



# GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

## **Design, construction, testing, and debugging of a Digital Power Supply (DPS) for an Antarctic Weather Station**

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Madrid

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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título  
Design, Construction, Testing, and Debugging of a Digital Power Supply (DPS) for an  
Antarctic Weather Station

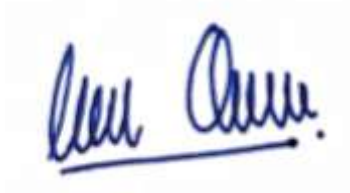
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Fecha: 31/08/2022

Autorizada la entrega del proyecto

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Fecha: 5/ 9/ 2022



# Diseño, construcción, testeo y depuración de una fuente de alimentación digital para una estación meteorológica en la Antártida

## *1. Problema a resolver*

El proyecto surge de un cliente ficticio que contrata a un equipo de ingenieros para resolver el siguiente problema:

"Se requiere el despliegue de una serie de estaciones meteorológicas en varios lugares remotos de la Antártida. Estas estaciones no tripuladas dispondrán de un enlace de radio bidireccional con una estación tripulada y realizarán mediciones bajo demanda. La estación debe ser lo suficientemente pequeña y ligera como para ser transportada a su ubicación en trineo y debe funcionar y ser capaz de ser reprogramada sin mantenimiento durante un período de 15 años" <sup>[1]</sup>.

## *2. Objetivos del proyecto*

Aunque el objetivo final del proyecto no es el desarrollo y diseño de la Estación Meteorológica Antártica completa debido a la falta de recursos y tiempo; se persigue un modelo óptimo de la alimentación digital y del sistema de carga de baterías de la estación meteorológica antártica. El desarrollo y la mejora de otros subsistemas de la estación meteorológica antártica, como los sensores o los sistemas de radioenlace, serían los siguientes pasos a seguir o una posible ampliación del proyecto.

El objetivo principal del proyecto es el diseño, la construcción, las pruebas y la depuración del DPS y del sistema de carga, intentando mejorar los aspectos antes mencionados que buscan las empresas (coste, rendimiento, tiempo de mantenimiento,

eficiencia...). En concreto, el proyecto nace de la demanda de un cliente ficticio que contrata a nuestra empresa para modelar el DPS que está sujeto a ciertas restricciones por parte del cliente <sup>[1]</sup>. De ahí que el diseño resultante y, por tanto, un objetivo esencial del proyecto sea satisfacer dichas exigencias.

### 3. Antecedentes del problema

Una estación meteorológica se compone de varios sistemas, como se puede ver en la Imagen 1. Este proyecto consiste específicamente en la construcción de la fuente de alimentación digital (DPS), su alimentación por batería y el sistema de carga de ésta. Un diagrama de bloques más detallado se muestra en Imagen 2, donde la relación entre los subsistemas se representa mediante flechas.

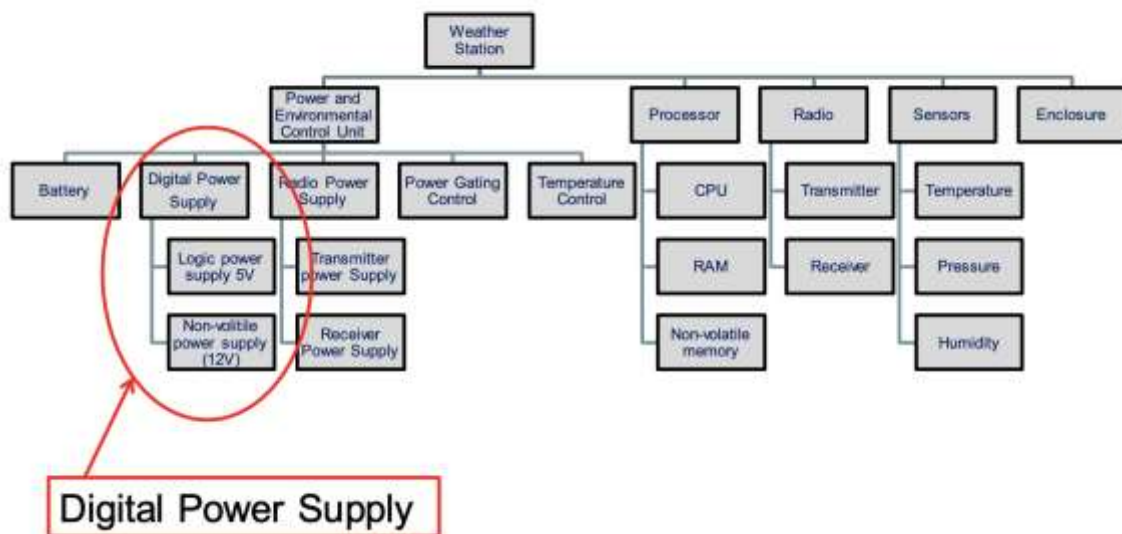


Imagen 1: Desglose de la estructura del producto para una estación meteorológica de la Antártida con permiso de los editores de [1].

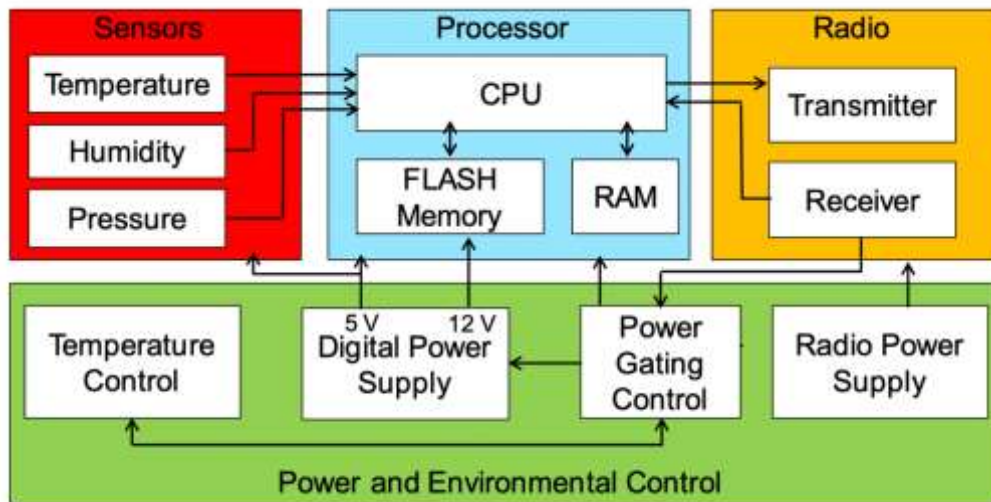


Imagen 2: Diagrama de bloques esquemático e interfaces de la Estación Meteorológica Antártica con permiso de los editores de [1].

El proyecto tiene como objetivo diseñar, construir, probar y depurar un circuito de subsistema de alimentación digital para una estación meteorológica en la Antártida que se ajuste a las especificaciones de los requisitos. La fuente de alimentación debe proporcionar dos tensiones estables de CC, 5 V y 12 V, que alimentarán los siguientes módulos:

Circuito	Tensión requerida (V)		Corriente máxima (mA)
	Mín	Máx	
CPU	4.7	5.3	12
RAM	4.5	5.5	3
Memoria flash	11.2	12.8	20
Sensores	4.85	5.15	5

Tabla 1: Circuitos alimentados por el subsistema de alimentación digital.

El proyecto debe documentar el diseño y demostrar rigurosamente que se han cumplido los requisitos. Para ello, se debe adoptar un enfoque de ingeniería de sistemas y exponer los siguientes documentos:

- Especificación de requisitos
- Datos de diseño, como esquemas, diseño, lista de componentes, etc.
- Plan de verificación
- Plan de fabricación
- Coste del proyecto
- Gestión de riesgos
- Datasheet

El DPS está constituido principalmente por una placa de circuito impreso (PCB) que debe diseñarse y construirse en el laboratorio para optimizar el coste, la eficiencia, el rendimiento y la mano de obra. Los componentes disponibles para la placa de circuito impreso se exponen en la Lista de Componentes.

Para alimentar el DPS, se utilizará un panel solar para cargar la batería y conseguir la tensión inicial deseada. Por lo tanto, el diseño del circuito para la energía solar para cargar la batería debe ser simulado, y luego construido en una PCB. Este circuito debe utilizar únicamente componentes de la [Lista de Componentes](#) mencionada anteriormente. Además, la batería y el panel solar óptimos también deben elegirse dentro de la lista que satisfaga los demás requisitos.

La PCB y el circuito de carga de la batería deben ser la combinación óptima de coste, rendimiento y eficiencia, todo ello en un único diseño que, al mismo tiempo, cumpla los requisitos. Este informe también describirá, mediante una matriz de riesgos, los pasos más peligrosos del proyecto. Por último, el informe incluirá un estudio económico, con un análisis completo del coste tanto fijo como variable del dispositivo (componentes, fabricación, verificación...) teniendo en cuenta el coste de contingencia en caso de que se produzca alguno de los riesgos mencionados.



#### 4. *Estado de la cuestión*

Las estaciones meteorológicas de la Antártida son dispositivos automatizados que captan los datos meteorológicos de este inhóspito continente y los envían a personal profesional para que los interprete. La red de estaciones meteorológicas de la Antártida, que abarca todo el continente, proporciona información para un mejor conocimiento de la meteorología y la climatología de superficie en todo este continente <sup>[2]</sup>. Estos dispositivos llevan funcionando desde principios de los años 80, cuando la División Antártica Australiana (AAD) colocó la primera estación meteorológica automatizada <sup>[3]</sup>. Estas sencillas estaciones ayudan a los meteorólogos a recoger información que crea un registro climático en el lugar remoto elegido. Este registro climático contribuye a la elaboración de previsiones meteorológicas. Además, otra función fundamental, que hoy en día tiene gran relevancia e importancia, es la comprensión del cambio climático global. Dado que la red de estaciones meteorológicas antárticas lleva más de cuarenta años funcionando, el clima de muchas regiones de la Antártida ha dejado de ser un misterio.

La estación meteorológica antártica realiza mediciones tanto por encima como por debajo de la superficie de la nieve. Mide <sup>[2]</sup>:

- La temperatura del aire
- La presión atmosférica
- La humedad atmosférica
- La velocidad del viento
- Dirección del viento
- Radiación solar
- Acumulación de nieve

Una vez captada esta información, se transfiere a una estación mayor, dotada de personal, donde se reciben y procesan los datos. Estos dispositivos funcionan gracias a una batería que se carga mediante un panel solar siempre que el tiempo lo permita.

Sin embargo, las estaciones meteorológicas automatizadas siguen requiriendo un mantenimiento regular cada cierto tiempo. Un especialista debe acudir a cada uno de los lugares en los que se encuentra el dispositivo y comprobar los "signos vitales" de la máquina. Esto se traduce en ciertos gastos, en la necesidad de que los especialistas vayan o se queden en la Antártida, y en el transporte hasta el lugar. Por ello, las empresas y divisiones, como la ADD, están deseosas de actualizar estas estaciones para ayudarles a reducir los costes, mejorar la eficacia, afinar el rendimiento y la precisión, aumentar la esperanza de vida y prolongar el tiempo entre las revisiones de mantenimiento <sup>[4]</sup>. En consecuencia, se logrará un mejor resultado, previsión y comprensión del clima, manteniendo los costes bajos. Esta reducción de costes acabaría probablemente en el crecimiento de esta red de estaciones meteorológicas antárticas que, de nuevo, da una visión más completa del tema.

## 5. *Motivación*

Durante esta última década, el cambio climático y el calentamiento global han ido ganando atención e importancia. Se han propuesto cientos de programas de diferentes gobiernos y empresas para solucionar este asunto o, al menos, para disminuir el ritmo de avance del calentamiento global.

En consecuencia, se ha vuelto imperativo participar en este movimiento contra este peligro inminente. Empresas de todo el mundo se están sumando a él, con la implantación de departamentos ESG (Environmental, Social & Governance) que intentan

llegar a ser Net-Zero en los próximos años. Ya no sólo los beneficios crean el valor de una empresa, sino que también las calificaciones ESG la hacen digna o no.

Por lo tanto, nosotros, como empresa, tenemos que estar a la altura de las expectativas y contribuir al asunto. Al mejorar estas estaciones meteorológicas, la adquisición de conocimientos necesarios para detener el cambio climático se hace más fácil y accesible, lo que esperamos que acabe con el peligro.

## *6. Metodología del proyecto*

Para llevar a cabo el proyecto, hay que seguir una serie de pasos y acciones:

1. Diseños iniciales para la fuente de alimentación digital. Este proyecto se basa en un proyecto menos detallado realizado durante la semana de prácticas en University College London. Durante esta semana, se diseñaron seis modelos diferentes con distintas tensiones de entrada, componentes y disposiciones. Los diseños asumían una libertad total siempre que cumplieran los requisitos utilizando los componentes dados. Dos circuitos con una tensión de entrada inferior a 5V, dos con una tensión superior a 12V, y los dos últimos con una tensión entre 5V y 12V.
2. Simulación de los diseños. Mediante la simulación de estos modelos se obtienen las medidas de tensión, corriente y formas de onda deseadas. De este modo, se realiza una comparación entre los modelos y se descartan los cuatro peores diseños, que o bien no satisfacen los requisitos o bien tienen la combinación de coste-eficiencia más baja.
3. Construcción de los diseños. Los dos diseños restantes se construyeron en el laboratorio y se soldaron en el horno. Para evitar cualquier posible fallo en los procesos de construcción y soldadura por reflujo, se construyeron tres muestras

de cada diseño (durante los procesos de construcción y soldadura por reflujo es probable que se produzcan algunas malas conexiones entre los componentes y la placa de circuito).

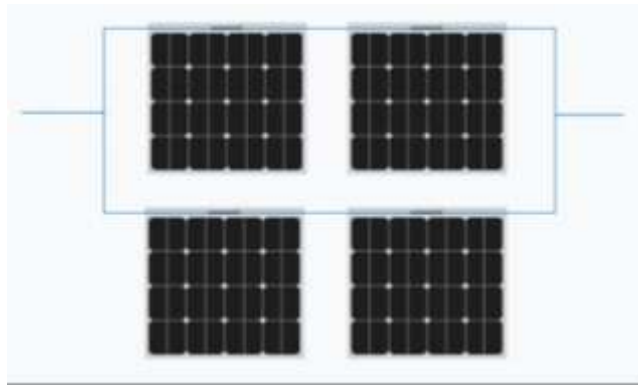
4. Prueba de los modelos de muestra. De las seis muestras, una debe ser elegida para ser el modelo final. Las mediciones de tensión, corriente y formas de onda deseadas se adquieren probando estos modelos. De este modo, se realiza una comparación entre las muestras y se elige la que mejor se ajusta a los requisitos.
5. Diseño de la placa de circuito impreso individual y rediseño de la muestra elegida a partir del escenario de la semana. Los pasos anteriores se realizaron en grupo durante la semana de prácticas. En adelante, los pasos se hicieron de forma individual y constituyen la parte gruesa del proyecto. Dicho esto, se diseña una PCB individual y se rediseña y simula la muestra elegida de la semana de prácticas.
6. Construcción y prueba de los diseños individuales. Siguiendo un proceso similar a los pasos 3 y 4, se construye y se prueba una muestra individual de cada diseño. Se comparan la PCB grupal elegida, su rediseño y la PCB individual y se elige la óptima.
7. Selección de la carga de la batería de energía solar. Una vez elegida la PCB, se selecciona la batería y el panel solar de acuerdo con los requisitos y la tensión de entrada del DPS.
8. Diseño de la carga de la batería de energía solar. Se diseña, simula, construye y prueba el circuito entre el panel solar y la batería de acuerdo con las tensiones y corrientes requeridas.

9. Estudio de costes. Una vez conseguido el diseño final completo, es el momento de analizar el coste por unidad teniendo en cuenta no sólo los componentes sino también el proceso de fabricación y pruebas.
10. Gestión de riesgos. Se identifican los posibles riesgos que puede sufrir el proyecto y se desarrolla un nuevo estudio de costes con el plan de contingencia.

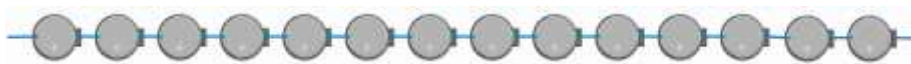
## *7. Resultados*

Una vez construidos y probados todos los PCB, se comparan los resultados de todos ellos. Entre estos, los resultados óptimos son los de la placa grupal construido durante la semana de prácticas. Esta decisión se basa principalmente en la eficiencia global (50,1%) de los resultados y se contrasta con los requisitos de la [Sección de Requisitos](#). De ellos, las restricciones de temperatura se cumplen, la masa y el volumen son adecuados, la eficiencia está por debajo del requisito, las especificaciones de voltaje se cumplen al variar la entrada (que también está dentro del rango permitido), y la corriente de cortocircuito está por debajo del límite en una de las salidas. En cuanto al sistema de carga de la batería, la masa y el volumen están de nuevo por debajo del límite, y se cumplen las limitaciones de tiempo de descarga y carga. Además, se cumplen todos los requisitos físicos relativos a la construcción de la placa de circuito impreso.

