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Energy and Power Demand of Food Production in Space based on Results of the EDEN ISS Antarctic Greenhouse

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The EDEN ISS greenhouse is a space-analogue test facility near the German Neumayer III station in Antarctica. The facility is part of the project of the same name and was designed and built since 2015 and eventually deployed in Antarctica in January 2018. The first operational phase of the greenhouse started on February the 7th and continued until the 20th of November 2018. The purpose of the facility is to enable multidisciplinary research on topics related to future plant cultivation on human space exploration missions. Research on food quality and safety, plant health monitoring, microbiology, system validation, human factors, horticultural sciences and resource demand were conducted. Part of the latter were measurements of the electrical energy and power demand. Those measurements were conducted on the facility and subsystem level, which were complemented by determining the demand of single components like LED lamps at different illumination settings. This paper describes the electrical energy and power demand during the experiment season between February and November 2018. Furthermore, the impact of these results on designing and planning future plant cultivation system in space are evaluated.

Nomenclature

AMS = Atmosphere Management Subsystem
AWI = Alfred-Wegener Institute for Polar and Marine Research
CDHS = Control and Data Handling Subsystem
CPO = Cold Porch
EMS = Energy Measurement System
FEG = Future Explroation Greenhouse
ILS = Illumination Subsystem
MTF = Mobile Test Facility
NDS = Nutrient Delivery Subsystem
NM III = Neumayer Station III
PDS = Power Distribution Subsystem
SES = Service Section
TCS = Thermal Control Subsystem

I. Introduction

THE implementation of space greenhouse systems into future habitats and their utilization in conjunction with other life support systems poses a number of challenges. One of these challenges is the electrical energy required to cultivate plants in a closed controlled environment. Maintaining such an environment is only possible with the extensive use of technologies for e.g. regulating the composition, temperature and humidity of the atmosphere; sustaining the nutrient and water supply; supplying illumination and monitoring plant health. All of these technologies require electrical energy to be operated. Information about the electrical energy demand of space greenhouses is scarce, due to the lack of any large scale systems operational in space. Only small experimental plant cultivation systems have been deployed during space missions[1] so far. Data regarding power and energy demand of these systems

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is almost never published and it can be doubted that this data can be used to estimate the energy demand of a large scale food production system providing the majority of the food to a future space crew.

Analogue experiments with plant cultivation facilities in a relevant environment on Earth can fill this gap. Suitable locations for such experiments are Antarctic research bases, which face similar difficulties like future space habitats. In fact, several of these research bases deployed plant cultivation facilities over the last decades[2]. Although, many of these greenhouse systems have not been designed as space research and innovation experiments, but as food supplement facilities. The South Pole Food Growth Chamber and the EDEN ISS Mobile Test Facility are two Antarctic greenhouses which were designed, built and operated with a focus on testing plant cultivation in a remote environment as a precursor for future space missions. Both facilities were used for a large number of different experiments, which also included measurements regarding the electrical energy demand.

This paper focuses on analyzing the energy measurement data generated during the 2018 experiment phase of the EDEN ISS project. A dedicated energy measurement system was installed in the greenhouse system from the beginning to monitor the electrical power and energy demand of the whole facility, its subsystems and a few components. This data allows a detailed view on the energy usage of a space greenhouse analogue test facility and helps to draw recommendations for future space systems.

II. Materials and Methods

A. EDEN ISS Mobile Test Facility Infrastructure

The EDEN ISS Mobile Test Facility (MTF) is located in the immediate vicinity of the Neumayer Station III (NM III) which is operated by the German Alfred-Wegener Institute for Polar and Marine Research (AWI). The MTF was designed and built as an experimental facility for plant cultivation systems, allowing the testing of essential technologies and production procedures for future long-duration human space missions[3]. Detailed system analysis was conducted by the consortium partners resulting in a solid design[4–6], including a complete risk assessment[7]. The MTF consists of two customized 20 foot high-cube shipping containers, which are placed on top of a raised platform located approximately 400 meters south of NM III. The research facility can be subdivided into three distinct sections:

- Airlock/ Cold Porch (CPO) (Blue section in Figure 1): A small room providing storage and a small air buffer to limit the entry of cold air when the main access door of the facility is used. This area is used for changing clothes. Furthermore, the main fresh water tank and the waste water tank are both located in the subfloor space of this section.
- Service Section (SES) (Red section in Figure 1): This section houses the primary control, atmosphere management, thermal control, power control and nutrient delivery systems of the MTF[8]. Additionally, this section provides a working table including sink, trash bins, and storage for tools and consumables. In addition this section housed an independent rack-like plant cultivation system as part of the plant growth demonstrator for future deployment onboard the International Space Station (ISS)[9,10].
- Future Exploration Greenhouse (FEG) (Green section in Figure 1): The main plant cultivation space of the MTF which includes multi-level plant growth racks with a total growth area of 12.5 m^2 operating in a controlled environment. The FEG is used to study plant cultivation and the related technologies for future planetary habitats[11].

The technologies required to cultivate plants in a controlled environment are arranged in six different subsystems, which are briefly described in the following. Detailed information about the subsystems can be found in other publications of the authors[11,8].

- The nutrient delivery subsystem (NDS) adjusts the irrigation water's pH and EC value. Depending on the plant type (leafy or fruit-building crop), the mixing computer provides a dedicated nutrient solution that is delivered directly to the roots. Eight high-pressure pumps spray a fine nutrient mist inside the root compartment of each plant tray.
- The atmosphere management subsystem (AMS) regulates the temperature, humidity, and CO_2 concentration within the FEG. Furthermore, the air flow is filtered (particle filter, HEPA, and activated carbon filter) and the humidity condensate water is recovered and fed back to the fresh water tank.
- The thermal control subsystem (TCS) is used to remove excess heat from the MTF and to provide a cooling fluid to the dehumidifier for condensation of the humidity produced by the plants.
- The illumination control subsystem (ILS) consists of 42 fluid-cooled LED fixtures integrated into the FEG. The light spectrum can freely be composed of red, blue, far-red, and white for each plant tray.

