging current	2	4	2
Recycling	3	4	4
TOTAL SCORE		126	111

Appendix K SCADA: detailed structure

Figure 90 is a more detailed overview of the complete SCADA structure. All related systems are mapped and the communication structure is integrated in the design.

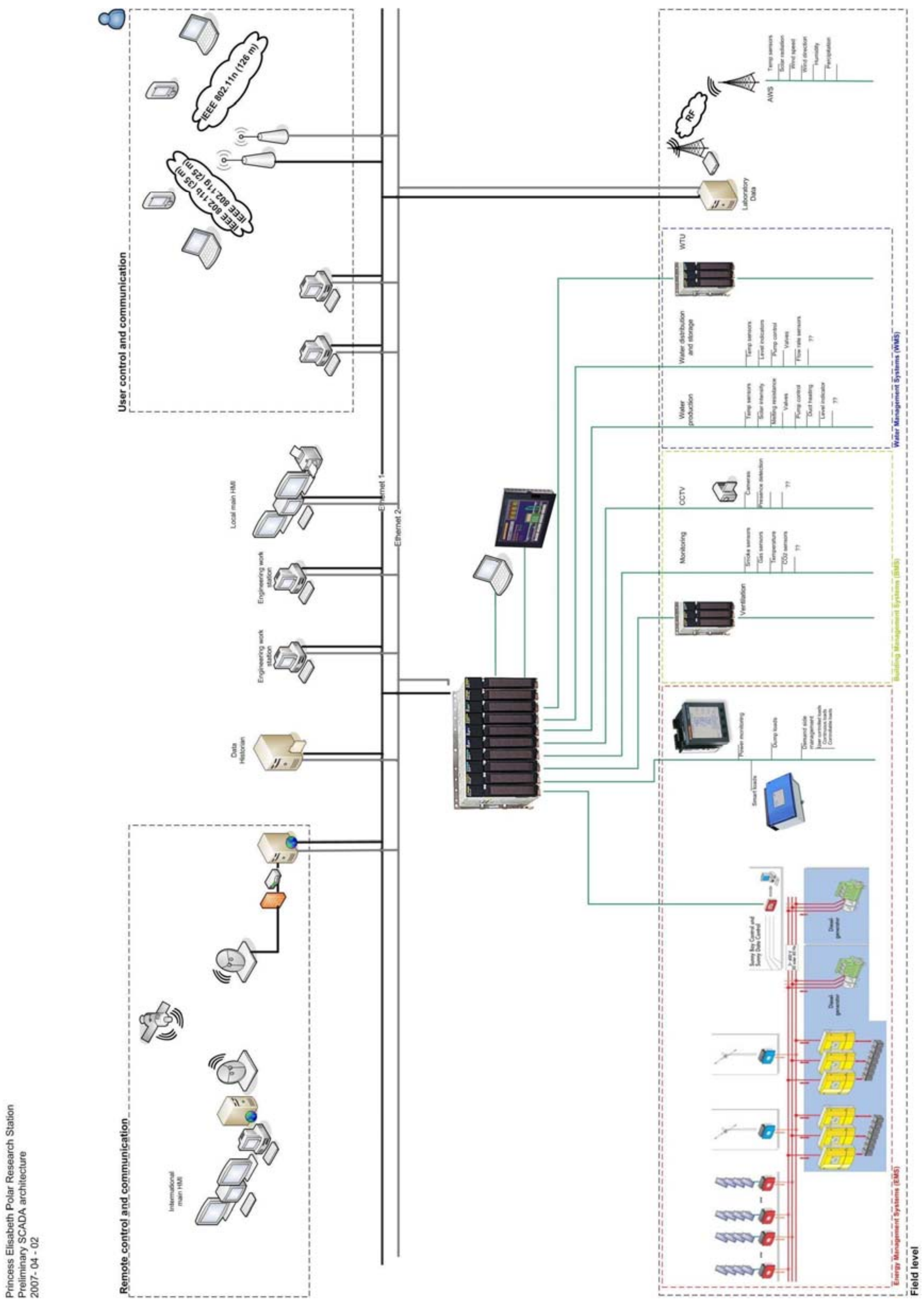


Figure 90: detailed SCADA architecture

Figure 91 is a detailed overview of the physical integration of the EMS in the principal electrical scheme. The blue lines correspond for connections needed for sensing. The orange connections are needed for control.