El subsistema de carga de la batería está formado por una disposición de paneles solares, un circuito entre el panel y la batería y una configuración de baterías. La disposición de los paneles solares consiste en 4 paneles solares 10 PV Logic conectados en serie-paralelo como se muestra en la Imagen 3. La configuración de la batería consiste en 14 baterías VARTA en serie, como se muestra en la Imagen 4.



*Imagen 3: Disposición de paneles solares formada por 4 PV Logic 10 conectados en serie-paralelo.*



*Imagen 4: Configuración de la batería formada por 14 baterías VARTA en serie.*

Además, el coste unitario para producir 1000 dispositivos teniendo en cuenta el plan de contingencia es de £221,51/dispositivo. El peso y el volumen total del dispositivo son de 6,202kg y  $2,89 \cdot 10^{-3} \text{m}^3$ , respectivamente.

## 8. Conclusiones

Con los resultados anteriores, se puede concluir que se han cumplido casi todos los requisitos. Sin embargo, no se ha cumplido el requisito de eficiencia (parámetro que mide esencialmente el rendimiento).

En cuanto al coste, parece excesivamente elevado y, analizándolo, se observa que los costes variables son mucho mayores. Entre los costes variables, los del panel solar y la batería son los más elevados. Por tanto, habría que estudiar otros componentes alternativos o renegociar el contrato con los proveedores. Si esto no es posible, se podrían desarrollar nuevos diseños para ganar eficiencia y, por tanto, obtener mejores combinaciones de los paneles solares y las baterías.

## 9. Bibliografía

- [1] D. Selviah, "Requirements and Verification", lecture, ELEC0008 module, University College London, 2021.
- [2] "AMRC / AWS -- SSEC", *Amrc.ssec.wisc.edu*, 2018. Accessed: Apr. 06, 2022. [Online]. Available: <http://amrc.ssec.wisc.edu/>.
- [3] "Australian Antarctic Program", *Antarctica.gov.au*, 2022. Accessed: May. 07, 2022. [Online]. Available: <https://www.antarctica.gov.au/>.
- [4] K Vex, *Automated Weather Station In Antarctica - What is it?*. 2022. Accessed: Apr. 04, 2022. [Online]. Available: [https://www.youtube.com/watch?v=jfeJETH\\_TPU](https://www.youtube.com/watch?v=jfeJETH_TPU).

# Design, construction, testing, and debugging of a Digital Power Supply (DPS) for an Antarctic Weather Station

## *1. Problem to solve*

The project rises from a fictitious customer which hires a team of engineers to solve the following problem:

“A series of weather stations are required to be deployed at various remote locations in Antarctica. These unmanned stations will have a two-way radio link with a manned station, and they will make measurements on demand. The station must be small and light enough to be carried to its location by sledge and must operate and be capable of being reprogrammed without maintenance for a period of 15 years” <sup>[1]</sup>.

## *2. Project aims*

Even though the final objective of the project is not the development and design of the entire Antarctic Weather Station due to the lack of resources and time; an optimal model of the digital supply and the battery charging system from the Antarctic weather station is pursued. The development and enhancement of further subsystems of the Antarctic weather station, such as the sensors or the radio link systems, would be the next steps to follow or a possible extension for the project.

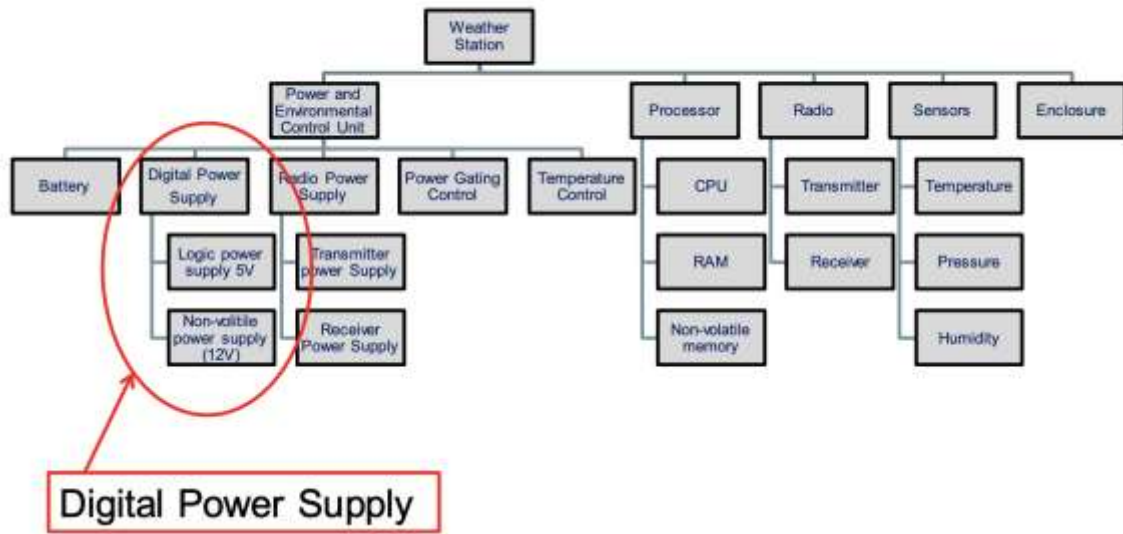
The project's principal aim is the design, construction, testing, and debugging of the DPS and charging system, attempting to improve the aforementioned issues companies are seeking (cost, performance, maintenance time, efficiency...). In particular, the project is born from a fictitious client demand which hires our company to model the DPS which is subject to certain constraints from the client <sup>[1]</sup>. Hence, the resulting design and therefore, an essential objective of the project is to satisfy those requirements.

## *3. Background of the problem*

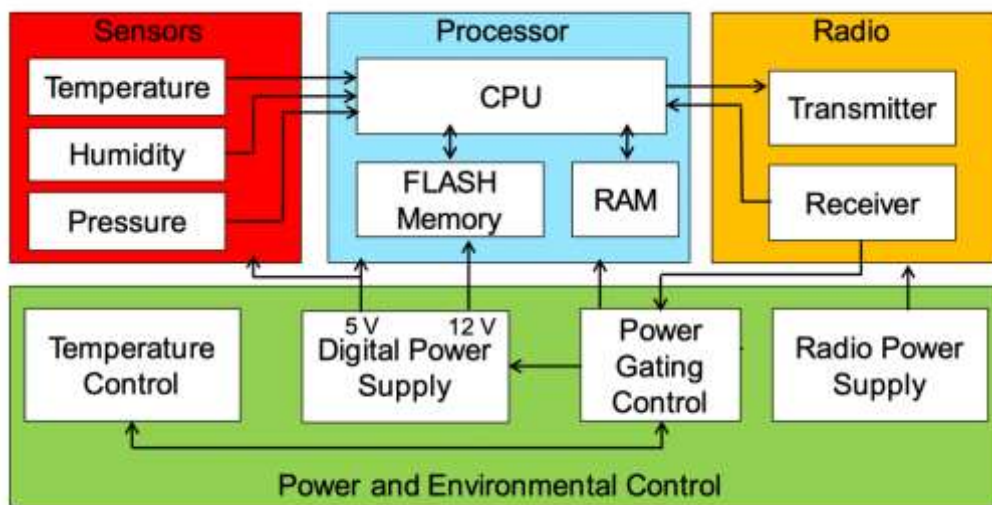
A weather station is composed of several systems as seen in Figure 1. This project specifically consists of the construction of the digital power supply (DPS), its battery supply, and the battery charging system. A more detailed block diagram is shown in



Figure 2, where the relationship between subsystems is represented using arrows.



*Illustration 1: Product breakdown structure for an Antarctic weather station with permission from the publishers of [1].*



*Illustration 2: Schematic block diagram and interfaces of an Antarctic weather station with permission from the publishers of [1].*

The project aims to design, construct, test, and debug a digital power supply subsystem circuit for an Antarctic weather station to closely meet the requirements specification. The power supply should provide two stable DC voltages, 5 V and 12 V which will supply the following modules:

Circuit	Required Voltage (V)		Maximum Current (mA)
	Min	Max	
CPU	4.7	5.3	12
RAM	4.5	5.5	3
Flash Memory	11.2	12.8	20
Sensors	4.85	5.15	5

*Chart 1: Circuits powered from the Digital Power Supply Subsystem.*

The project should document the design and rigorously demonstrate that the requirements have been met. To do so, a system engineering approach should be adopted, and the next documents should be exposed:

- Requirements specification
- Design data such as schematics, layout, component list, etc
- Verification plan
- Manufacturing plan
- Project cost
- Risk management
- Datasheet

The DPS is primarily constituted by a printed circuit board (PCB) that should be designed and built in the laboratory to optimise cost, efficiency, performance, and manpower. The available components for the PCB are exposed in the [List of Components](#).

In order to supply the DPS, a solar panel will be used to charge the battery and achieve the desired source voltage. Hence, the circuit design for solar power to charge the battery must be simulated, and then constructed on a PCB. This circuit should only use components from the aforementioned component list. Moreover, the optimal battery and solar panel should also be chosen from within the list satisfying the further requirements.

The PCB and the battery charging circuit should be the optimal combination of cost, performance, and efficiency, all in one single design that, at the same time, fulfils

the requirements. This report will also describe using a risk matrix the most dangerous steps of the project. Lastly, the report will include an economic study, with a full analysis of the cost both fixed and variable of the device (components, manufacturing, verification...) taking into account the contingency cost in case any of the aforementioned risks take place.

#### *4. State of the question*

Antarctica weather stations are automated devices which capture data from the weather of this inhospitable continent and send this data to professional personnel to be interpreted. The continent-wide Antarctic weather station network provides information for a better understanding of surface meteorology and climatology throughout this continent <sup>[2]</sup>. These devices have been operative since the early 1980's when the Australian Antarctic Division (AAD) placed the first automated weather station <sup>[3]</sup>. These simple stations help meteorologists collect information that creates a climate record in the remote site. This climate record contributes to the development of weather forecasts. In addition, another fundamental function, that nowadays has great relevance and importance, is the understanding of global climate change. Since the Antarctic weather station network has been running for more than forty years, the climate over many regions of Antarctica is no longer a mystery.

An Antarctic weather station takes measurements from both above and below the surface of the snow. It measures <sup>[2]</sup>:

- Air temperature
- Atmospheric pressure
- Atmospheric humidity
- Wind speed
- Wind direction
- Solar radiation
- Snow accumulation

Once this information is captured, it is transferred to a bigger, manned station where the data is received and processed. These devices operate thanks to a battery which is charged by a solar panel whenever the weather allows it.

However, automated weather stations still require some regular maintenance done every certain period of time. A specialist must go to every single site where the device can be found and check the machine's "vital signs". This translates into certain expenses, the need for specialists to go or stay in the Antarctic, and transportation to the site. Therefore, companies and divisions, such as the ADD, are eager to upgrade these stations to help them reduce costs, improve efficiency, sharpen performance and precision, increase life expectancy, and extend the time between maintenance checks <sup>[4]</sup>. Consequently, a better outcome, forecast and understanding of the climate will be achieved while keeping costs low. This cost reduction would likely end up in the growth of this Antarctic weather station network which again gives a more complete insight into the subject.

### *5. Motivation*

During this last decade, climate change and global warming have been gaining attention and importance. Hundreds of programs from different governments and companies have been proposed in order to solve this matter or, at least, to decrease the rate at which global warming is advancing.

Consequently, it has become imperative to participate in this movement against this incoming danger. Companies from all around the world are joining it, with the implementation of ESG (Environmental, Social & Governance) departments which attempt to become Net-Zero in the following years. Not only does profit create a company's value anymore, but also ESG ratings make it worthy or not.

Therefore, we, as a company, have to be up to the expectations and contribute to the matter. By enhancing these weather stations, the required acquisition of knowledge about how to stop climate change becomes easier and more accessible which hopefully will ultimately terminate the peril.

### *6. Project methodology*

To carry out the project, a series of steps and actions have to be followed:

1. Initial designs for the digital power supply. This project is based on a less detailed project carried out during Scenario Week at University College London. During this week, six different models were designed with different

input voltages, components, and arrangements. The designs assumed total freedom as long as they satisfy the requirements using the given components. Two circuits with input voltage below 5V, two with a source above 12V, and the last two with a voltage between 5V and 12V.

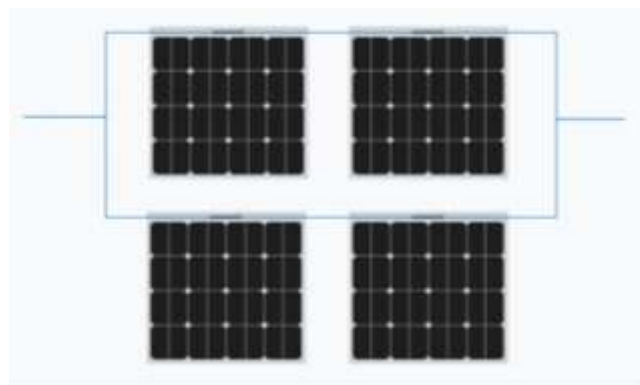
2. Simulation of the designs. The desired voltage, current measurements and waveforms are acquired by simulating those models. This way, a comparison between the models is done and the four worst designs, that either do not satisfy the requirements or have the lowest cost-efficiency combination, are discarded.
3. Construction of the designs. The remaining two designs were built in the laboratory and soldered in the oven. To avoid any possible flaws in the construction and reflow soldering processes, three samples of each design were constructed (during the construction and reflow soldering processes it is likely to get some bad connections between the components and the circuit board).
4. Testing of the sample models. Out of the six samples, one must be chosen to be the final model. The desired voltage, current measurements and waveforms are acquired by testing these models. This way, a comparison between the samples is done and the one that best fits the requirements is chosen.
5. Design of the individual PCB and redesign of the chosen sample from Scenario Week. The previous steps were carried out in a group during Scenario Week. Henceforth, the steps were done individually and constitute the gross part of the project. Having said this, an individual PCB is designed and the chosen sample from Scenario Week is redesigned and simulated.
6. Construction and testing of the individual designs. Following a similar process to steps 3 and 4, a single sample of each design is constructed and tested. The chosen group PCB, its redesign, and the individual PCB are compared and the optimal one is chosen.
7. Solar power battery charging selection. Once the PCB has been chosen, the battery and solar panel are selected in accordance with the requirements and the DPS input voltage.
8. Solar power battery charging design. The circuit between the solar panel and the battery is designed, simulated, constructed, and tested according to the required voltages and currents.

9. Cost study. Once the complete final design is achieved, it is time to analyse the cost per unit taking into account not only the components but also the manufacturing and testing process.
10. Risk management. The possible risks the project may suffer are identified and a new cost study with the contingency plan is developed.

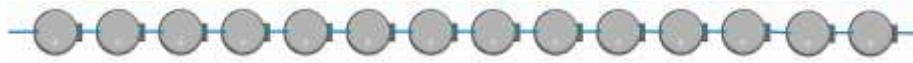
## 7. Results

Once all the PCBs are constructed and tested, the results from all of them are compared. Out of these, the optimal results are from the group PCB constructed during Scenario Week. This decision is based primarily on the overall efficiency (50.1%) of the outputs and is contrasted with the requirements from the [Requirement Section](#). Out of these, the temperature constraints are accomplished, the mass and volume are appropriate, the efficiency is below the requirement, the voltage specifications are accomplished when varying the input (which is also inside the permitted range), and the short circuit current is below the limit in one of the outputs. Regarding the battery charging system, the mass and volume are again below the limit, and the discharging and charging time constraints are fulfilled. All the physical requirements regarding the PCB construction are accomplished.

The battery charging subsystem is formed by a solar panel arrangement, a panel-to-battery circuit, and a battery configuration. The solar panel arrangement consists of 4 10 PV Logic solar panels connected in series-parallel as shown in Illustration 3. The battery configuration consists of 14 VARTA batteries in series as shown in Illustration 4.