- The power distribution subsystem (PDS) provides electrical energy to all subsystems of the MTF. The electrical energy is generated in NM III and transmitted to the MTF.
- The control and data handling subsystem (CDHS) consists of a set of independent programmable logic controllers which receive information from a wide range of sensors. Based on this information and defined program logics this subsystem controls all functions of the MTF. The CDHS sends system telemetry to the mission control center in Bremen, Germany. Furthermore, every day a set of images taken from fixed positions inside the FEG is sent to the mission control center to allow remote experts to observe plant development and to assist the on-site operator[12].

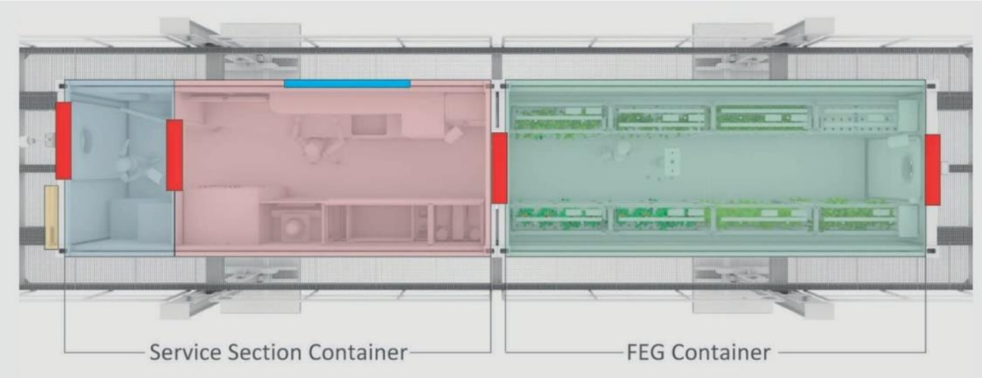

Figure 1: Schematic top-view of the MTF. The blue section indicates the Cold Porch. The red area is called Service Section and houses a work desk and almost all greenhouse subsystems. The green section is the main plant cultivation space, called the Future Exploration Greenhouse. Red boxes indicate doors between the sections and to the outside. The light blue box indicates a window.

B. Experiment timeframe

The MTF arrived in Antarctica on the 3rd of January 2018. The deployment took around five weeks and was finished in early February [13]. The winter-over on-site operator remained in Antarctica for the following 10 months until December 2018. In the following chapters 'experimental phase' refers to the period from mid-February 2018 to mid-November 2018. The timeline of the experiment phase is shown in Figure 2.

The first plants were sown on February 7th 2018. The winter-over period started with the departure of the last summer crew on February 18th. The first harvest of lettuce and leafy greens was on March 20th. The first cucumber harvest (29th of March) and first tomato harvest (16th of May) took place in the weeks that followed. The coldest temperature of the season was recorded in the morning of the 8th of October 2018 with -43.5 °C. The winter-over period ended with the arrival of the first summer crew on November 2nd. The experiment campaign of the MTF ended with the final harvest which took place on November 20th. The EDEN ISS winter-over operator departed a few days before Christmas 2018.

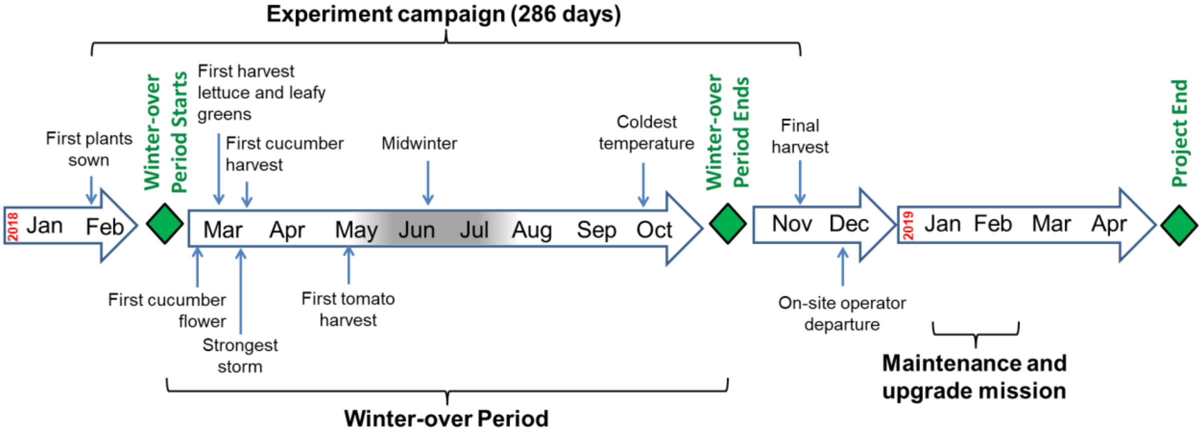

Figure 2: Timeline of the EDEN ISS experiment phase (early 2018 to early 2019).

C. Energy Measurement System

The hardware of the energy measurement system (EMS) utilizes the DIRIS Digiware energy measurement devices sold by the company Socomec. DIRIS Digiware is a modular system which allows a customized solution for energy and power measurements. It is possible to combine a variety of electrical voltage and current measurement modules. Depending on the module type three to six sensors can be connected Different types of sensors are available depending on the cable diameter and the current flowing through the cable.