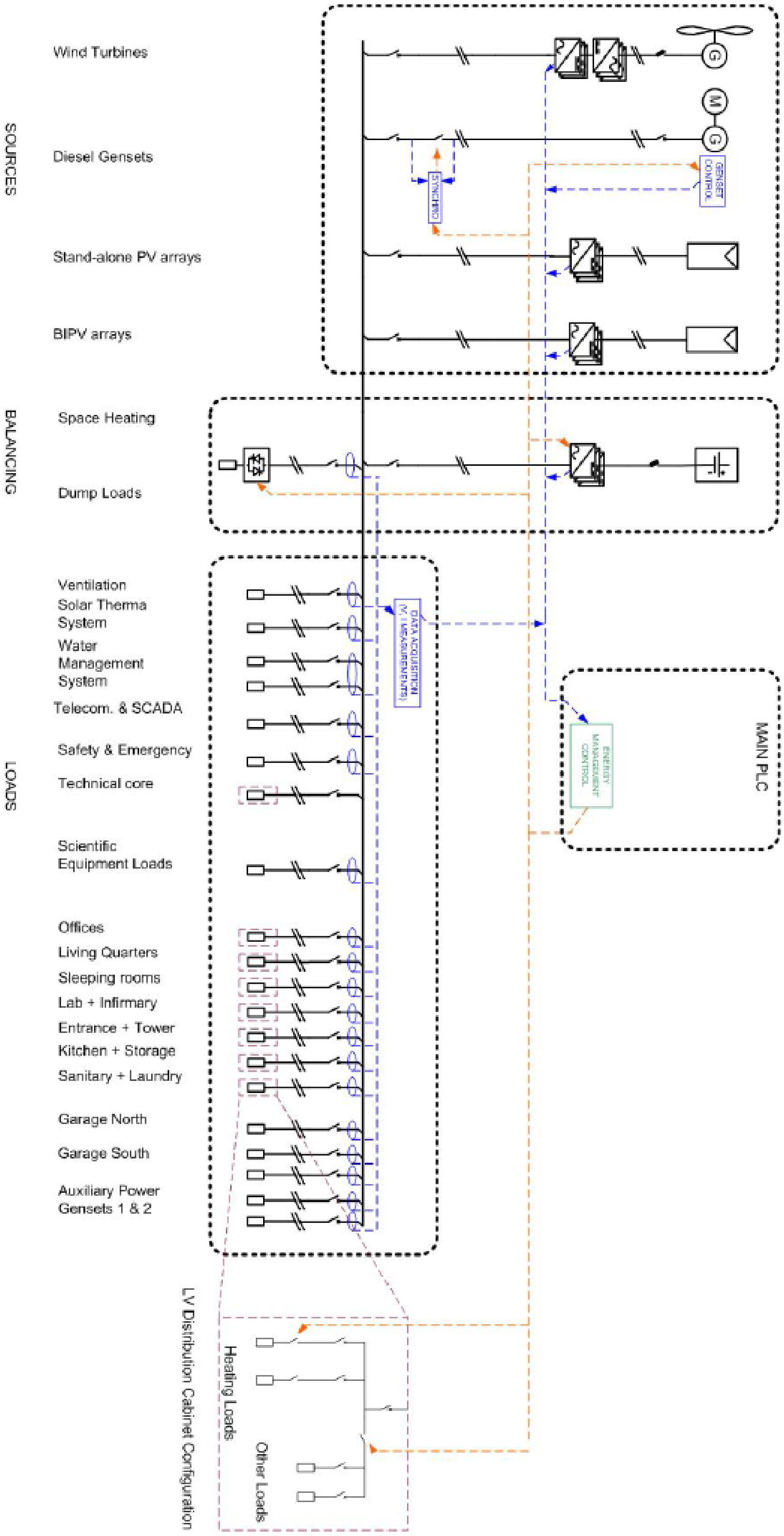


Figure 91: EMS - overview of data interchange [Source: 3E]

Figure 92 is a more detailed view over the different type of loads in the principal electrical scheme.