*Illustration 3: Solar panel arrangement formed by 4 PV Logic 10 connected in series-parallel.*



*Illustration 4: Battery configuration formed by 14 VARTA batteries in series.*

Furthermore, the unitary cost to produce 1000 devices taking into account the contingency plan is £221.51/device. The total weight and volume of the device are 6.202kg and  $2.89 \cdot 10^{-3} \text{m}^3$ , respectively.

## 8. Conclusions

With the previous results, it can be concluded that almost all the requirements have been fulfilled. However, the efficiency (parameter that essentially measures the performance) constraint has not been accomplished.

Regarding the cost, it seems excessively high and analysing it, it is noted that the recurring costs are much higher. Among the recurring costs, the solar panel and battery costs are the highest. Therefore, other alternative components should be studied or the contract with the suppliers should be renegotiated. If this is not possible, new designs could be developed to gain efficiency and therefore, obtain better combinations of the solar panels and batteries.

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# I. INTRODUCTION

## *1.1. Problem to solve*

The project rises from a fictitious customer which hires a team of engineers to solve the following problem:

“A series of weather stations are required to be deployed at various remote locations in Antarctica. These unmanned stations will have a two-way radio link with a manned station, and they will make measurements on demand. The station must be small and light enough to be carried to its location by sledge and must operate and be capable of being reprogrammed without maintenance for a period of 15 years”<sup>[1]</sup>.

## *1.2. Project aims*

Even though the final objective of the project is not the development and design of the entire Antarctic Weather Station due to the lack of resources and time; an optimal model of the digital supply and the battery charging system from the Antarctic weather station is pursued. The development and enhancement of further subsystems of the Antarctic weather station, such as the sensors or the radio link systems, would be the next steps to follow or a possible extension for the project.

The project's principal aim is the design, construction, testing, and debugging of the DPS and charging system, attempting to improve the aforementioned issues companies are seeking (cost, performance, maintenance time, efficiency...). In particular, the project is born from a fictitious client demand which hires our company to model the DPS which is subject to certain constraints from the client<sup>[1]</sup>. Hence, the resulting design and therefore, an essential objective of the project is to satisfy those requirements.

## *1.3. Background of the problem*

A weather station is composed of several systems as seen in Figure 1. This project specifically consists of the construction of the digital power supply (DPS), its battery supply, and the battery charging system. A more detailed block diagram is shown in

Figure 2, where the relationship between subsystems is represented using arrows.

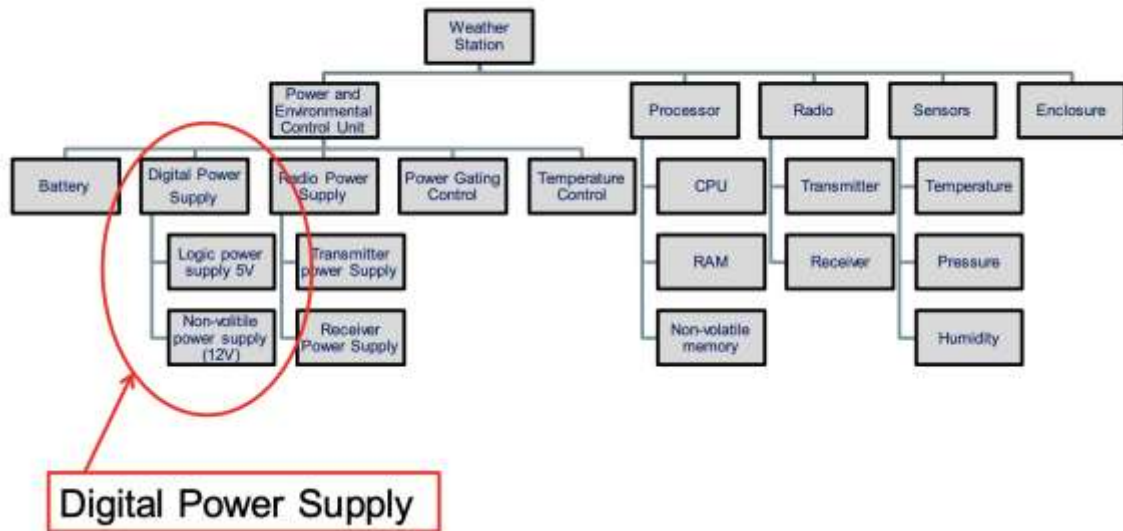


Figure 1: Product breakdown structure for an Antarctic weather station with permission from the publishers of [1].

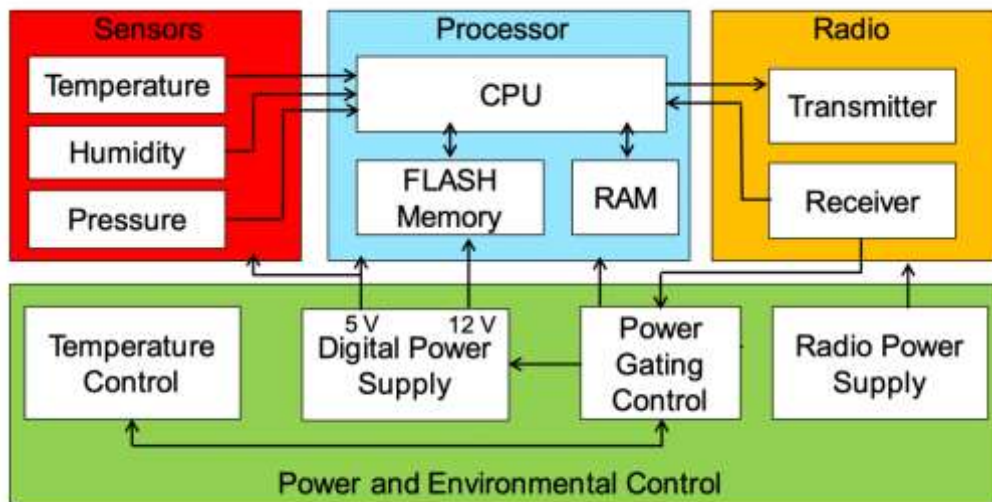


Figure 2: Schematic block diagram and interfaces of an Antarctic weather station with permission from the publishers of [1].

The project aims to design, construct, test, and debug a digital power supply subsystem circuit for an Antarctic weather station to closely meet the requirements specification. The power supply should provide two stable DC voltages, 5 V and 12 V which will supply the following modules:

Circuit	Required Voltage (V)		Maximum Current (mA)
	Min	Max	
CPU	4.7	5.3	12
RAM	4.5	5.5	3
Flash Memory	11.2	12.8	20
Sensors	4.85	5.15	5

*Table 2: Circuits powered from the Digital Power Supply Subsystem.*

The project should document the design and rigorously demonstrate that the requirements have been met. To do so, a system engineering approach should be adopted, and the next documents should be exposed:

- Requirements specification
- Design data such as schematics, layout, component list, etc
- Verification plan
- Manufacturing plan
- Project cost
- Risk management
- Datasheet

The DPS is primarily constituted by a printed circuit board (PCB) that should be designed and built in the laboratory to optimise cost, efficiency, performance, and manpower. The available components for the PCB are exposed in the [List of Components](#).

In order to supply the DPS, a solar panel will be used to charge the battery and achieve the desired source voltage. Hence, the circuit design for solar power to charge the battery must be simulated, and then constructed on a PCB. This circuit should only use components from the aforementioned component list. Moreover, the optimal battery and solar panel should also be chosen from within the list satisfying the further requirements.

The PCB and the battery charging circuit should be the optimal combination of cost, performance, and efficiency, all in one single design that, at the same time, fulfils the requirements. This report will also describe using a risk matrix the most dangerous steps of the project. Lastly, the report will include an economic study, with a full analysis of the cost both fixed and variable of the device (components, manufacturing,

verification...) taking into account the contingency cost in case any of the aforementioned risks take place.

#### *I.4. State of the question*

Antarctica weather stations are automated devices which capture data from the weather of this inhospitable continent and send this data to professional personnel to be interpreted. The continent-wide Antarctic weather station network provides information for a better understanding of surface meteorology and climatology throughout this continent <sup>[2]</sup>. These devices have been operative since the early 1980's when the Australian Antarctic Division (AAD) placed the first automated weather station <sup>[3]</sup>. These simple stations help meteorologists collect information that creates a climate record in the remote site. This climate record contributes to the development of weather forecasts. In addition, another fundamental function, that nowadays has great relevance and importance, is the understanding of global climate change. Since the Antarctic weather station network has been running for more than forty years, the climate over many regions of Antarctica is no longer a mystery.

An Antarctic weather station takes measurements from both above and below the surface of the snow. It measures <sup>[2]</sup>:

- Air temperature
- Atmospheric pressure
- Atmospheric humidity
- Wind speed
- Wind direction
- Solar radiation
- Snow accumulation

Once this information is captured, it is transferred to a bigger, manned station where the data is received and processed. These devices operate thanks to a battery which is charged by a solar panel whenever the weather allows it.

However, automated weather stations still require some regular maintenance done every certain period of time. A specialist must go to every single site where the device can be found and check the machine's "vital signs". This translates into certain expenses, the need for specialists to go or stay in the Antarctic, and transportation to the site.

Therefore, companies and divisions, such as the ADD, are eager to upgrade these stations to help them reduce costs, improve efficiency, sharpen performance and precision, increase life expectancy, and extend the time between maintenance checks <sup>[4]</sup>. Consequently, a better outcome, forecast and understanding of the climate will be achieved while keeping costs low. This cost reduction would likely end up in the growth of this Antarctic weather station network which again gives a more complete insight into the subject.

### *1.5. Motivation*

During this last decade, climate change and global warming have been gaining attention and importance. Hundreds of programs from different governments and companies have been proposed in order to solve this matter or, at least, to decrease the rate at which global warming is advancing.

Consequently, it has become imperative to participate in this movement against this incoming danger. Companies from all around the world are joining it, with the implementation of ESG (Environmental, Social & Governance) departments which attempt to become Net-Zero in the following years. Not only does profit create a company's value anymore, but also ESG ratings make it worthy or not.

Therefore, we, as a company, have to be up to the expectations and contribute to the matter. By enhancing these weather stations, the required acquisition of knowledge about how to stop climate change becomes easier and more accessible which hopefully will ultimately terminate the peril.

### *1.6. Alignment with the Sustainable Development Goals (SDG)*

The sustainable development goals were established in 2015 by the United Nations to be applied in the social, economic, and environmental sectors. The United Nations Development Programme defines these goals to be “a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity” <sup>[5]</sup>. This project aligns with the following UN's proposed goals: 7, 9, and 13.

Goal #7: Affordable and clean energy. The Antarctic Weather Station is powered by a solar panel that charges the battery that serves as the voltage source for the DPS. This solar panel provides the system with green, sustainable, and renewable energy



liberating the source from fuel combustion that would emit detrimental gases to the environment. Furthermore, a better design leads to higher efficiency which ultimately provokes less energy consumption. In addition, it also leads to less maintenance of the Antarctic weather station which means fewer trips from one site to another which are extremely long and so, fuel-consuming.

Goal #9: Industry, Innovation, and Infrastructure. With innovation and investigation, these automated weather stations become less costly and more precise. Consequently, the possibility of constructing these infrastructures in the least developed countries is becoming more feasible. This development would support and enhance human well-being, with affordable and equitable access for all.

Goal #13: Climate action: This last decade (2010-2019) was the warmest one ever recorded. Weather patterns are changing, sea levels are rising, and weather events are becoming more extreme. Humanity is facing a climate emergency and the point of no return is behind the corner. Dealing with all these weather issues and events requires utter comprehension of the matter which can be achieved with the help of these weather stations.

### *1.7. Project methodology*

To carry out the project, a series of steps and actions have to be followed:

11. Initial designs for the digital power supply. This project is based on a less detailed project carried out during Scenario Week at University College London. During this week, six different models were designed with different input voltages, components, and arrangements. The designs assumed total freedom as long as they satisfy the requirements using the given components. Two circuits with input voltage below 5V, two with a source above 12V, and the last two with a voltage between 5V and 12V.
12. Simulation of the designs. The desired voltage, current measurements and waveforms are acquired by simulating those models. This way, a comparison between the models is done and the four worst designs, that either do not satisfy the requirements or have the lowest cost-efficiency combination, are discarded.

13. Construction of the designs. The remaining two designs were built in the laboratory and soldered in the oven. To avoid any possible flaws in the construction and reflow soldering processes, three samples of each design were constructed (during the construction and reflow soldering processes it is likely to get some bad connections between the components and the circuit board).
14. Testing of the sample models. Out of the six samples, one must be chosen to be the final model. The desired voltage, current measurements and waveforms are acquired by testing these models. This way, a comparison between the samples is done and the one that best fits the requirements is chosen.
15. Design of the individual PCB and redesign of the chosen sample from Scenario Week. The previous steps were carried out in a group during Scenario Week. Henceforth, the steps were done individually and constitute the gross part of the project. Having said this, an individual PCB is designed and the chosen sample from Scenario Week is redesigned and simulated.
16. Construction and testing of the individual designs. Following a similar process to steps 3 and 4, a single sample of each design is constructed and tested. The chosen group PCB, its redesign, and the individual PCB are compared and the optimal one is chosen.
17. Solar power battery charging selection. Once the PCB has been chosen, the battery and solar panel are selected in accordance with the requirements and the DPS input voltage.
18. Solar power battery charging design. The circuit between the solar panel and the battery is designed, simulated, constructed, and tested according to the required voltages and currents.
19. Cost study. Once the complete final design is achieved, it is time to analyse the cost per unit taking into account not only the components but also the manufacturing and testing process.
20. Risk management. The possible risks the project may suffer are identified and a new cost study with the contingency plan is developed.

## *I.8. Resources*

- Laboratory material:
  - Oscilloscope, DC voltage source, signal generator...
  - Circuit board
  - Components list
- Software:
  - Multisim (Version 14.3.0): Circuit design
  - DipTrace (Version 4.3): PCB layout
  - MATLAB\_R2021a
- PC:
  - MacBook Pro
  - CPU: Apple M1 Chip, 8-core CPU with 4 performance cores and 4 efficiency cores
  - GPU: 8-core
  - 16 GB RAM
  - Operating system: macOS Monterey

## II. REQUIREMENTS

The following requirements shall be met to arrange both the solar-panel-to-battery charging system and the DPS. These requirements consist of both functional and physical restrictions for the operation and construction of the system. Some of these constraints were given by the question of the Scenario Week, some were completed, and others were added. The given requirements are marked with \*.

1. The Antarctic Weather Stations shall survive and operate in temperatures down to -70 °C and when covered in snow/ice.
  - a. The Power and Environmental Control Unit (PECU) shall always maintain the temperature within the enclosure above -40 °C.
    - i. \*The digital power supply shall not suffer damage at temps down to -40 °C.
      1. Electronic components shall have a minimum storage temperature < -40 °C.
    - ii. The panel-battery charging system shall not suffer damage at temps down to -40 °C.
      1. Electronic components shall have a minimum storage temperature < -40 °C.
  - b. The PECU shall maintain the temperature within the enclosure above 0 °C when the processor and sensors are operating.
    - i. \*The DPS shall maintain the voltage output specifications over a temperature range of at least 0 – 70 °C.
      1. Electronic components shall have an operating temperature range of at least 0 – 70 °C.
    - ii. The panel-battery charging system shall maintain the voltage output specifications over a temperature range of at least 0 – 70 °C.
      1. Electronic components shall have an operating temperature range of at least 0 – 70 °C.
2. \*The Antarctic Weather Station shall operate from a single battery for 15 years.
3. \*The Antarctic Weather Station shall have a mass of <10 kg and a volume of <1 m<sup>3</sup>.

- a. \*The DPS shall have a mass of no more than 25 g including PCB and components (without the leads).
  - b. \*The total weight of the battery and solar panel should be within 10 kg.
4. The Antarctic Weather Station shall have certain performance requirements.
- a. \*The DPS shall have a power efficiency  $>60\%$  with a 20 mA load current on either of the two outputs.
  - b. \*The DPS shall operate with a single voltage input from 0 to 30V. The input shall not be within  $\pm 10\%$  of either of the output voltages (5 V and 12 V).
  - c. \*The DPS shall have a 5V output.
    - i. The DPS shall provide voltage to the CPU, RAM, and sensors in the circuit; and drive them to work. The minimum voltage of the three components is 4.85 V (for the sensors to start working) and the maximum voltage is 5.15 V (for the sensors to not be damaged). Any voltage not in the range of 4.85 V to 5.15 V does not meet the output voltage requirements. Hence, the voltage and current specification of the 5 V output shall provide  $5 \pm 0.15$  V with current loads varying from 0 to 12 mA of CPU, from 0 to 5 mA of sensors, and from 0 to 3 mA of RAM.
  - d. \*The DPS shall have a 12 V output.
    - i. The DPS shall provide voltage to the flash memory in the circuit and drive it to work. The minimum voltage of the flash memory components is 11.2 V (to start working) and the maximum voltage is 12.8 V (not to be damaged). Any voltage not in the range of 11.2 V to 12.8 V does not meet the output voltage requirements. Hence, the voltage and current specification of the 12 V output shall provide  $12 \pm 0.8$  V with current loads varying from 0 to 20 mA.
  - e. \*The DPS shall maintain voltage specifications with an input voltage  $\pm 20\%$  from nominal.
  - f. \*The DPS shall generate a maximum output current of 30 mA under a short circuit condition on either output.
  - g. \*The battery shall be able to support the designed DPS and the circuit supplied for at least 12 hours, where the DPS provides 20 mA on both the 5 V and the 12 V outputs.
  - h. \*The battery charger shall charge the battery within 4 hours.