The EDEN ISS EMS consists of a voltage measurement module (U-30) and two sorts of current measurement modules (I-35 and I-61). The U-30 module has three sensor inputs and measures the voltage of the three-phase main power supply to the MTF. Hereby, the voltage between each phase and neutral is measured. One current measurement module I-35 measures the electrical current of each of the three main power supply phases. Six I-61 current measurement modules, each of which has six sensor slots, measure the electrical current on the subsystem and component level. The measurement module setup is shown in Figure 3. The actual sensors performing the measurement are located on the respective power line inside the PDS cabinet directly after the fuse securing the respective subsystem or component. All modules are connected to each other in a row via an integrated bus. In addition to the measurement modules, the EDEN ISS EMS also has a small display integrated in the power box to visualize data inside the MTF. A gateway module is used to connect the EMS to the network infrastructure of the MTF which allows access to the EMS from each computer connected to the EDEN ISS local network in Antarctica and also remotely from the mission control center in Bremen, Germany.

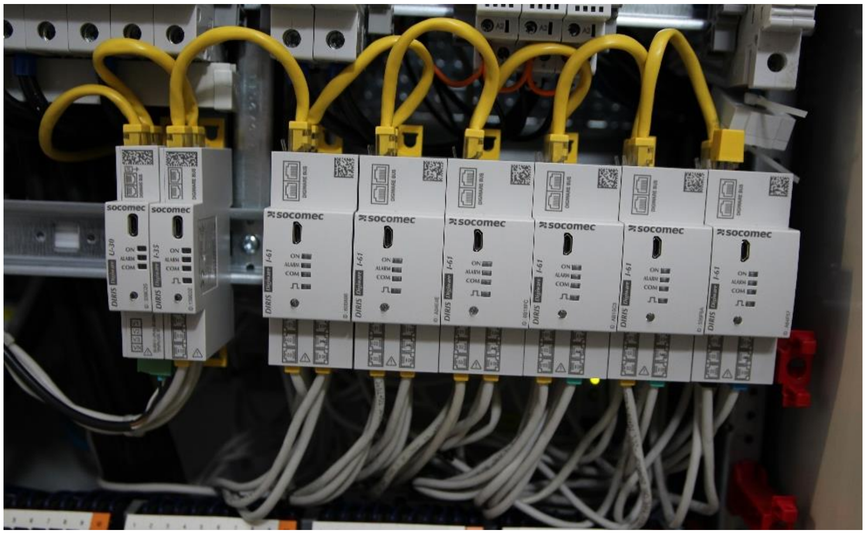

Figure 3: The EMS as installed in the power distribution box of the MTF. Modules from left to right: One voltage measurement module U30, one current measurement module I-35, six current measurement modules I-61.

The EDEN ISS EMS setup with the DIRIS Digiware hardware allows for precise measurements of voltage and current due to the high accuracy class of the modules and attached sensors, see Table 1. In addition to the measured voltage and current values the EMS can calculate power and energy demand internally and display those values. The EMS also allows export of the data via csv files, which makes it easy to analyze the data. Besides the mere measurement of voltage and current, the EMS is also capable of analyzing the status of the power distribution system of the MTF by measuring values such as frequency or inductive loads.

Table 1: Sensor types and accuracy class for each measurement module.

Module	Sensor type	Accuracy class
U-30 (voltage)	Directly wired	Class 0.2
I-35 (current)	TE-35	Class 0.5
I-61 (current)	TE-18	Class 0.5

D. Electrical Power Generation

As mentioned previously the MTF has no means to generate electrical power by its own, but it is connected to the power grid of NM III. The station has four combined heat and power plants (CHP) running with diesel, of which one is an emergency back-up and up to three are operational on demand. Each CHP provides up to 150 kW electrical power. The thermal load resulting from the power generation is used to heat the station living and working areas. The CHPs are supplemented with a wind turbine, which can generate up to 30 kW electrical power.

III. Results

A. System level – MTF overall energy and power demand

The electrical energy demand of the MTF ranged from 6,600 to 7,800 kWh per month, see Figure 4, with February and November being the exception because only 21 respectively 20 days of those months account to the experiment phase. The total demand from February to November 2018 was around 68,516 kWh which corresponds to 5,481 kWh/m² cultivation area.

The drop of the energy demand in June was caused by the failure of one of the two free cooler fans on the roof of the MTF mid of May. The fans have a large power demand. The remaining fan was shut down from June until September, because the low temperatures of the Antarctic environment were enough to cool the cooling fluid without the need for forced convection by the fans. The rise in energy demand from June to October is most likely associated with the dropping temperatures during the winter months and the corresponding need for additional electrical heating. Without the shut down of the freecooler fans, the energy demand in the June-October period would be around 900 kWh per month higher than shown in Figure 4.