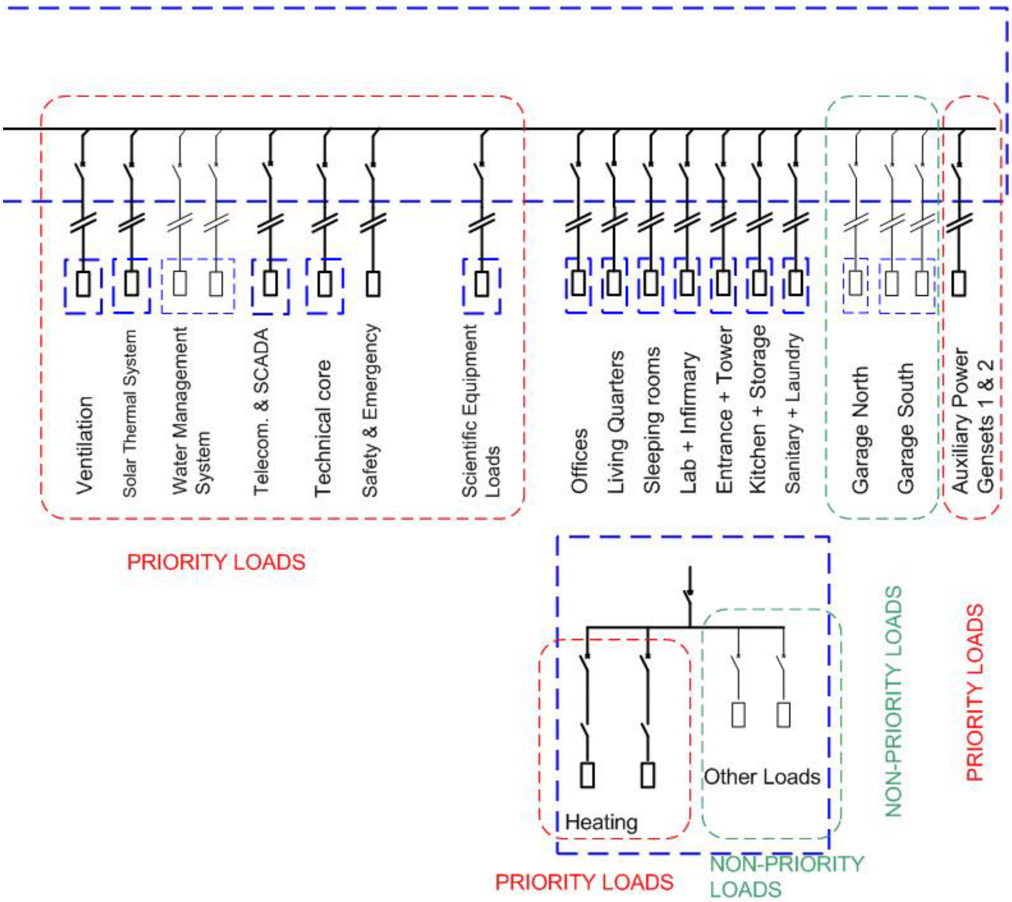


Figure 92: EMS: priority and non-priority loads [Source: 3E]

Appendix L Wind generation

Figure 93 shows the AWS on Antarctica. Due to the Antarctic treaty, the data from these AWS are public available.

Figure 93: Overview of Antarctic AWS [Source: Google earth]

Figure 94 shows the monthly observations of the AWS data. The blue line represents the statistical Weibull estimation. Figure 95 compares the monthly observations of the AWS data with the synthetically generated observations.