5. The Antarctic Weather Station shall have certain shape and form requirements.
  - a. \*The board dimensions of the PCB shall be a square of 4.5 cm x 4.5 cm or less (not odd shapes).
  - b. The PCB shall have certain design requirements to be manufactured with the available equipment in the laboratory.
    - i. \*Hole and pad diameter: vias must be 0.8 mm and copper pad 1.6 mm, holes for attachment of wires or test pins must be 1.0 mm with the copper pad of 1.8mm.
    - ii. \*Track width: Minimum 0.4 mm.
    - iii. \*Track to track/Track to pad separation: Minimum 0.4 mm.
    - iv. \*Copper pour spacing: 1 mm.
    - v. \*Track/Via/Pad to board edge separation: No tracks within 2 mm of edge.
  - c. \*The DPS shall have test pins for the output voltages.
  - d. \*The DPS shall have flying leads for the connection to the battery.
6. \*The Antarctic Weather Station shall have 2-way radio communications in the 1.8 GHz frequency band with a range of 500 km.
7. The Antarctic Weather Station shall be non-polluting.
8. The Antarctic Weather Station shall be capable of making measurements up to 12 times per day.
9. The Antarctic Weather Station shall be capable of working under extreme natural disasters, such as blizzards, avalanches, glacial melting, crustal shaking, etc.
10. The Antarctic Weather Station of manpower, efficiency, and cost optimization should be considered simultaneously.

### III. DIGITAL POWER SUPPLY PCBs

In this section, the design, debugging, manufacturing, and testing process of the printed circuit boards for the digital power supply will be discussed. It is crucial to distinguish between a prototype and the final product. Prototypes go through much more exhaustive testing called Verification Plan whereas final products go through less detailed and complete testing called Manufacturing Plan. The PCB manufacturing process follows certain steps that promote the better performance of the device. First of all, an initial model in Multisim is developed where the different performance requirements from the [Requirement List](#) shall be met using the available components from the [Component List](#). Then, a PCB layout is carried out in DipTrace where the different physical requirements shall be met. Furthermore, once the PCB is constructed, it is time to build it by adding and soldering the components. Finally, when the PCB construction is finished, both prototypes and final products are tested following the Verification Plan and Manufacturing Plan, respectively, where different parameters are measured, and the results are compared to the theoretical ones. These tests are carried out to assure the safety and correct performance and quality of the product.

#### *III.1. Multisim's simulation*

Three different PCBs will be discussed in this part: the first one is from the group scenario from the UCL Design and Professional Practice 2 module from which this project has been extracted and extended; the second one is a reconstruction of the aforementioned as the former was not available after the Scenario Week that took place from the 22<sup>nd</sup> of February to the 26<sup>th</sup> of February 2022; finally, the design and testing of an individual PCB (not a group design) are also examined. The Multisim model from the former and the second PCB is exposed in Figure 3 while the latter is in Figure 4.

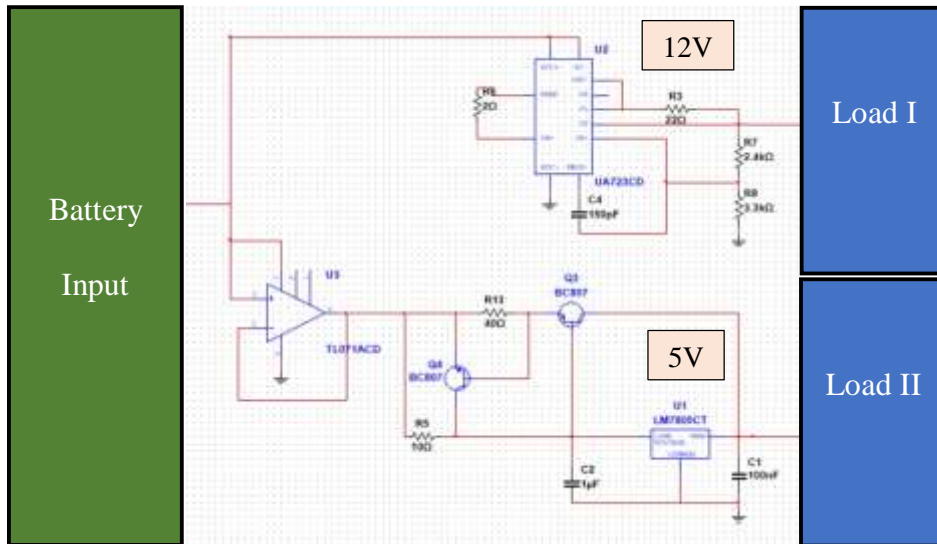


Figure 3: Multisim model from both the group DPS PCB and its reconstruction.

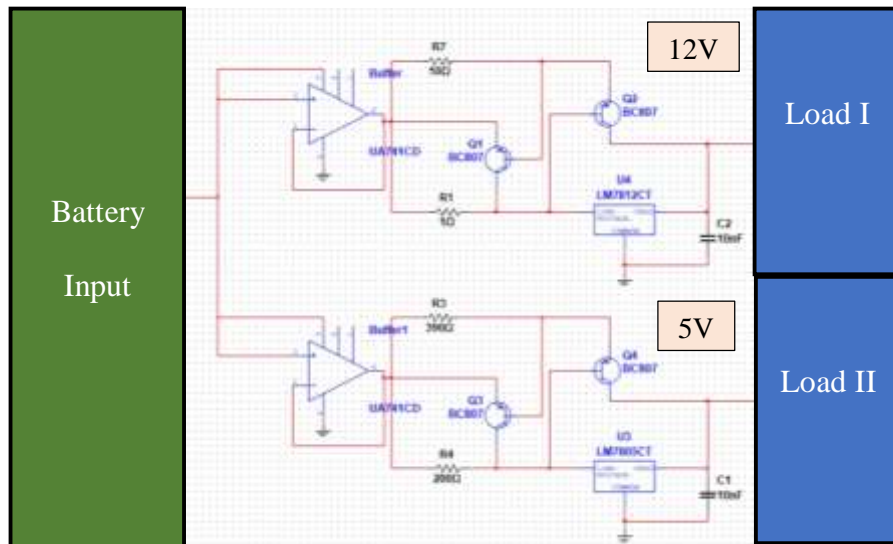


Figure 4: Multisim model from the individual DPS PCB.

To ensure [Requirement 4.a](#) is met, the loads must be the necessary to supply 20mA in both of the outputs. Therefore, to obtain those resistance values, Ohm's law is used as shown in Eq. 1.

Eq. 1

$$R_{Load} = \frac{V_{Output}}{I_{Output}} \Rightarrow$$

$$\Rightarrow R_{Load} = \frac{5}{20 \cdot 10^{-3}} = 250\Omega \quad \& \quad \Rightarrow R_{Load} = \frac{12}{20 \cdot 10^{-3}} = 600\Omega$$



However, these resistances should be adjusted to the available resistors from the [Component List](#). For the 5V output, an exact resistance value can be achieved by using a 100 $\Omega$  and a 150 $\Omega$  resistor in series adding up to 250 $\Omega$ . For the 12V output, resistors of 560 $\Omega$  and 39 $\Omega$  are connected in series to obtain a resistance of 599 $\Omega$ . Three different possibilities arise when setting the input voltage: from 0V to 5V, from 5V to 12V, and over 12V. Different designs for these possibilities were carried out during the group scenario, and the discussed design with an input voltage over 12V was selected over the alternative designs due to performance, cost, and precision criteria. This design offered higher precision and performance while keeping the cost down and fulfilling all the requirements. The input voltage must also meet the conditions of [Requirement 4.b](#), and therefore, should be higher than 13.2V and below 30V. Furthermore, following [Requirement 4.g](#), the DPS must supply outputs of 12V and 5V with a current load of 20mA.

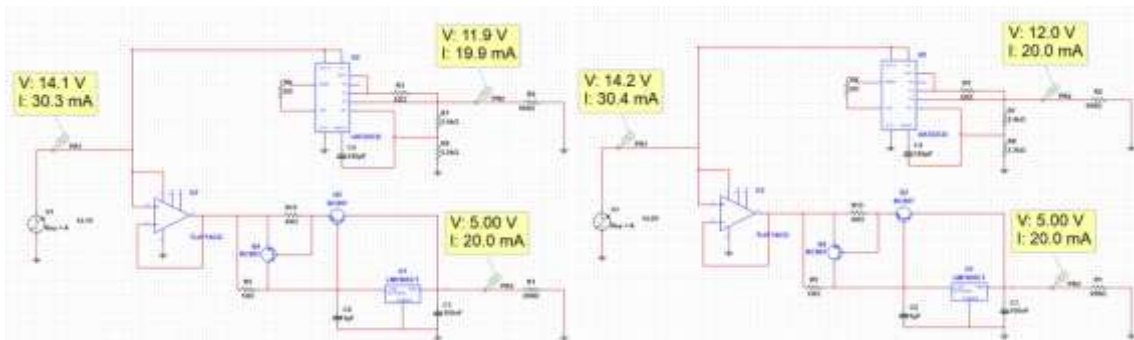


Figure 5: Loaded group DPS Multisim simulations to obtain 12V 20mA output.

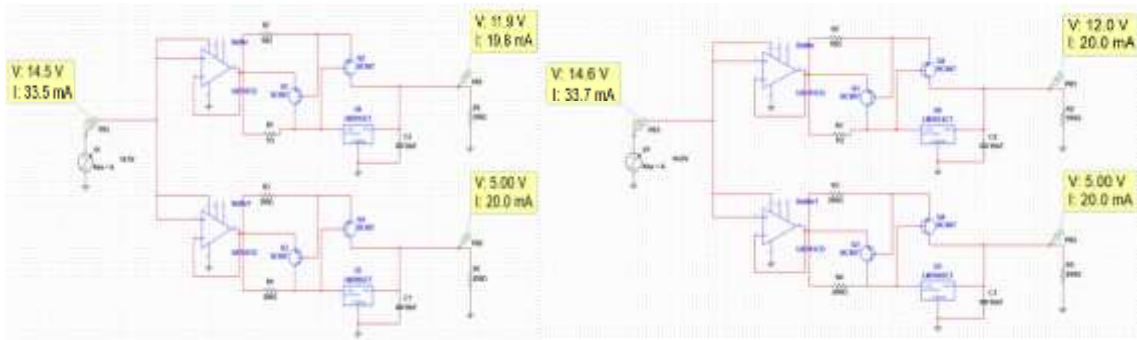


Figure 6: Loaded individual DPS Multisim simulations to obtain 12V 20mA output.

It has been seen in the Multisim simulations from Figure 5 and Figure 6, that the group DPS needs at least a 14.2V supply voltage and the individual DPS needs 14.6V to satisfy the aforementioned requirement. However, considering [Requirement 4.d.i](#), the DPS must be able to supply, at least, 11.2V to follow voltage specifications. Consequently, we need to find the input voltage at which the output is 11.2V.

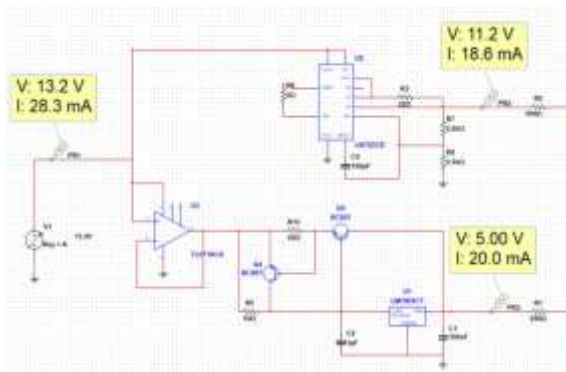


Figure 7: Loaded group DPS simulation to obtain an output voltage of 11.2V.

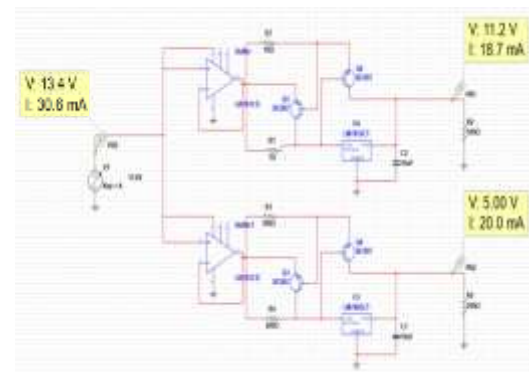


Figure 8: Loaded individual DPS simulation to obtain an output voltage of 11.2V.

As seen in Figure 7 and Figure 8, an 11.2V voltage is obtained when the input supplies 13.2V for the group DPS and 13.6V for the individual DPS. Furthermore, considering [Requirement 4.e](#), the voltage specifications shall be maintained when the

input voltage varies from +/-20% from the nominal voltage. Hence, we can declare that the nominal output voltage must be at least:

$$\begin{aligned}
 \text{Eq. 2} \quad V_N &= \frac{V(V_{In}=11.2V)}{(1-0.2)} \Rightarrow \\
 \Rightarrow V_{N_{GR}} &= \frac{13.2}{1-0.2} = 16.5V \\
 \Rightarrow V_{N_{IND}} &= \frac{13.4}{1-0.2} = 16.7V
 \end{aligned}$$

Having said that, the exact value of the input voltages for the DPS is set to be 16.7V. The reason behind this value will be explained later in the paper, as it depends on the battery configuration that supplies the DPS which is explained in the Battery Selection section. With those values and simulating the model in Multisim, the current and voltage values from Figure 9 and Figure 10 are obtained:

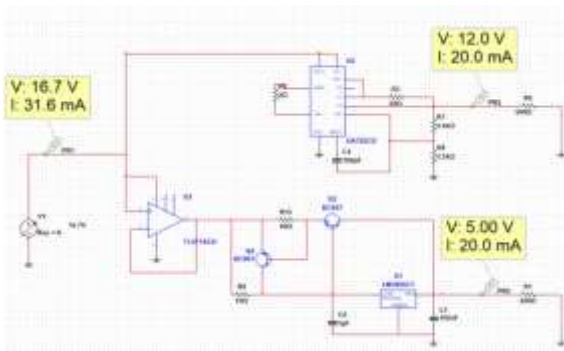


Figure 9: Multisim simulation of the group DPS at 20mA loaded outputs.

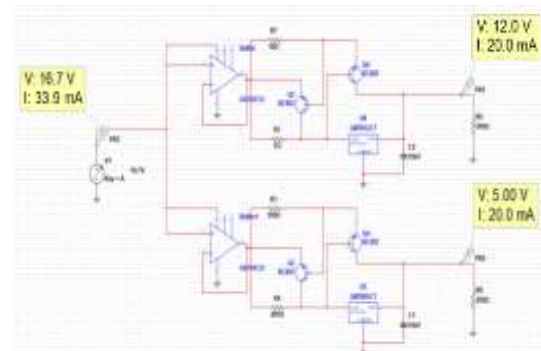


Figure 10: Multisim simulation of the individual DPS at 20mA loaded outputs.

The overall efficiency can now be calculated using the output power divided by the input power. This efficiency, as stated in the requirements, shall be higher than 60% when loaded at this current. Using Eq. 3, we obtain the following values:

$$\begin{aligned}
 \text{Eq. 3} \quad \eta &= \frac{P_{Output}}{P_{Input}} \Rightarrow \eta = \frac{V_{5V} \cdot I_{5V} + V_{12V} \cdot I_{12V}}{V_{Input} \cdot I_{Input}} \\
 \Rightarrow \eta &= \frac{(5 \cdot 20 + 12 \cdot 20) \cdot 10^{-3}}{16.7 \cdot 31.6 \cdot 10^{-3}} = 64.4\% & \Rightarrow \eta = \frac{(5 \cdot 20 + 12 \cdot 20) \cdot 10^{-3}}{16.7 \cdot 33.9 \cdot 10^{-3}} \\
 &= 60.1\%
 \end{aligned}$$

As it can be seen, the overall efficiencies does fulfil the performance constraint from [Requirement 4.a](#). In addition, despite the fact that we can presume that, with a higher voltage than the aforementioned 16.5V (group DPS) and 16.7V (individual DPS), the voltage specifications will still be met, a simulation with +20% of the nominal input voltage (+20% 16.7V = 20.0V) is modelled. As it can be seen in Figure 11 and Figure 12, the result was well predicted and, therefore, it complies with [Requirement 4.e](#).