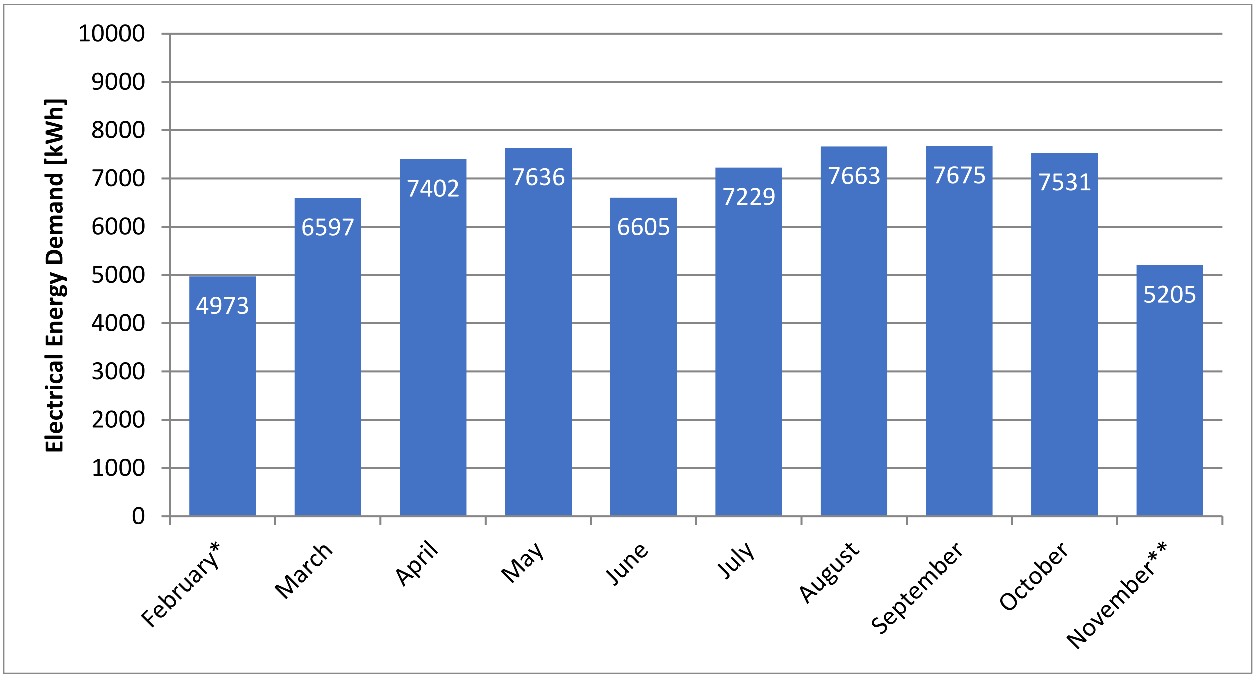

Figure 4: Monthly electrical energy demand (in kWh) of the MTF in 2018. (*February data starting from the 7th. **November data until the 20th)

The overall power demand of the MTF from March to November 2018 is shown in Figure 5. The February data could not be used, because of recording issues of the measurement system. The graph shows a cyclic behaviour, which is caused mainly by the daily cycle of the LED lamps. During the photoperiod of 17 hours the LED lamps were on, during the dark period of 7 hours the LEDs were off. The average power demand during the photoperiod is 11.23 kW and during the dark period 8.21 kW which corresponds to an average of, respectively, 898.4 W/m² and 656.8 W/m² cultivation area.

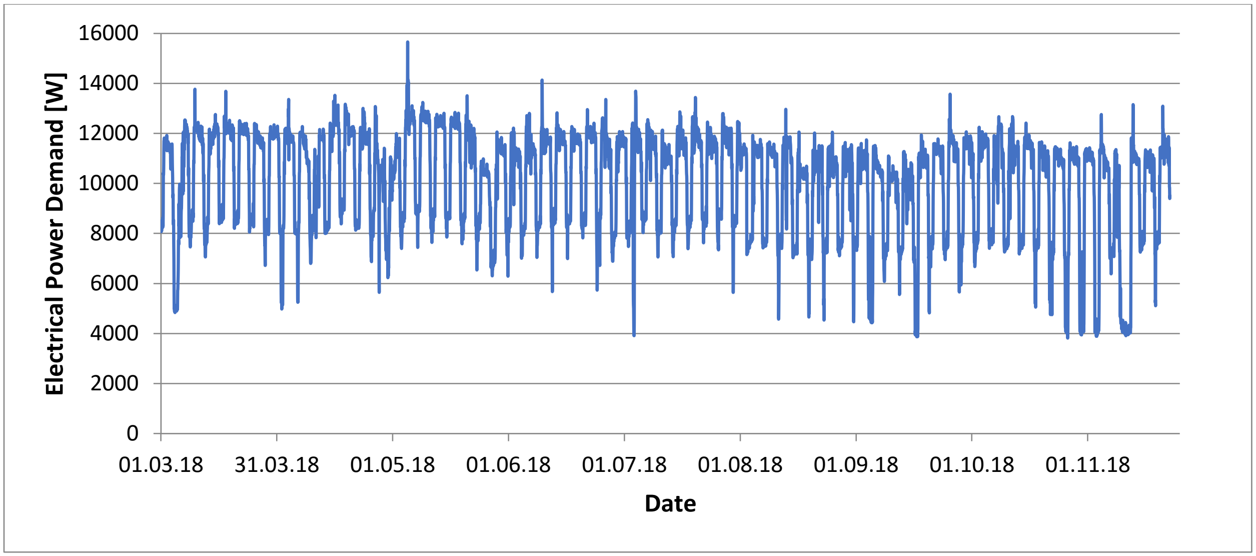

Figure 5: Electrical power demand (in W) of the MTF from March 1st until November 20th 2018.

B. Subsystem level – Energy and power demand of each subsystem

The energy demand of each subsystem is shown in Figure 6. The aforementioned effect of the shutdown of the free cooler fans is clearly visible in the values of the TCS. The values of the common equipment rise constantly from May to October. This behaviour is caused by the room heaters located in the three sections of the MTF. These heaters turn on, when the temperature drops below a certain threshold. The values of the common equipment consequently follow the dropping external temperatures during winter (April to October), because the heaters turn on more frequently. The energy demand of the AMS, ILS, NDS and CDHS are relatively constant throughout the year. Please note, that the data for February and November is only available for 21 respectively 20 days.