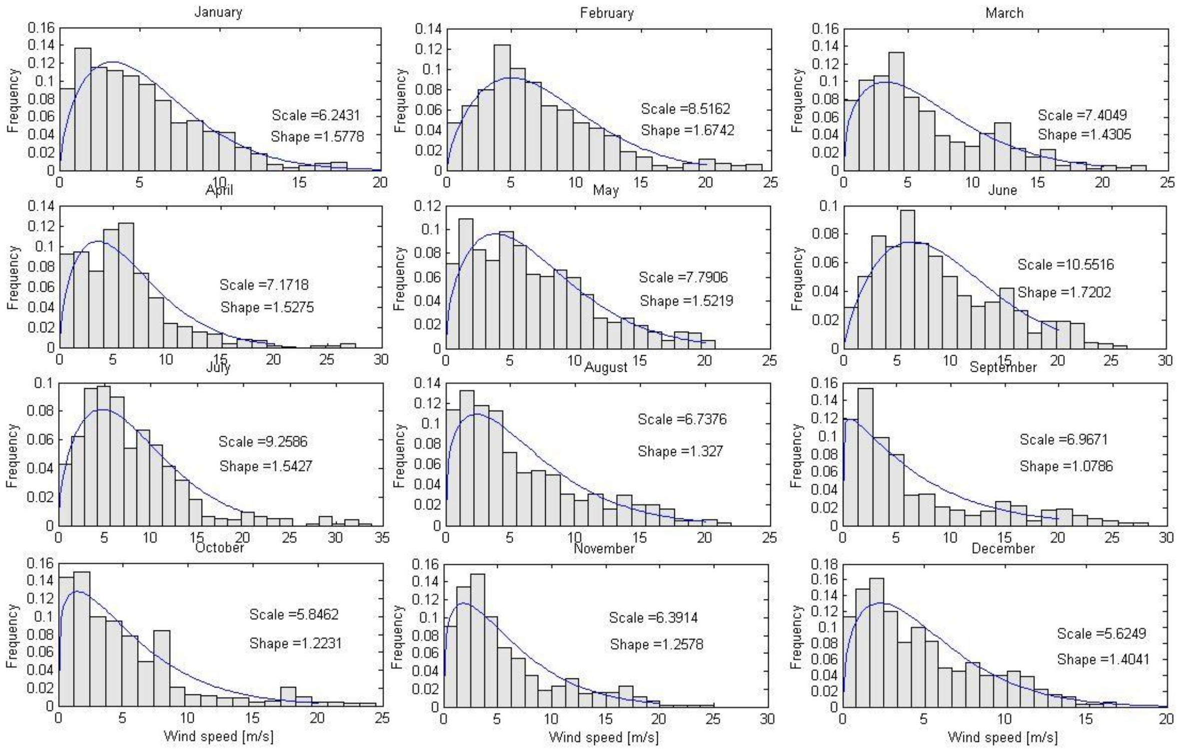


Figure 94: Monthly observation based on the transformed AWS data - 10 m

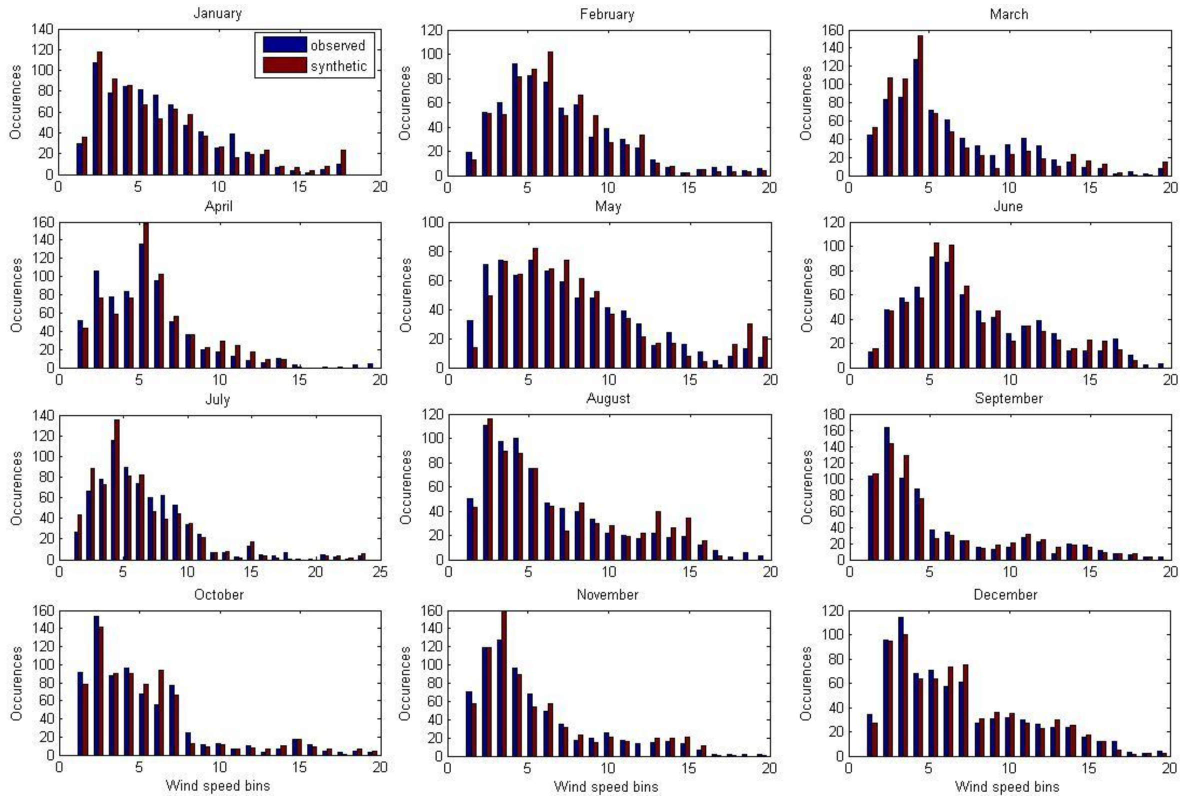
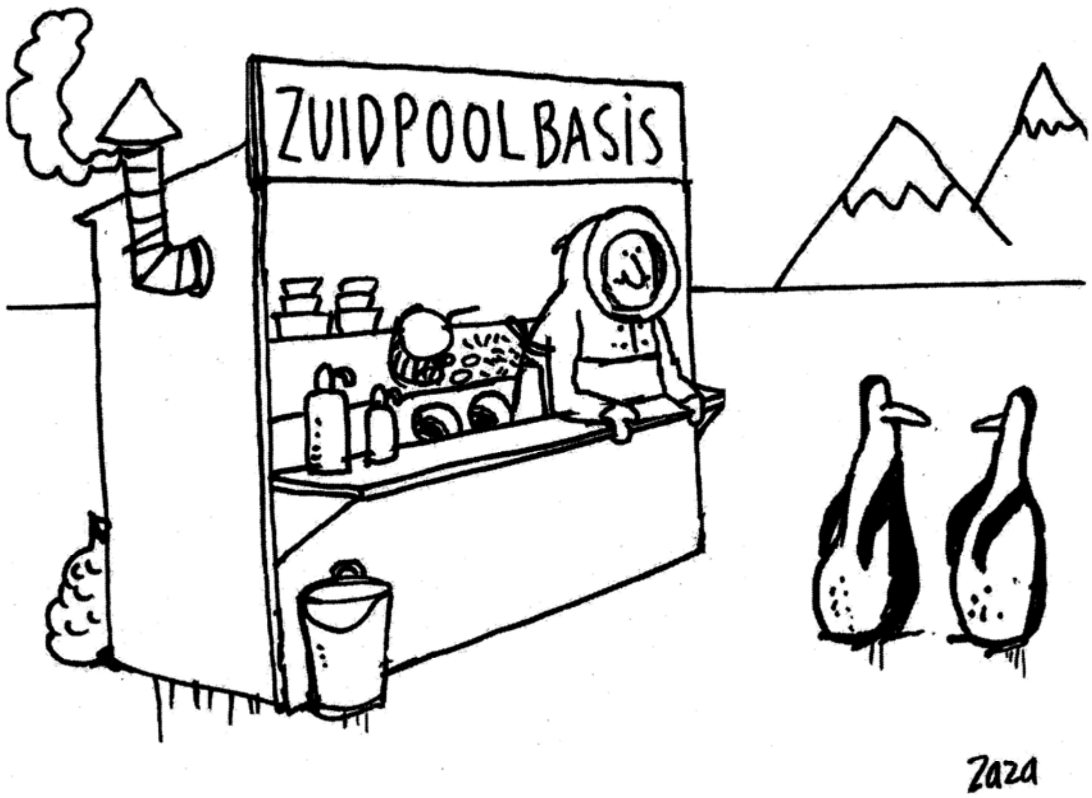


Figure 95: Monthly occurrences in wind speed bins observation versus synthetic

Table 80 is the transition probability matrix for the month November 2005.

Table 80: TPM November 2005

Bins	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.67	0.28	0.04	0.01												
2	0.16	0.48	0.30	0.06												
3	0.03	0.28	0.40	0.24	0.04	0.01										
4	0.01	0.06	0.31	0.40	0.17	0.04	0.01									
5		0.01	0.07	0.25	0.40	0.19	0.06	0.02								
6			0.06	0.08	0.27	0.37	0.14	0.05	0.03							
7				0.01	0.11	0.20	0.51	0.09	0.06			0.02				
8					0.12	0.15	0.18	0.18	0.15	0.18	0.04					
9		0.03				0.08	0.10	0.13	0.25	0.30	0.10	0.01				
10								0.12	0.24	0.36	0.26	0.02				
11								0.06	0.12	0.38	0.18	0.15	0.09		0.02	
12							0.04		0.04	0.04	0.18	0.50	0.11	0.07	0.02	
13											0.10	0.10	0.27	0.27	0.13	0.13
14												0.06	0.25	0.44	0.16	0.09
15											0.04	0.04	0.14	0.18	0.50	0.10
16													0.21	0.21	0.14	0.44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