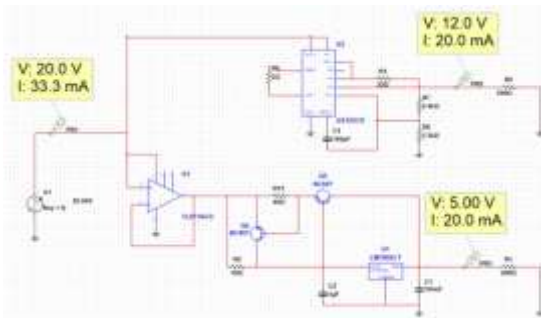


Figure 11: Multisim simulation of the group DPS with an input voltage of 20.0V (+20%).

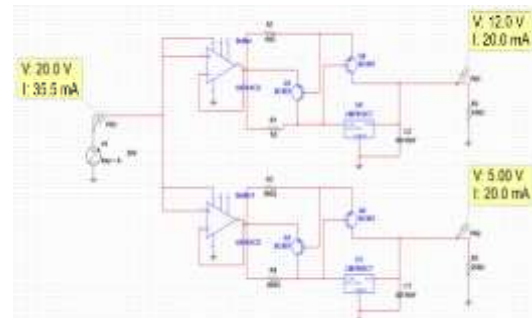


Figure 12: Multisim simulation of the individual DPS with an input voltage of 20.0V (+20%).

Finally, [Requirement 4.f](#) shall be met and the output current shall not be over 30mA under a short-circuit condition on either output. This condition is simulated, and the favourable results are shown in Figure 13 and Figure 14:

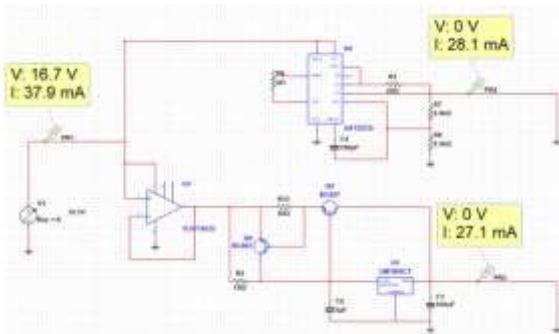


Figure 13: Multisim simulation of the group

DPS at short-circuit condition.

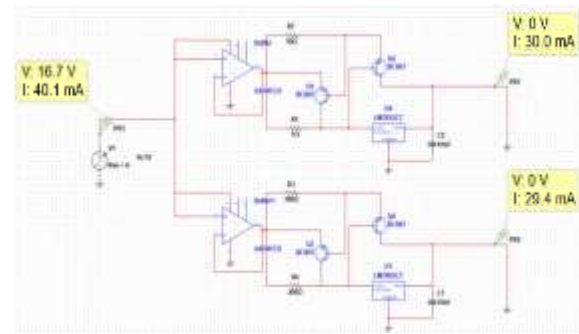


Figure 14: Multisim simulation of the individual

DPS at short-circuit condition.

### III.2. DipTrace layout

Once the simulations in Multisim have proved the design meets the performance requirements, a PCB layout is carried out using DipTrace. The layout must follow certain design requirements to facilitate the construction and favour a better performance of the PCB. These requirements ([Requirement 5.a](#) and [Requirement 5.b](#)) consist of shape, width, and distance separation constraints. In the case of the former requirement, it is a matter of reducing the needed material and not complicating the construction (not odd shapes). The latter is a matter of easing the construction to whoever is building the board by requiring less precision which may be a necessity due to the lack of highly advanced technology which may cause imperfections that, for example, might produce undesired short circuits. Having said this, the PCB layout is developed for the group PCB done during Scenario Week. Hereafter, the DipTrace layout and its respective physical form are shown in Figure 15 and Figure 16. When the PCB is physically constructed, all the lines must be checked to assure proper connection. To do so, a multimeter is used in continuity mode.

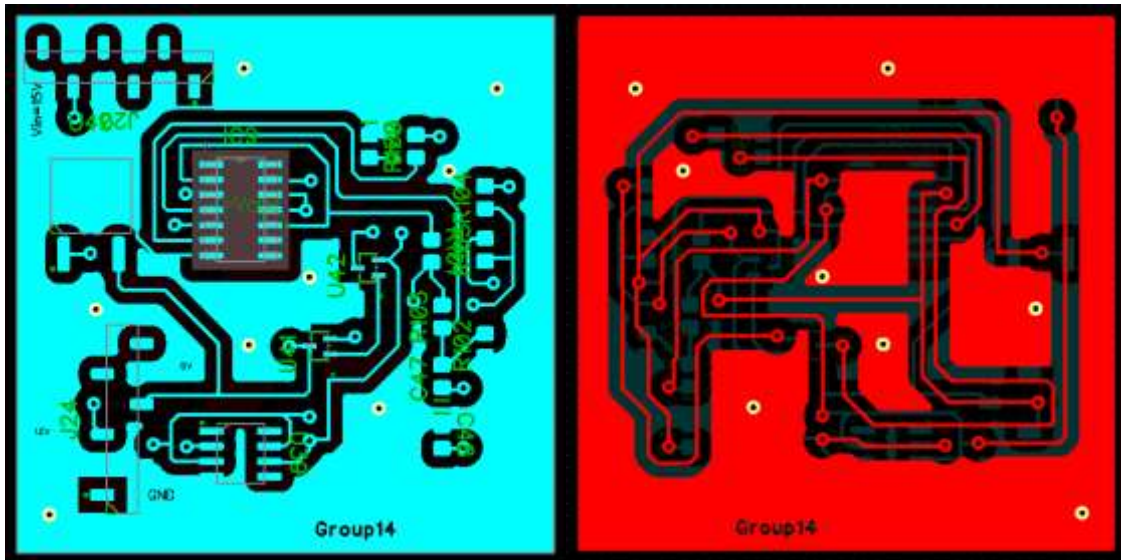


Figure 15: Group PCB layout from Scenario Week. Top view on the left and bottom view on the right.

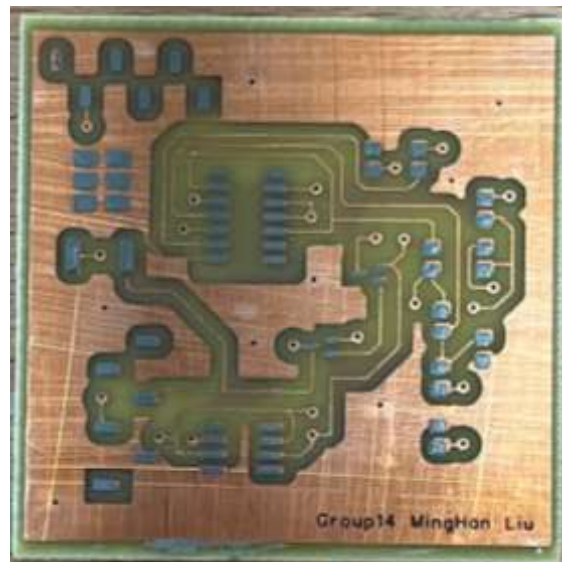
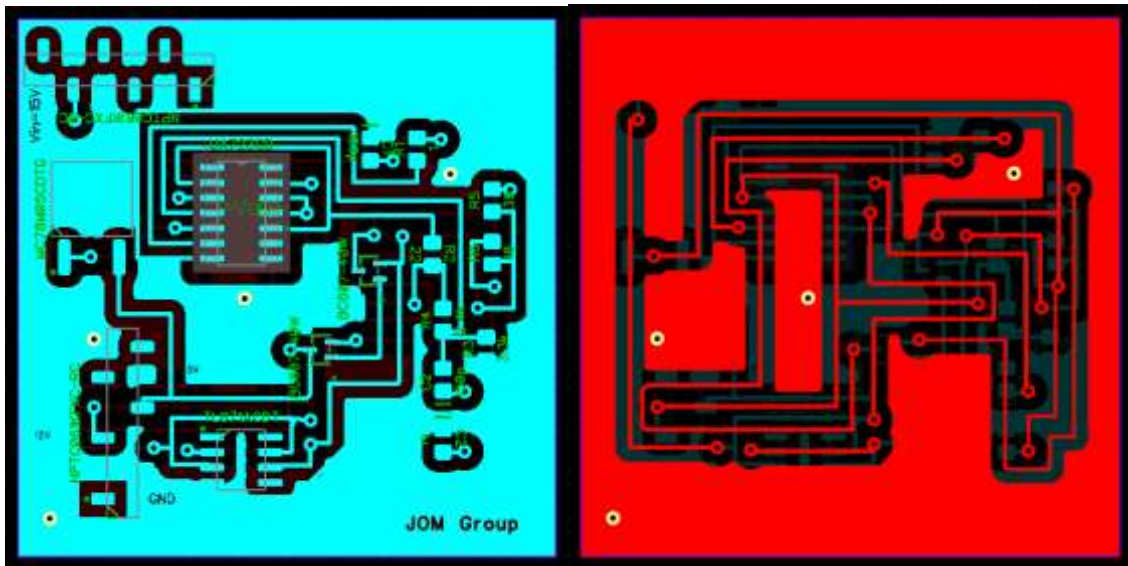


Figure 16: Top view of the built group PCB from the Scenario Week.

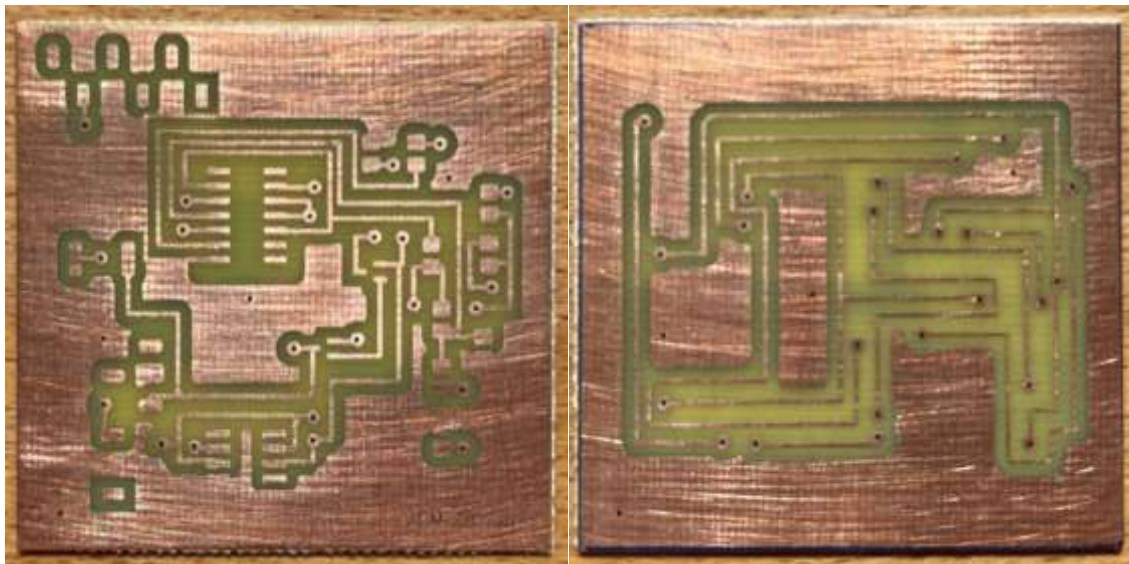
This layout design (Figure 15) was then enhanced for the second PCB as, despite meeting the requirements, some improvements were doable. These consist of eliminating any unnecessary unconnected copper islands (observed in the bottom view), eliminating any oblique lines that might harden the work or worsen the connectivity, increasing the line widths to avoid any connectivity problems, and other aesthetic changes such as



symmetry of components... The resulting layout and printed circuit board can be seen in Figure 17 and Figure 18.



*Figure 17: Enhanced PCB layout from the group DPS from Scenario Week. Top view on the left and bottom view on the right.*



*Figure 18: Enhanced built PCB from the group DPS from Scenario Week. Top view on the left and bottom view on the right.*

For the third and final printed circuit board (individual DPS design), the following layout was designed (Figure 19). It is already out of any oblique lines, out of any

unnecessary copper islands, and it follows the respective requirements. The built printed circuit board is exposed in Figure 20.

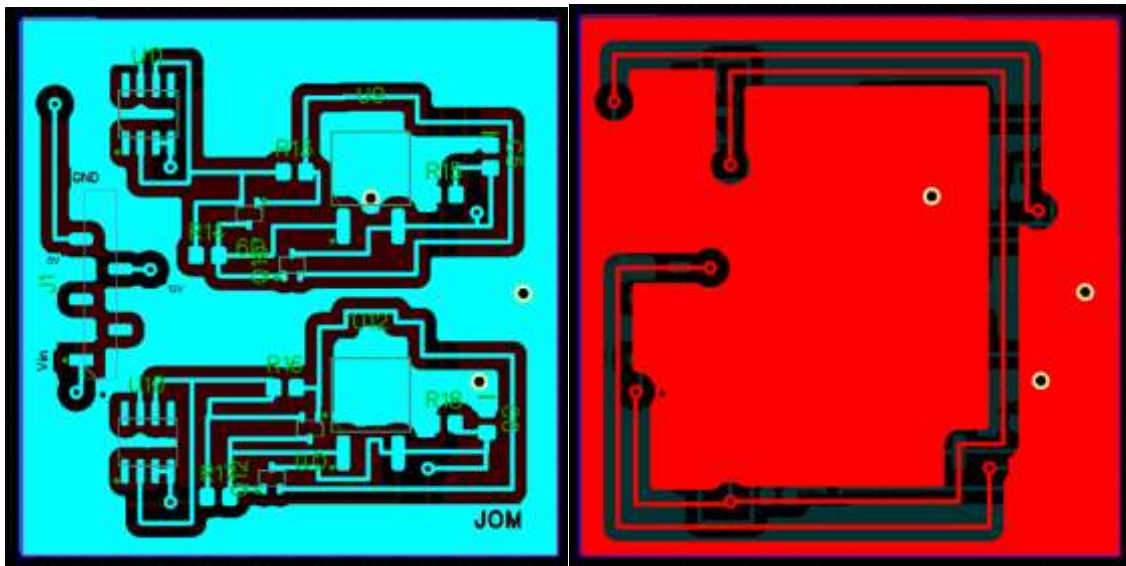


Figure 19: PCB layout from the individual DPS. Top view on the left and bottom view on the right.

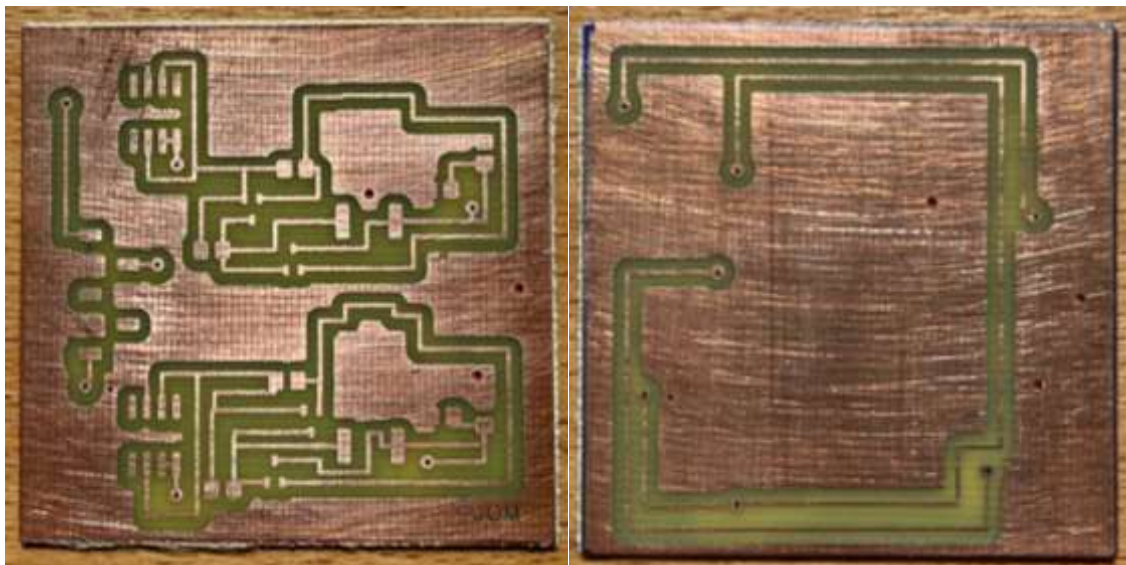


Figure 20: Built PCB from the individual DPS. Top view on the left and bottom view on the right.