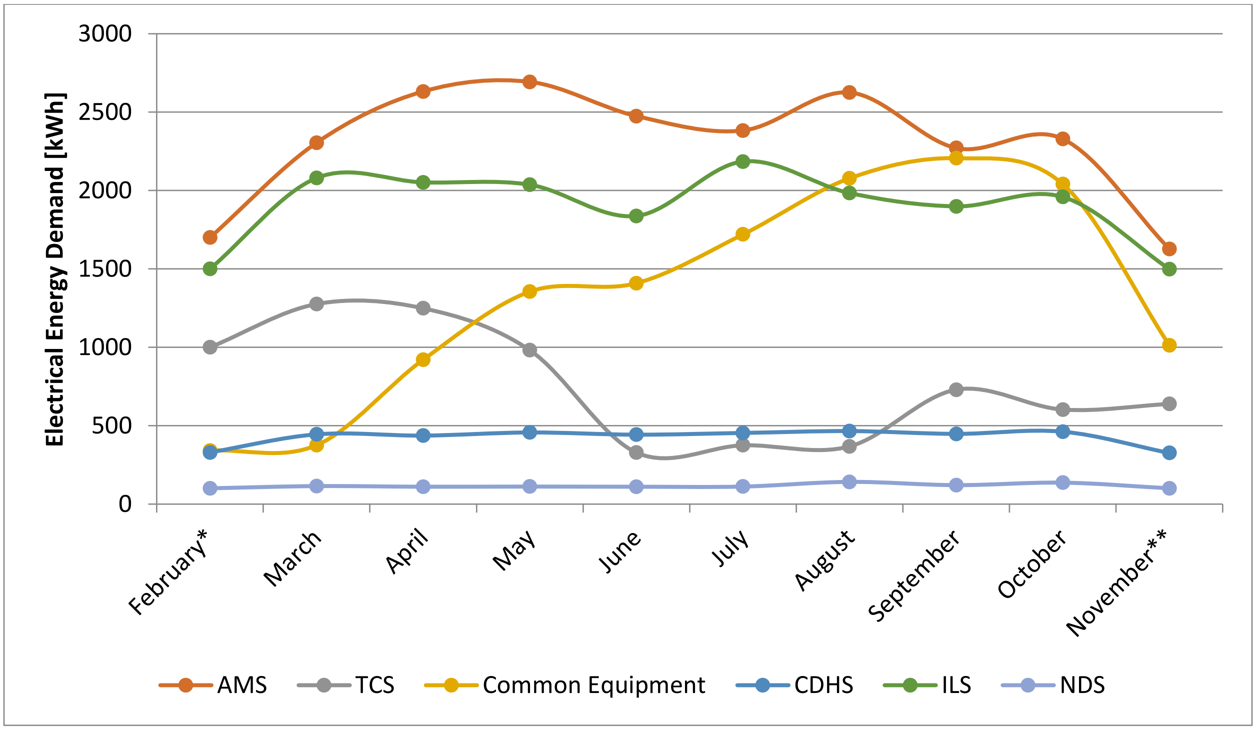

Figure 6: Monthly electrical energy demand (in kWh) of each MTF subsystem in 2018. (*February data starting from the 7th. **November data until the 20th)

Table 2 shows the absolute and relative energy demand of each subsystem from March to November 2018. The AMS had the highest demand followed by the ILS, the common equipment and the TCS. The demand of the CDHS is relatively small and the demand of the NDS is almost negligible.

Table 2: Absolute and relative electrical energy demand for each subsystem between February and November 2018.

Subsystem	**AMS**	**TCS**	**Common Equipment**	**CDHS**	**ILS**	**NDS**
Absolute electrical energy demand [kWh]	23,040	7,551	13,461	4,268	19,033	1,163
Relative electrical energy demand	33 %	11 %	20 %	6 %	28 %	2 %

C. Variation in subsystem power demand throughout a typical day

The power demand of some subsystems varies throughout the day, because those subsystems are subject to a specific schedule or react to certain parameters. The illumination subsystem is on a day-night cycle. All LEDs inside the FEG are turned on and off together based on a specific schedule. At 00:00, the LEDs are switched from normal illumination to a dusk setting with reduced intensity and therefore reduced power demand. After an hour the LEDs are turned off completely for the dark period which is scheduled during the normal night rhythm of the crew. At 08:00, the lamps are switched on to a dawn setting with reduced intensity. At 09:00 the lamps are switched to the normal intensity level until 23:59. This day-night cycle can also be seen in the power demand graph of the ILS in Figure 7 and Figure 8, which show exemplary graphs for two days.

The power demand of the AMS largely depends on the temperature inside the FEG which in turn depends on the external conditions and the amount of heat produced by the LED lamps. Some of the electrical energy used by the LEDs is converted to heat which warms the air inside the FEG. The FEG in turn loses heat to the Antarctic environment. The AMS has heating rods to warm the atmosphere of the FEG in case the temperature drops below a certain set point, which is necessary throughout the whole day and especially during the night period, when the LEDs are shut off.

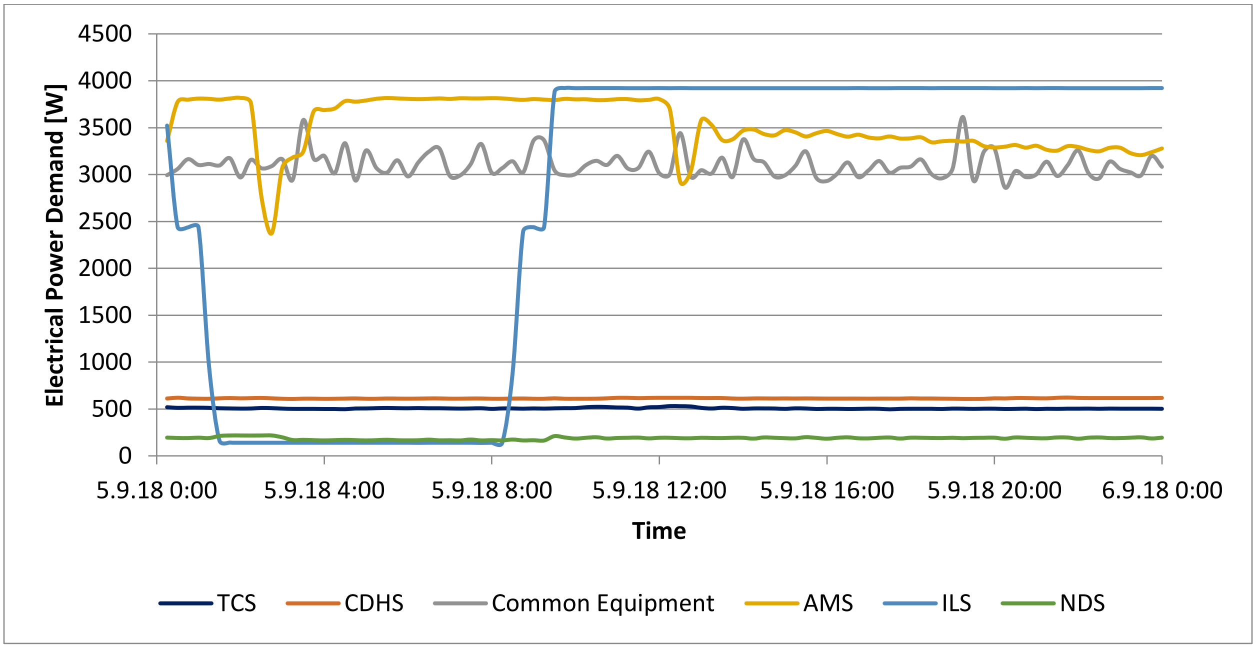

Figure 7: Subsystem power demand on September 5th 2018.

The power demand of the TCS, CDHS and NDS are nearly constant throughout each day. Whereas the power demand of the common equipment shows some oscillations. Figure 7 shows daily graphs from September 5th, which means in the mid of the Antarctic winter and corresponding low external temperatures, and Figure 8 shows daily graphs from April 28th, a day with mild external temperatures. The main difference between the two days is the power demand of the common equipment, which is higher on September 5th compared to April 28th. This is caused by the electrical room heaters installed in the Cold Porch and Service Section which keep the air temperature stable. One can see the additional electrical power demand of around 1,500 W on September 5th compared to April 28th associated with those room heaters.

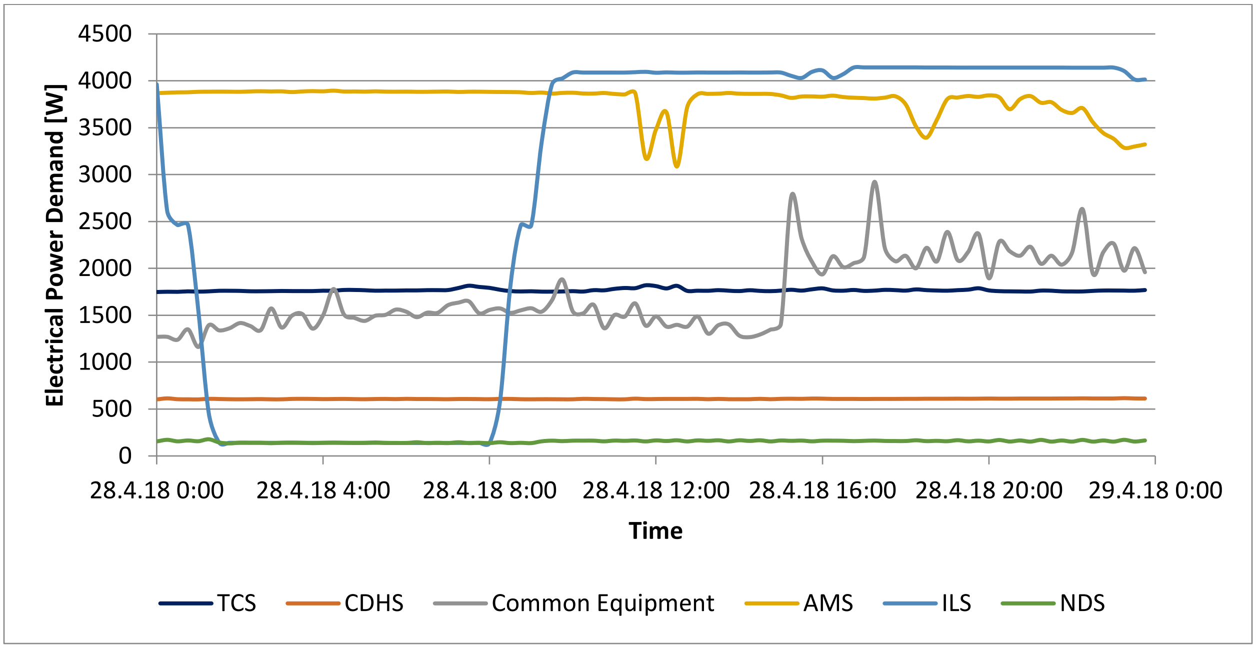

Figure 8: Subsystem power demand on April 28th 2018.

IV. Discussion

A. Comparing the MTF energy demand to other Antarctic greenhouses

While there are many other greenhouse facilities in Antarctica[2], data on their electrical energy demand is scarce. Only for the South Pole Food Growth Chamber (SPFGC) data is available[14]. The SPFGC was operational around the year 2010 and located inside a building of the American Amundsen-Scott South Pole Station. Several plant species were cultivated inside the SPFGC, which had a cultivation area of around 22.7 m². The SPFGC and the EDEN ISS MTF are hard to compare, because the SPFGC was a set of customized rooms inside a heated building whereas the MTF is a stand-alone facility. Furthermore, the SPFGC used high-pressure sodium lamps instead of LEDs for plant illumination. The electrical energy demand of the former is much higher compared to LEDs.