### III.3. Population of the PCBs

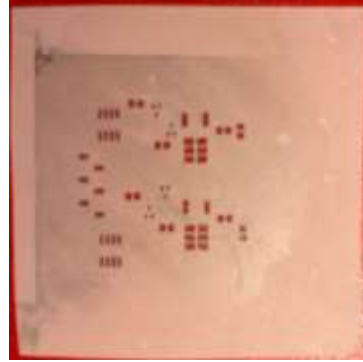
Then, once the boards have been constructed, the population is carried out. To do so, a stencil is needed to guarantee precision in the soldering process. A PCB stencil is a



thin sheet of material with laser-cut openings used to solder paste on PCB for a surface mount component population [6]. Each design requires a different stencil as exposed in Figure 21, Figure 22, and Figure 23.



*Figure 21: Stencil from the initial group DPS.*

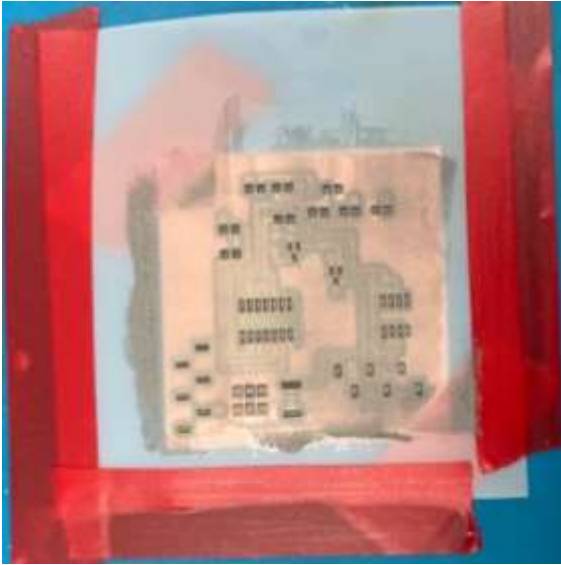


*Figure 22: Stencil from the reconstructed group DPS.*

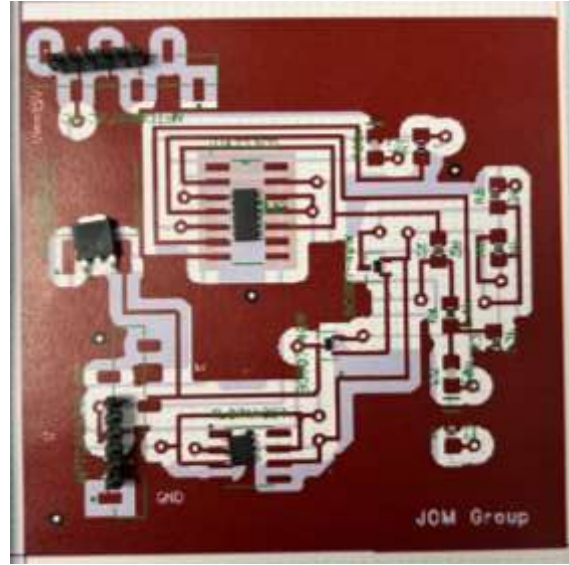


*Figure 23: Stencil from the individual DPS.*

The stencil is accurately placed on top of the PCB and a thin layer of solder paste is added to the stencil (Figure 24). It is crucial to have distinguished the components and have them sorted out (as shown in Figure 25) as the solder paste dries in about 20 to 30 minutes.



*Figure 24: Solder paste added to the stencil that covers the PCB.*

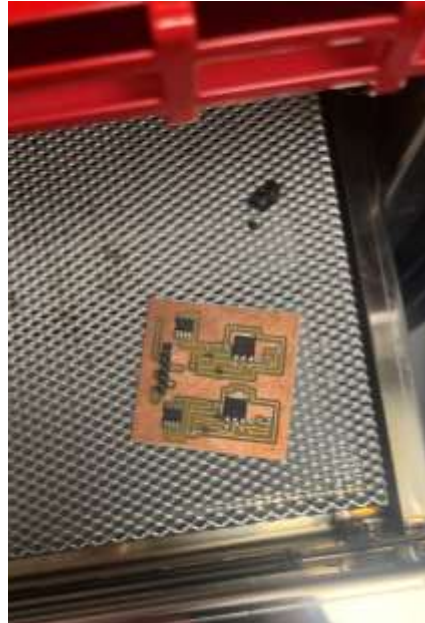


*Figure 25: Pre-placement of the components on a sketch of the PCB.*

In case there has not been time to place all the components, a dissolvent shall be used, the paste shall be wiped out, and the process shall be repeated. Once the solder paste is added to the PCB, the components are placed, and the device is deposited in the furnace (Figure 26 and Figure 27). When the components are finally soldered, the connection between pins and lines must be checked to assure the components have been properly soldered. Again, a multimeter is used in continuity mode.



*Figure 26: Furnace used to solder the components onto the PCB.*



*Figure 27: Individual PCB deposited in the furnace before soldering.*

#### *III.4. Verification Plan of the DPS*

After the population and soldering of the PCBs (Figure 28, Figure 29, and Figure 30), the prototypes follow the Verification Plan in order to guarantee they still meet the requirements as, despite having proven it in the simulations, results change when testing in practice (compared to theoretical results). This plan consists of certain tests that assure proper performance. First of all, the DPS must not suffer damage at temps down to  $-40^{\circ}\text{C}$  ([Requirement 1.a.i.1](#)) and must maintain voltage specifications at a temperature range of  $0 - 70^{\circ}\text{C}$  ([Requirement 1.b.i.1](#)); therefore, all the selected components have a minimum storage temperature of at least  $-40^{\circ}\text{C}$  and an operating temperature range of at least  $0 - 70^{\circ}\text{C}$ . Note that a test on how the DPS physically responds to temperature and long-lasting operations (12 hours run) should have been done. However, due to lack of equipment and time these tests have not been carried out.



Figure 28: Populated PCB  
from the initial group DPS.

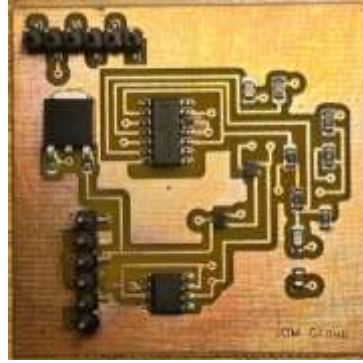


Figure 29: Populated PCB  
from the reconstructed group  
DPS.



Figure 30: Populated PCB  
from the individual DPS.

#### a. Initial group DPS

The results from the testing of the initial group PCB carried out during Scenario Week are the following. To ensure [Requirement 4.a](#) is met, the loads must be the necessary to supply 20mA in both of the outputs. As it was aforementioned, the available resistors to test the 20mA condition are  $560\Omega$  in series with  $39\Omega$  for the 12V output and  $250\Omega$  for the 5V output. Regardless of being in the component list, there were not any  $250\Omega$  resistors in the laboratory (an example of how theory and practice may differ) and therefore,  $100\Omega$  and  $150\Omega$  resistors were used (in series). The DPS was tested using the same configuration as in Figure 9 with an input voltage of 16.7V. The results are the following:

	Voltage (V)	Current (mA)
Input	16.7	40.0
5V output	4.98	20.0
12V output	11.9	19.8

Table 3: Voltage and current results from the initial group DPS at 20mA output.

The input current is much higher than in the simulation (26.6% higher); therefore, the efficiency will suffer a considerable reduction. With the previous values and using Eq. 3, an efficiency of 50.1% is obtained. Then, considering [Requirement 4.c.i](#) and [Requirement 4.d.i](#), a resistor of  $420\Omega$  is needed for the 5V output to obtain a current of 12mA (using Eq. 1 – Ohm’s law) and, again, a resistor of  $599\Omega$  for the 12V output to obtain a current of 20mA. In order to form the  $420\Omega$  resistance, a resistor of  $390\Omega$  in series with  $27\Omega$  ( $417\Omega$ ) are needed. However, despite appearing in the component list, resistors of  $27\Omega$  were not available at the laboratory. Thus, resistors of  $12\Omega$  and  $15\Omega$  were used in exchange. In Table 4, the voltage and current in this condition are exposed.

	Voltage (V)	Current (mA)
Input	16.7	35.3
5V output	4.98	12.0
12V output	11.9	19.8

Table 4: Voltage and current from the initial group DPS at 20mA and 12mA output.

Then, regarding [Requirement 4.e](#), when the DPS is brought under +/-20% input voltage conditions, it shall still maintain voltage specifications. The voltage outputs when the input voltage is 13.4V and 20.0V are shown in Table 5.

	-20% (V)	+20% (V)
5V output	4.97	4.99
12V output	11.3	12.6

Table 5: Voltage from the initial group DPS at a +/-20% input voltage.

Finally, considering [Requirement 4.f](#), the output current must be under 30mA on either output. This constraint shall be met under short-circuit conditions. The results are exposed in Table 6.

	Current (mA)
5V output	32.6
12V output	26.3

Table 6: Output current of the initial group DPS under short-circuit conditions.

Once the PCB has been constructed and tested, it is time to calculate its weight considering [Requirement 3.a](#). Using a scale, the mass of the populated board is 6g (5g before population). Another magnitude to consider is the volume as the complete device must be  $<1\text{m}^3$  ([Requirement 3](#)). Using a ruler, we obtain the DPS's size is 4.5cm x 4.5 cm x 1cm which is  $20.25\text{cm}^3$  ( $2.03 \cdot 10^{-5}\text{m}^3$ ).

*b. Reconstructed group DPS*

The results from the testing of the reconstructed group PCB carried out individually much later than the Scenario Week. To ensure [Requirement 4.a](#) is met, the loads must be the necessary to supply 20mA in both of the outputs. The DPS was tested using the same configuration as in Figure 9 with an input voltage of 16.7V. The results are the following:

	Voltage (V)	Current (mA)
Input	16.7	44.0
5V output	4.98	19.9
12V output	12.4	20.9

Table 7: Voltage and current results from the reconstructed group DPS at 20mA output.

The input current is much higher than in the simulation (39.2% higher); therefore, the efficiency will suffer a considerable reduction. With the previous values and using Eq. 3, an efficiency of 48.8% is obtained. Then, considering [Requirement 4.c.i](#) and [Requirement 4.d.i](#), a resistor of  $420\Omega$  is needed for the 5V output to obtain a current of 12mA (using Eq. 1 – Ohm’s law) and, again, a resistor of  $599\Omega$  for the 12V output to obtain a current of 20mA. In Table 8, the voltage and current in this condition are exposed.

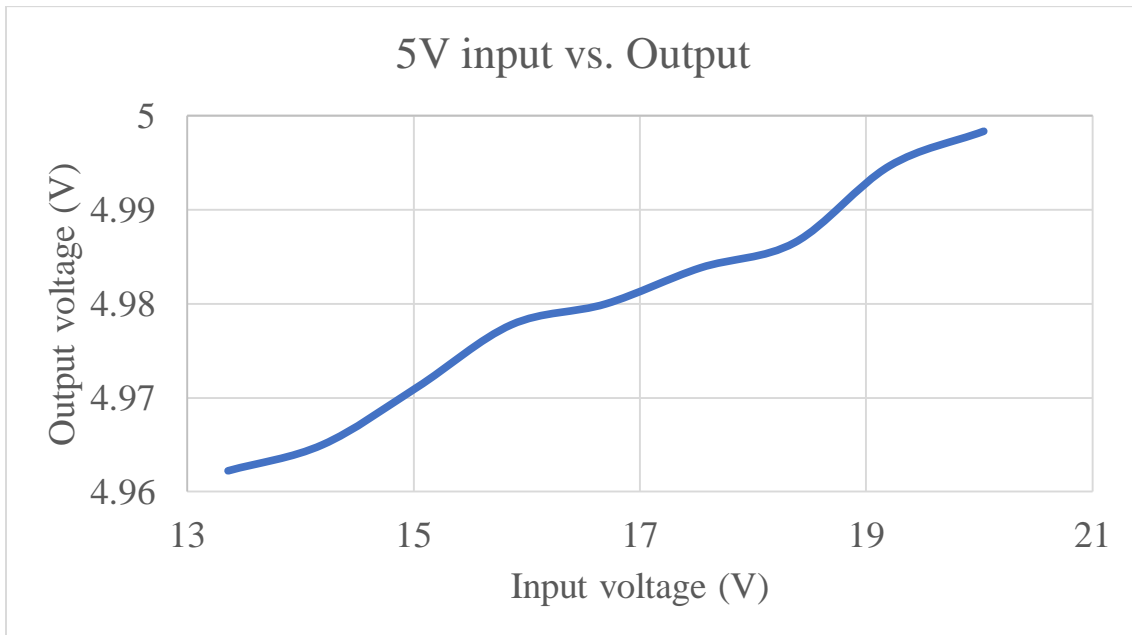
	Voltage (V)	Current (mA)
Input	16.7	39.1
5V output	4.98	12.0
12V output	12.4	20.8

Table 8: Voltage and current from the reconstructed group DPS at 20mA and 12mA output.

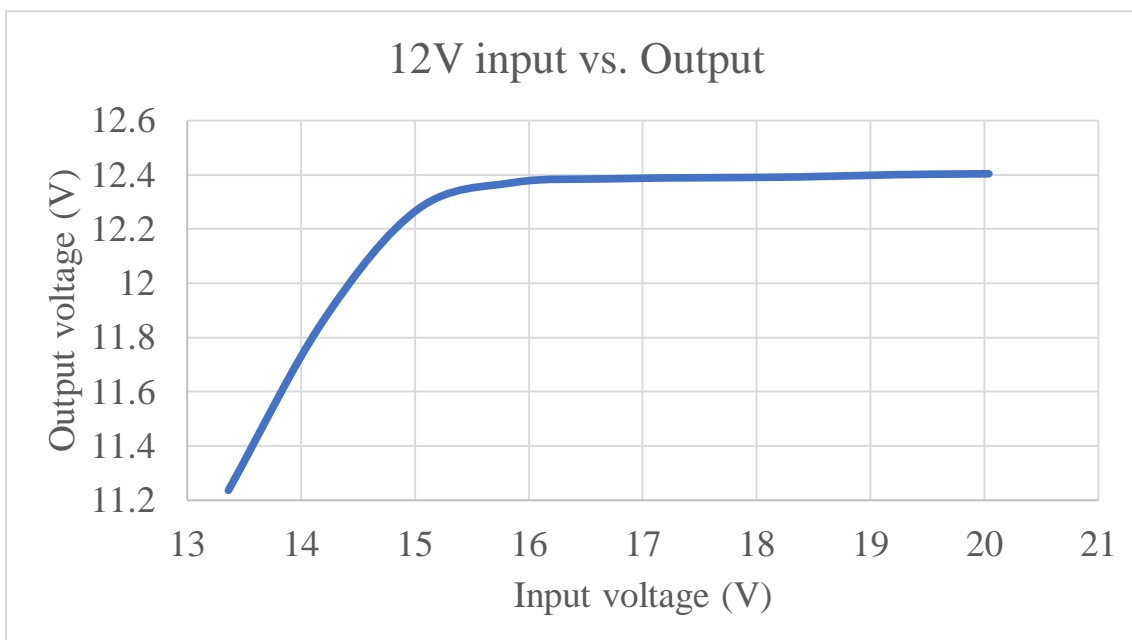
Then, regarding [Requirement 4.e](#), when the DPS is brought under +/-20% input voltage conditions, it shall still maintain voltage specifications. The voltage outputs when the input voltage is 13.4V and 20.0V are shown in Table 9. In addition, in Graph 1 and Graph 2, the evolution of output voltages when the input voltage goes from -20% to +20% is represented. The curve has been produced with points each of 5%.

	-20% (V)	+20% (V)
5V output	4.96	5.00
12V output	11.2	12.4

Table 9: Voltage from the reconstructed group DPS at a +/-20% input voltage.



*Graph 1: Evolution of the 5V output voltage when varying the input voltage from -20% to +20% of nominal voltage of the reconstructed group DPS.*



*Graph 2: Evolution of the 12V output voltage when varying the input voltage from -20% to +20% of nominal voltage of the reconstructed group DPS.*



Finally, considering [Requirement 4.f](#), the output current must be under 30mA on either output. This constraint shall be met under short-circuit conditions. The results are exposed in Table 10.