The energy demand of the SPFGC was around 281 kWh/d which is in the same range as the EDEN ISS MTF (240 kW/h). However, when considering the cultivation area, the SPFGC required 12.8 kWh/m²/d and the MTF required 19.2 kWh/m²/d. The higher demand of electrical energy of the MTF compared to the SPFGC was most likely caused by the different environments in which the two facilities were located. Furthermore, it is not clear whether the SPFGC recovered the moisture transpired by the plants. Recovering moisture from the atmosphere is energy intensive and is also one factor which might have caused EDEN ISS to have a higher energy demand.

B. Considerations regarding the influence of the Antarctic environment

The EDEN ISS MTF stands on a platform and is year-round exposed to the Antarctic environment. Consequently, equipment is required to counteract the heat loss to the environment and other equipment which is only required for this location. This equipment is not associated with plant growth in general. For example, a facility with a different purpose in the same location would also need electrical heaters to keep the internal air temperature in a comfortable zone. Most of the equipment not directly related to plant cultivation (e.g. room heaters, water boiler, room illumination or tea kettle) is encompassed in the category ‘Common Equipment’. This category alone required 13,461 kWh of electrical energy (20% of total MTF demand) in the experiment season 2018 and had an average power demand of 2,280 W.

Another influence of the Antarctic environment is on the energy demand of the atmosphere management subsystem and the thermal control subsystem, which maintain the temperature and humidity inside the greenhouse, among others. However, it cannot clearly determined how much of the energy demand of both subsystems is caused by the Atnarctic environment and which can be attributed to plant cultivation alone. Doing that would require to position the whole facility in a location with moderate climate conditions to have data for comparison.

C. Energy demand for illumination

Besides the atmosphere management subsystem and the thermal control subsystem, the illumination subsystem also has a high electrical energy demand, e.g. 28% of the total energy demand of EDEN ISS in 2018. This demand depends on the lamp technology used, the lighting schedule, the spectrum and the intensity provided for plant cultivation and therefore varies with the day-night cycle and also with the maturity of the plants. Younger plants typically receive less light compared to fully mature plants. The illumination subsystem is independent of the Antarctic environment and therefore analogue experiment data allows a better projection for furute space greenhouses.

When comparing again EDEN ISS with the SPFGC, the SPFGC required 9.5 kWh/m²/d and the EDEN ISS required 5.7 kWh/m²/d for plant illumination. This large difference is mainly caused by the used technology. The SPFGC data is from an operational period during which high-pressure sodium lamps were used for plant illumination, whereas EDEN ISS uses LED lamps. When comparing the energy demand for plant illumination, it is clear that LED lamps are superior over high-pressure sodium lamps, which was expected. The EDEN ISS ILS required only 60% of the electrical energy the SPFGC used for providing light for the cultivation crops. This comparison was only made on the basis of energy demand and cultivation area. For a detailed comparison of the energy demand of the illumination systems additional information like the length of the photoperiod per day and the light intensity are required which were not available in that detail for the SPFGC.

D. Electrical energy demand for food production

The EDEN ISS MTF produced in total 517 kg of biomass during the 2018 season, of which 268 kg were food[15]. The remaining biomass were roots, stems, inedible leaves. The production of this amount of biomass required around 55,055 kWh, this value only includes the hardware required for plant cultivation and excludes the electrical energy demand of the common equipment. This means that ~205 kWh electrical energy per kilogram produced food was required in 2018. For comparison, the SPFGC used around 22.8 kWh/kg[14]. This is partly caused by the different energy requirements mentioned before and partly by the different biomass productivity. SPFGC was reported to have a productivity of 0.13 kg/m²/d [14] and EDEN ISS had a productivity of around 0.08 kg/m²/d in 2018[15]. One should keep in mind, that both Antarctic facilities cultivated salad and vegetable crops and no legumes and no grains.

V. Conclusion

This paper presented the results of measuring the electrical energy and power demand of an experimental plant cultivation system for future bio-regenerative life support systems. Comparable systems are scarce making comparisons on the demand and efficiency nearly impossible. However, the data shown in this paper will be helpful for future investigations of such systems.

The location of the EDEN ISS MTF, Antarctica, had several impacts on the measurements. Equipment that would not be installed in a space greenhouse (e.g. electrical room heaters) was necessary to counteract the low temperatures of the external environment. Although, most of this additional equipment was grouped in the Common Equipment subsystem and measured separately, the Antarctic environment also affected the energy demand of the TCS and AMS. The ILS measurement results were not affected by the Antarctic environment. These effects cannot be separated from the nominal measurements (operation in a norml environment), because this kind of reference measurements have not been conducted so far. However, the EDEN ISS MTF is going to be brought back from Antarctica in the next years and operated in a location in Germany, which will allow these measurements. The 2018 data and the data from subsequent could then be reevaluated and interpreted based on these reference measurements.

Despite the influence of the Antarctic environment on the measurements, it is safe to say, that the highest demand of electrical energy is required for illumination and atmosphere, including thermal, management. Since the efficiency of LEDs is already very close to its theoretical limit, improvements will only have small effects on reducing the energy demand. However, reductions of the energy demand is possible by more effectively illuminating the crop canopy by reducing stray light and also by better determining the illumination demand of each crop to avoid over-illumination. The authors see more room for energy reductions in the atmosphere management subsystem. There it is important to find efficient ways to ventilate the growth area and simultaneously control the temperature and humidity. It should also be investigated to make use of the spare heat that is produced by the subsystems of the plant cultivation system, which would improve its overall efficiency. Thus a holistic approach to the energy system of the whole spacecraft or habitat including a plant cultivation system could also bring improvements.