	Current (mA)
5V output	38.8
12V output	25.9

Table 10: Output current of the initial group DPS under short-circuit conditions.

Once the PCB has been constructed and tested, it is time to calculate its weight considering [Requirement 3.a](#). As it was predictable, the mass has not changed since the previous PCB and it weighs 6g (5g before population). Using a ruler, we obtain the DPS's size is 4.5cm x 4.5 cm x 1cm which is 20.25cm<sup>3</sup> ( $2.03 \cdot 10^{-5} \text{m}^3$ ).

*c. Individual DPS*

The results from the testing of the individual PCB carried out at the same time than the reconstruction of the group DPS. To ensure [Requirement 4.a](#) is met, the loads must be the necessary to supply 20mA in both of the outputs. The DPS was tested using the same configuration as in Figure 10 with an input voltage of 16.7V. The results are the following:

	Voltage (V)	Current (mA)
Input	16.7	46.0
5V output	4.97	19.9
12V output	12.0	20.2

Table 11: Voltage and current results from the individual DPS at 20mA output.

The input current is much higher than in the simulation (35.7% higher); therefore, the efficiency will suffer a considerable reduction. With the previous values and using Eq. 3, an efficiency of 44.4% is obtained. Then, considering [Requirement 4.c.i](#) and [Requirement 4.d.i](#), a resistor of  $420\Omega$  is needed for the 5V output to obtain a current of 12mA (using Eq. 1 – Ohm’s law) and, again, a resistor of  $599\Omega$  for the 12V output to obtain a current of 20mA. In Table 12, the voltage and current in this condition are exposed.

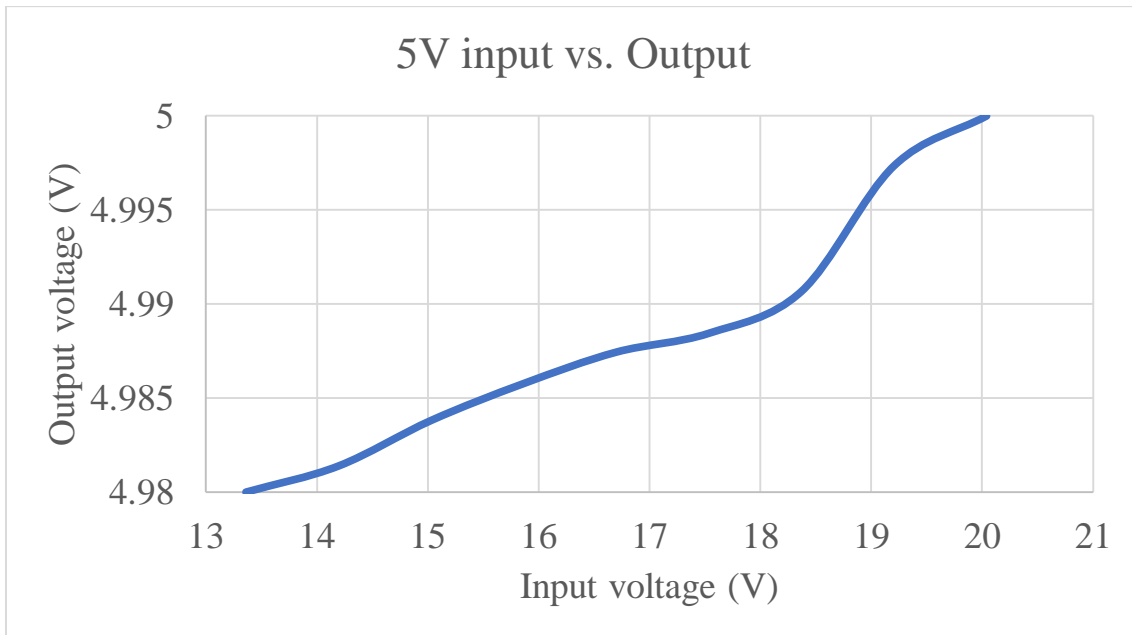
	Voltage (V)	Current (mA)
Input	16.7	39.1
5V output	4.98	12.0
12V output	12.0	20.2

Table 12: Voltage and current from the individual DPS at 20mA and 12mA output.

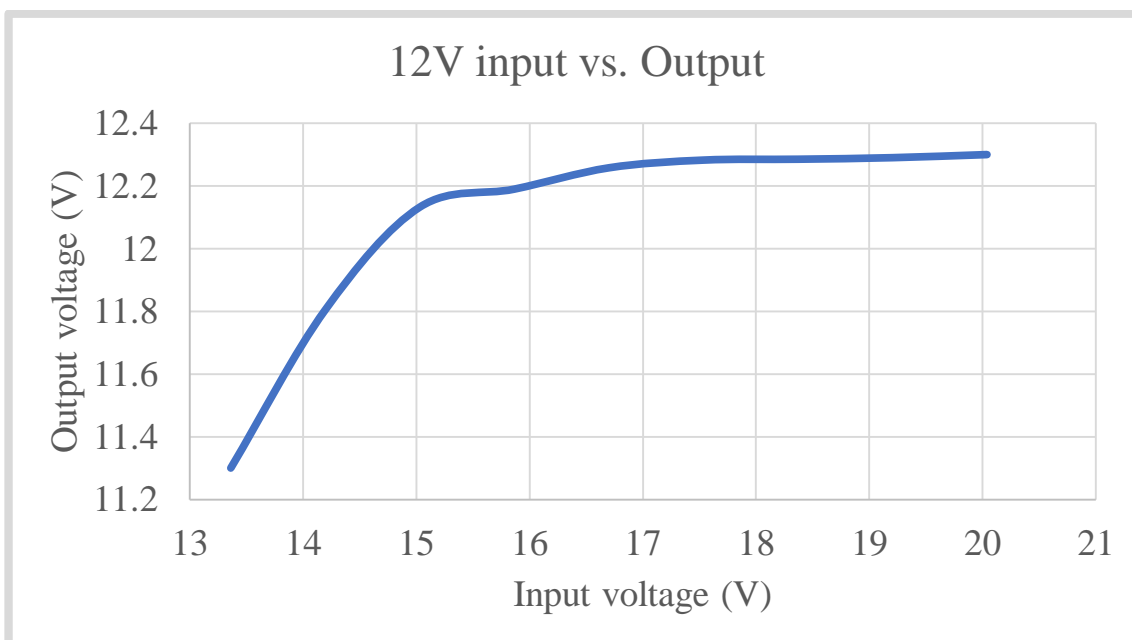
Then, regarding [Requirement 4.e](#), when the DPS is brought under +/-20% input voltage conditions, it shall still maintain voltage specifications. The voltage outputs when the input voltage is 13.4V and 20.0V are shown in Table 13. In addition, in Graph 3 and Graph 4, the evolution of output voltages when the input voltage goes from -20% to +20% is represented. The curve has been produced with points each of 5%.

	-20% (V)	+20% (V)
5V output	4.98	5.00
12V output	11.3	12.3

Table 13: Voltage from the individual DPS at a +/-20% input voltage.



*Graph 3: Evolution of the 5V output voltage when varying the input voltage from -20% to +20% of nominal voltage of the individual DPS.*



*Graph 4: Evolution of the 12V output voltage when varying the input voltage from -20% to +20% of nominal voltage of the individual DPS.*

Finally, considering [Requirement 4.f](#), the output current must be under 30mA on either output. This constraint shall be met under short-circuit conditions. The results are exposed in Table 14.

	Current (mA)
5V output	42.3
12V output	25.9

Table 14: Output current of the initial group DPS under short-circuit conditions.

Once the PCB has been constructed and tested, it is time to calculate its weight considering [Requirement 3.a](#). Using a scale, the mass of the populated board is 6g (5g before population). Using a ruler, we obtain the DPS's size is 4.5cm x 4.5 cm x 1cm which is 20.25cm<sup>3</sup> ( $2.03 \cdot 10^{-5} \text{m}^3$ ).

### III.5. Conclusions

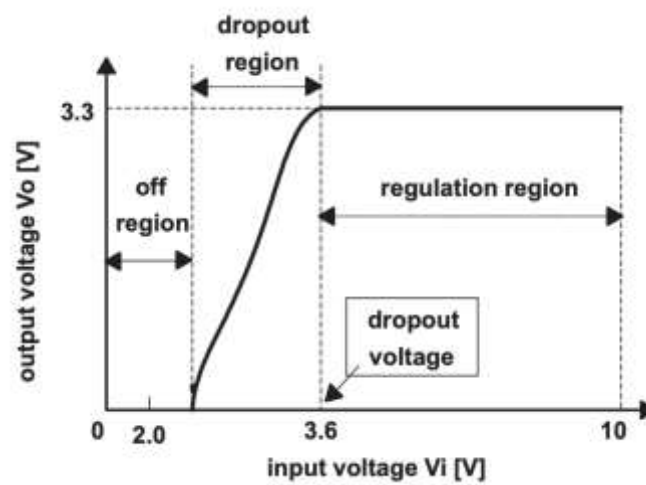
As it was predicted, laboratory results differ from theoretical ones. The input current for the three DPSs was much higher than when it was simulated with a minimum of 26.6% difference (initial group DPS). This means the input power increases and therefore, the efficiency decreases, *ceteris paribus*. All the simulations obtained an efficiency of over 60%; nevertheless, the maximum efficiency obtained when testing the PCBs is 50.1% (initial group PCB).

This reduction is probably caused by several reasons. First of all, there are certain discrepancies between the simulation's capacitance and resistance values and the ones that populate the PCBs as some of them were not available in the laboratory. Therefore, in those cases, the closest value is used (e.g., in the group model a capacitor of 150pF is used, and in contrast, the PCB is populated with a 100pF). In this example, a capacitor of

47pF could be placed in parallel with the 100pF one in order to obtain a capacitance of 147pF (closer to the desired value). However, at the time of the population, the PCB has already been constructed and therefore, it is too late to add the new capacitor without redoing the PCB. Another reason is the range of possible values for resistors, capacitors, ICs, and/or the input voltage due to the tolerance these components possess. Furthermore, this discrepancy may be due to an issue with the measurement devices as they work within a tolerance error as well. In addition, there might be some connectivity problems as the manufacturing of the PCB might not be flawless.

Furthermore, it can be seen in Table 3 and Table 4 (initial group PCB), Table 7 and Table 8 (reconstructed group PCB), Table 11 and Table 12 (individual PCB) that all the boards meet the voltage specifications as [Requirement 4.c.i](#) and [Requirement 4.d.i](#) request. Then, in Table 5, Table 9, and Table 13, it can be observed how the boards remain in the voltage ranges (4.85V – 5.15V and 11.2V – 12.8V) when the input voltage is +/- 20% of the nominal voltage (16.7V) as specified in [Requirement 4.e](#). Moreover, the mass and volume of all the PCBs is inside the permitted range (below 25 grams and below 1m<sup>3</sup>) as indicated in [Requirement 3](#). Then, for the two most recent PCBs, in Graph 1 and Graph 2 (reconstructed group PCB), Graph 3 and Graph 4 (individual PCB), the evolution of the output voltage in terms of the input voltage is represented. In these graphs, it can be seen that, as predicted, while the input voltage is away from the output voltages, the latter do not notably vary. This statement can be observed in the 5V output curve as, in both DPSs and along the whole curve, it is approximately 5V as the input voltage is permanently considerably different from the desired output. In addition, in the 12V output curves, when the input is increasing and hence, moving away from 12V, the percentage of change of the output lowers. Nevertheless, when the input voltage approaches the output voltage, as in the case of the beginning of the 12V curves, the operational

amplifiers cease to correctly regulate the output voltage, and the latter begins to differ from the desired value [7]. This input-to-output differential voltage is called dropout voltage and it is specified in the op-amps datasheet. The behaviour of op-amps (for instance, a TPS76733 op-amp), in this scenario, is represented in the following image (Graph 5) where the desired output is 3.3V but, when the input voltage is below 3.6V (dropout voltage), the former voltage is not obtained:



Graph 5: Dropout behaviour of a TPS76733 operational amplifier with permission from the publishers of

[7].

## IV. BATTERY SELECTION

In order to supply the digital power supply, four different batteries were considered. In Table 15, the voltage, capacity, weight, and price of each available battery are exposed. Using this and further information from the datasheets, the optimal configuration of batteries will be found regarding weight, cost, voltage, power and satisfying the constraints.

	Voltage (V)	Capacity (Ah)	Weight (kg)	Price (£)	Datasheet
VARTA	1.2	0.50	0.014	6.54	<a href="#">Datasheet 1<sup>[8]</sup></a>
ANSMANN	1.2	2.85	0.031	9.71	<a href="#">Datasheet 2<sup>[9]</sup></a>
BAK	3.7	4.5	0.095	24.71	<a href="#">Datasheet 3<sup>[10]</sup></a>
YUASA	12	24	9	132.99	<a href="#">Datasheet 4<sup>[11]</sup></a>

Table 15: Characteristics of the available batteries.

### IV.1. Calculations and results

In order to find out what battery is optimal, the output power must be calculated. This power is obtained after going through the PCB considering the output current is 20mA for both the 5V and 12V voltage outputs:

$$Eq. 4 \quad P_{Output} = (V_{Output_1} + V_{Output_2}) \cdot I_{Output} = (5 + 12) \cdot 20 \cdot 10^{-3} = 0.340 W$$

To select the correct battery configuration, the PCB's overall efficiency needs to be taken into account. This efficiency is calculated when the PCB is delivering 20mA in the 12V output and 12mA in the 5V output. These currents are the maximum currents necessary to supply the different loads from the Antarctica Weather Station. In the case of the 12V output and following [Requirement 4.d.i](#), the current is 20mA to supply the flash memory. In the case of the 5V output and following [Requirement 4.c.i](#), the current is 12mA to supply the PCU. A reference efficiency is needed as the all the calculations

depend on it, i.e., in this case, a battery is selected which determines the PCB's input voltage which, at the same time, determines the overall efficiency which may change the optimal battery configuration. This process may end up being cyclical; therefore, to simplify this process a reference efficiency has been used with which both the battery and the solar panel arrangements have been selected. However, these calculations could be adapted for any efficiency given, and the battery and solar panel selection would follow the same process as the following.

The efficiency used for the battery and solar panel selection is from the PCB which offered the highest efficiency (50.1%) out of the three possible designs. This efficiency was obtained after the debugging and testing of the group PCB carried out during the Scenario Week from which this project has been extracted and extended. The battery's load power is calculated by rearranging Eq. 3 and using the overall PCB efficiency. A battery load power of 0.679W is obtained.

Once we have the load power, it is time to go through the different battery combinations. The optimal configuration should be able to supply this power taking into account other factors such as weight, price, and required power to charge them. In addition, it ought to follow all the aforementioned requirements.

The first attempted combinations consisted of several batteries (same model) connected in series to increase their voltage to be able to supply the PCB. When batteries are connected in series, the total voltage is the sum of the individual voltages. Hence, if the batteries are the same model, then the voltage is  $n_{\text{Bat}} \cdot V$  (where  $n_{\text{Bat}}$  is the number of units and  $V$  is the voltage of one battery). Regarding the amp hours, the overall capacity is the minimum capacity of all the batteries connected in series. This is because, once one battery is depleted, no more current flows through the batteries, which means no more



discharging. Consequently, when having batteries of the same model, the total capacity is the individual capacity. Having different batteries connected together in series will ultimately cause damage to one or both batteries <sup>[12]</sup>. Therefore, this possibility will not be considered in the paper. Similarly to the capacity, the current will also remain the same independent of the number of batteries <sup>[13]</sup>.

Therefore, to begin with, the combinations will be the necessary so that the total voltage (using the nominal voltage) is, at least, 16.5V as explained in the Laboratory Work section. To do so, the number of units needed is the closest integer above the result of the next equation:

$$\text{Eq. 5} \quad n_{Bat} = \frac{V_{In}}{V_{NBat}} = \frac{16.5}{V_{NBat}}$$

Each datasheet must be analysed and interpreted accordingly as the nomenclature and procedures change from one battery to another. For each battery, we first analyse the charging process, then the discharging one and finish with the weight and price.