Another conlusion that can be drawn indirectly from the experimental results presented in this paper, is the lack of available data regarding the energy demand of plant cultivation systems for bio-regenerative life support. Measuring electrical energy and power demand during the operation of such a system is only rarely conducted. However, it is of uttermost importance for designing future systems to understand these demands. Only then conlusions on the overall effectivity can be drawn. Consequently, the authors of this paper recommend to include energy measurements in every future experiment or technology demonstrator. The absolute minimum of measurements to be taken are on the demand of the overall system. The next step would be to perform measurements on subsystem level, which eventually should be complemented with measurements on component level, especially if specific components (e.g. new LED illumination systems) are tested. Measurements should be done in a frequency that matches the subsystem and plant cycles, e.g. a sum only over one day of operation is not enough, because it would ignore the daily variation caused by the plant illumination schedule.

As expected, the demand of electrical energy of plant cultivation systems is high, but only with consistent and consequent measurements can components and operation techniques identified and tested for reducing this demand.

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References

[1] P. Zabel, M. Bamsey, D. Schubert, M. Tajmar, Review and analysis of over 40 years of space plant growth systems, *Life Sci. Space Res. (Amst)* 10 (2016) 1–16. https://doi.org/10.1016/j.lssr.2016.06.004.

[2] M. Bamsey, P. Zabel, C. Zeidler, D. Gyimesi, D. Schubert, E. Kohlberg, D. Mengedoht, J. Rae, Review of Antarctic greenhouses and plant production facilities: A historical account of food plants on the ice, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

[3] P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, B.-W. Johannes, P. Rettberg, D. Schubert, O. Romberg, B. Imhof, R. Davenport, W. Hoheneder, R. Waclavicek, C. Gilbert, M. Hogle, A. Battistelli, W. Stefanoni, S. Moscatello, S. Proietti, G. Santi, F. Nazzaro, F. Fratianni, R. Coppola, M. Dixon, M. Stasiak, E. Kohlberg, D. Mengedoht, L. Bucchieri, E. Mazzoleni, V. Fetter, T. Hummel, G. Boscheri, F. Massobrio, M. Lamantea, C. Lobascio, A. Petrini, M. Adami, G. Bonzano, L. Fiore, T. Dueck, C. Stanghellini, G. Bochenek, A. Gilley, M. McKeon-Bennett, G. Stutte, T. Larkin, S. Moane, P. Murray, P. Downey, R. Fortezza, A. Ceriello, Introducing EDEN ISS - A European project on advancing plant cultivation technologies and operations, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

[4] M. Bamsey, P. Zabel, C. Zeidler, L. Poulet, D. Schubert, E. Kohlberg, T. Graham, Design of a containerized greenhouse module for deployment to the Neumayer III Antarctic Station, *44th International Conference on Environmental Systems,* Tucson, Arizona, 2014.

[5] M. Bamsey, P. Zabel, C. Zeidler, V. Vrakking, D. Schubert, E. Kohlberg, M. Stasiak, T. Graham, Early Trade-offs and Top-Level Design Drivers for Antarctic Greenhouses and Plant Production Facilities, *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.

[6] P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, D. Schubert, O. Romberg, G. Boscheri, T. Dueck, The preliminary design of the EDEN ISS Mobile Test Facility - An Antarctic greenhouse, *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.

[7] A. Santos, V. Infante, M. Bamsey, D. Schubert, A case study in the application of failure analysis techniques to Antarctic Systems: EDEN ISS, *2016 IEEE International Symposium on Systems Engineering (ISSE),* Edinburgh, United Kingdom, IEEE, 03.10.2016 - 05.10.2016, pp. 1–7.

[8] V. Vrakking, M. Bamsey, P. Zabel, C. Zeidler, D. Schubert, O. Romberg, Service Section Design of the EDEN ISS Project, *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.

[9] G. Boscheri, V. Guarnieri, C. Iacopini, I. Locantore, M. Lamantea, C. Lobascio, D. Schubert, The EDEN ISS Rack-Like Plant Growth Facility, *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.

[10] G. Boscheri, M. Volponi, M. Lamantea, C. Lobascio, D. Schubert, P. Zabel, Main performance results of the EDEN ISS rack-like plant growth facility, *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.

[11] P. Zabel, M. Bamsey, C. Zeidler, V. Vrakking, D. Schubert, O. Romberg, Future Exploration Greenhouse Design of the EDEN ISS project, *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.

[12] C. Zeidler, P. Zabel, V. Vrakking, M. Dorn, M. Bamsey, D. Schubert, A. Ceriello, R. Fortezza, D. de Simone, C. Stanghellini, F. Kempkes, E. Meinen, A. Mencarelli, G.-J. Swinkels, A.-L. Paul, R.J. Ferl, The Plant Health Monitoring System

of the EDEN ISS Space Greenhouse in Antarctica During the 2018 Experiment Phase, *Frontiers in Plant Science* 10 (2019) 1457. https://doi.org/10.3389/fpls.2019.01457.

[13] D. Schubert, M. Bamsey, P. Zabel, C. Zeidler, V. Vrakking, Status of the EDEN ISS Greenhouse after on-site installation in Antarctica, *48th International Conference on Environmental Systems*, Albuquerque, New Mexico, 2018.

[14] R.L. Patterson, G.A. Giacomelli, M. Kacira, P.D. Sadler, R.M. Wheeler, Description, operation and production of the South Pole Food Growth Chamber, *Acta Hortic.* (2012) 589–596. https://doi.org/10.17660/ActaHortic.2012.952.75.

[15] P. Zabel, C. Zeidler, V. Vrakking, M. Dorn, D. Schubert, Biomass Production of the EDEN ISS Space Greenhouse in Antarctica During the 2018 Experiment Phase, *Frontiers in Plant Science* 11 (2020) 656. https://doi.org/10.3389/fpls.2020.00656.