For the VARTA batteries, 14 units (Eq. 5) are needed to obtain at least 16.5V (16.8V). In the [datasheet](#), an accelerated charging method is shown with a charging time of 4 hours ([Requirement 4.h](#)) and a current of 150mA. In this case, the battery has an internal resistance of 0.1Ω when fully charged. Then, the voltage and the necessary power to be extracted from the solar panel system can be estimated by:

$$\text{Eq. 6} \quad V_{Charge} = n_{Bat} \cdot (V_N + I_{Charge} \cdot R) \Rightarrow$$

$$\Rightarrow V_{Charge} = 14 \cdot (1.2 + 0.15 \cdot 0.1) = 17.0 \text{ V}$$

$$\text{Eq. 7} \quad P_{Solar} = V_{Charge} \cdot I_{Charge} \Rightarrow$$

$$\Rightarrow P_{Solar} = 17.0 \cdot 0.15 = 2.55 \text{ W}$$

The charging capacity is not the nominal one, as in the discharging. It depends on the current used to charge the battery and the time it takes. At this charge current and a total charge time of 4 hours, we obtain the following capacity:

$$\begin{aligned} \text{Eq. 8} \quad C_{\text{Charge}} &= I_{\text{Charge}} \cdot t_{\text{Charge}} \Rightarrow \\ &\Rightarrow C = 0.15 \cdot 4 = 0.6 \text{ Ah} \end{aligned}$$

Regarding the discharging method, to obtain a 12 hour lifetime or discharging time ([Requirement 4.g](#)), a C/12 (or 0.083C) C-rate is needed. C ratings are a measure of the rate at which a battery is discharged or charged relative to its nominal capacity. A 1C rated discharging means that the battery will discharge in 1 hour. For example, a 200Ah battery at 1C rate equates to a discharging current of 200A for 1 hour. For the same battery at C/10 (0.1C), it will discharge at 20A for 10 hours<sup>[19][20]</sup>. Hence, the discharging current is estimated by:

$$\begin{aligned} \text{Eq. 9} \quad I_{\text{Discharging}} &= \frac{C_N}{\text{Lifetime}} \Rightarrow \quad \text{where } C_N \equiv \text{Nominal capacity} \\ &\Rightarrow I_{\text{Discharging}} = \frac{0.5}{12} = 0.0417 \text{ A} \end{aligned}$$

When calculating the discharging voltage, the drop voltage caused by the internal resistance must be considered. Assuming a constant internal resistance, the discharging voltage and the available power can be estimated by<sup>[16]</sup>:

$$\begin{aligned} \text{Eq. 10} \quad V_{\text{Discharge}} &= n_{\text{Bat}} \cdot (V_N - I_{\text{Discharge}} \cdot R) \Rightarrow \\ &\Rightarrow V_{\text{Discharge}} = 14 \cdot (1.2 - 0.0417 \cdot 0.1) = 16.7 \text{ V} \end{aligned}$$

$$\begin{aligned} \text{Eq. 11} \quad P_{\text{Discharge}} &= V_{\text{Discharge}} \cdot I_{\text{Discharge}} \Rightarrow \\ &\Rightarrow P_{\text{Discharge}} = 0.698 \text{ W} \end{aligned}$$

Furthermore, the weight and price of the VANTA's configuration can be calculated from the number of units used in the arrangement and the individual weight and price of the VANTA battery. They are calculated using the next equations:

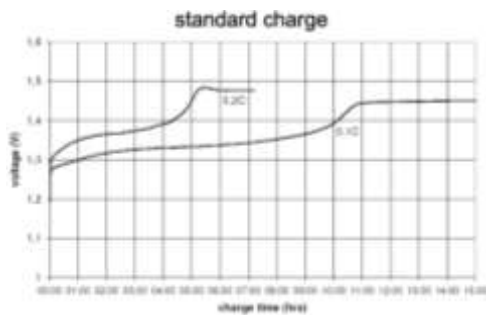
$$\text{Eq. 12} \quad \text{Weight}_{\text{TotBat}} = n_{\text{Bat}} \cdot \text{Weight}_{\text{Battery}} \Rightarrow$$

$$\Rightarrow \text{Weight}_{\text{TotBat}} = 14 \cdot 0.014 = 0.196 \text{ kg}$$

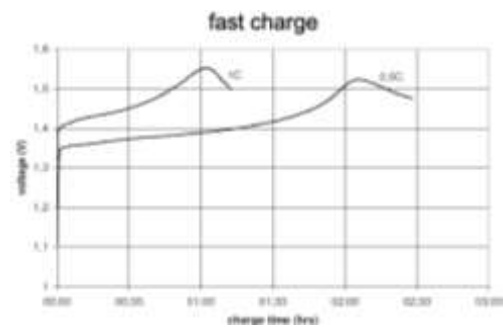
$$\text{Eq. 13} \quad \text{Price}_{\text{TotBat}} = n_{\text{Bat}} \cdot \text{Price}_{\text{Battery}} \Rightarrow$$

$$\Rightarrow \text{Price}_{\text{TotBat}} = 14 \cdot 6.54 = \text{£}91.6$$

For the ANSMANN batteries, 14 batteries (Eq. 5) are needed to obtain at least 16.5V (16.8V). In the [datasheet](#), a quick charge method is shown with a charging time of 4 hours ([Requirement 4.h](#)) and a current of 800mA. This current gives a C-rate (using Eq. 9) of 0.281C and a capacity of 3.2Ah (using Eq. 8).



Graph 6: Standard charge V-t characteristic of ANSMANN battery with permission from the publishers of [9].

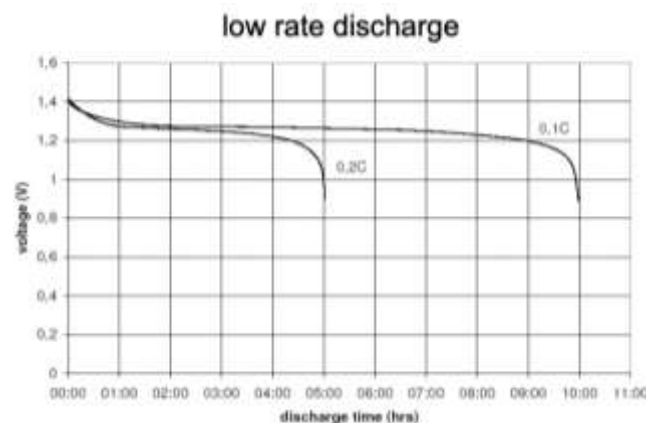


Graph 7: Fast charge V-t characteristic of ANSMANN battery with permission from the publishers of [9].

Graph 6 and Graph 7 represent charge voltage and time for specific C-rates. The quick charge method would be a graph between these two illustrations, and with a

function representing the 0.281C rate, we would obtain the voltage. As this graph does not exist, the charge is estimated to be 1.5V per battery<sup>[17]</sup>. Using Eq. 7, the power needed from the solar panel system is 16.8W.

Regarding the discharging method, to obtain a 12-hour lifetime ([Requirement 4.g](#)), a C/12 (0.083C) rate is needed. Then, the current at which it discharges is 0.238A using the aforementioned Eq. 9.



*Graph 8: Low-rate discharge V-t characteristic of ANSMANN battery with permission from the publishers of [9].*

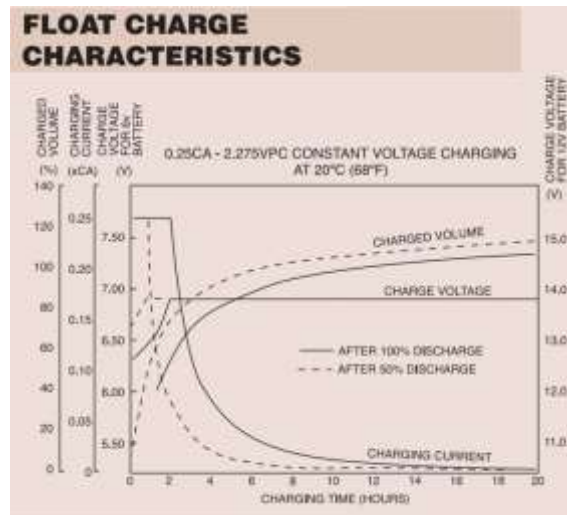
Basing our estimation on Graph 8 we can estimate that at this C-rate, the voltage after a 12-hour discharge is 0.9V per battery. This voltage is called the discharge cut-off voltage as the battery is considered to be fully discharged when this voltage is reached. With the discharge current and voltage and using Eq. 11, an available power of 2.99W is obtained. Considering the number of used batteries, the weight and price are 0.434kg and £136, respectively (Eq. 12 & Eq. 13).

For the BAK batteries, 5 batteries (Eq. 5) are needed to obtain at least 16.5V (18.5V). In this [datasheet](#), no graph is represented and only a standard charging method is exposed in which, with a 0.2C (5 hours) and a current of 1100 mA, the battery is charged to 4.2V (charge voltage). Assuming certain linearity, we can estimate the current

for 0.25C (4 hours) rate and the same charge voltage is 1.38A<sup>[18]</sup>. This current for 4-hour charging equates to a capacity of 5.5Ah (Eq. 8). Thus, the power needed from the solar panel is 28.9W (Eq. 7).

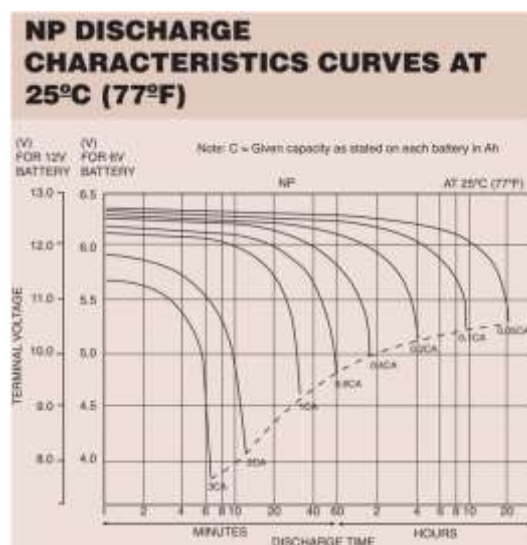
Regarding the discharge process, using a C-rate of C/12 to obtain the 12-hour lifetime ([Requirement 4.g](#)), a 0.375A current is obtained (Eq. 9). To obtain the required  $P_{Load}$  with a discharge time of 12 hours, a voltage of, at least, 1.81V is needed (Eq. 11). It has been seen in Graph 8 that, in the process of a battery discharging, the cut-off voltage between similar rates does not differ. Considering the cut-off voltage to be 2.5V (as expressed in the datasheet), we get an available power of 4.69W for 12 hours (Eq. 11). Considering the number of used batteries, the weight and price are 0.475kg and £124, respectively (Eq. 12 & Eq. 13).

For the YUASA batteries, two batteries (Eq. 5) would be needed to achieve, at least, 16.5V (24V). In the [datasheet](#), a graph which describes the float charge characteristics is represented (Graph 9)<sup>[19][20]</sup>. In this figure, we can estimate that at 4 hours of charging time ([Requirement 4.h](#)), the charging current is approximately  $0.075 \times CA$  which equals 1.8A ( $0.075 \times CA$  times nominal capacity 24Ah gives current in amperes)<sup>[21]</sup>. This translates to a capacity of 7.2 Ah (Eq. 8). In addition, we can estimate a charge voltage of 13.8V per battery (27.6V for both). Thus, the power needed from the solar panel is 49.7W (Eq. 7).



Graph 9: Float charge characteristics of YUASA battery with permission from the publishers of [11].

Regarding the discharging method, to obtain a 12 hour lifetime ([Requirement 4.g](#)), a C/12 (0.083C) rate is needed. Then, the current at which it discharges is 2A using the aforementioned Eq. 9.



Graph 10: Discharge characteristics curves of YUASA battery with permission from the publishers of [11].

Basing our estimation on Graph 10, we can estimate that at this C-rate (a curve between 0.1CA and 0.05 CA), the voltage after a 12-hour discharge is 10.55V (cut-off voltage) per battery. Using Eq. 11, an available power of 42.2W is obtained. Considering

the number of used batteries, the weight and price are 18kg and £266, respectively (Eq. 12 & Eq. 13). All the results from the previous configurations are gathered in Table 16.

	Units	V <sub>Tot</sub> (V)	V <sub>Discharge</sub> (V)	I <sub>Discharge</sub> (A)	P <sub>Available</sub> (W)	V <sub>Charge</sub> (V)	I <sub>Charge</sub> (A)	P <sub>Solar</sub> (W)	C <sub>Charge</sub> (Ah)	Weight (kg)	Price (£)
VARTA	14	16.8	16.7	0.042	0.70	17.0	0.15	2.55	0.6	0.196	91.56
ANSMAN N	14	16.8	12.6	0.238	2.99	21.0	0.80	16.8	3.2	0.434	135.9
BAK	5	18.5	12.5	0.375	4.69	21.0	1.38	28.9	5.5	0.475	123.6
YUASA	2	24.0	21.1	2	42.2	27.6	1.80	49.7	7.2	18	266.0

Table 16: Results from combinations of batteries in series with voltage over the input voltage of the DPS.

The possibility of connecting batteries in parallel must also be considered. When two batteries are connected in parallel, the resulting voltage is one intermediate between these two. This is because the battery with the higher voltage will discharge into the other one until they end up with equal voltages. The current flowing between the batteries is usually relatively high and can damage the batteries <sup>[22]</sup>. Hence, it is not a good idea to connect two different batteries in parallel and therefore, will not be considered in this paper. However, if the batteries are the same model, no current flows between the batteries, and this problem is solved. In that case, the resulting voltage is the voltage of one single battery. The total current is the sum of the currents that flow through each branch, then it is  $n_{\text{Bat}} \cdot I$  (where  $n_{\text{Bat}}$  is the number of units, and  $I$  is the current that flows through one battery). Similarly, the capacity is the sum of the individual capacities ( $n_{\text{Bat}} \cdot C$ , where, again,  $n$  is the number of units and  $C$  is the capacity of one battery) <sup>[23]</sup>.

	Branches	C <sub>N</sub> (Ah)	V <sub>Tot</sub> (V)	V <sub>Discharge</sub> (V)	I <sub>Discharge</sub> (A)	P <sub>Available</sub> (W)	V <sub>Charge</sub> (V)	I <sub>Charge</sub> (A)	P <sub>Solar</sub> (W)	C <sub>Charge</sub> (Ah)	Weight (kg)	Price (£)
VARTA	2	1.0	1.2	1.19	0.08	0.10	1.23	0.60	0.37	1.2	0.392	13.1
ANSMANN	2	5.7	1.2	0.90	0.48	0.86	1.5	1.60	2.40	6.4	0.868	19.4
BAK	2	9.0	3.7	2.50	0.75	3.75	4.2	2.75	11.6	11.0	0.950	49.4
YUASA	2	48	12	10.6	4	42.2	13.8	3.60	49.7	14.4	36	266

Table 17: Results from combinations of batteries in parallel (1 battery per branch).

The voltage still needs to be higher than 16.5V and as the resulting voltage is the voltage of one branch, the only parallel connection is not useful as none of the configurations would reach the desired voltage no matter the number of branches as seen in Table 17. Nevertheless, a combination between parallel and series could be useful. To be so, each branch must have the same number of units as when connected in only series to reach the required voltage. The number of branches depends on how much current is needed and therefore, how much power. Arrangements, with two branches and the same units as in series per branch, have been carried out hereafter:

	Units <sub>Tot</sub> /Branches	C <sub>N</sub> (Ah)	V <sub>Tot</sub> (V)	V <sub>Discharge</sub> (V)	I <sub>Discharge</sub> (A)	P <sub>Available</sub> (W)	V <sub>Charge</sub> (V)	I <sub>Charge</sub> (A)	P <sub>Solar</sub> (W)	C <sub>Charge</sub> (Ah)	Weight (kg)	Price (£)
VARTA	28/2	1.0	16.8	16.7	0.08	1.39	17.2	0.30	5.17	1.2	0.392	183.1
ANSMANN	28/2	5.7	16.8	12.6	0.48	5.99	21.0	1.60	33.6	6.4	0.868	271.9
BAK	10/2	9.0	18.5	12.5	0.75	9.38	21.0	2.75	57.8	11.0	0.950	247.1
YUASA	4/2	48	24.0	21.1	4	84.4	27.6	3.60	99.4	14.4	36	532.0

Table 18: Results from combinations of batteries in series and parallel.

The figures in Table 18 have been calculated using double current and capacity due to the number of branches (2). The rest of the figures are calculated using the same procedure as previously.



#### *IV.2. Battery selection conclusions*

Once the results from Table 16 are obtained, we can come to some conclusions. First of all, the VARTA configuration is capable of supplying the DPS as the available power that the configuration offers is higher than the power from the loaded DPS. Another conclusion is that if the power from the cut-off voltage (aforementioned) and the current is higher than the load, it can be assured that the battery will supply the DPS as the cut-off voltage is the lowest voltage that has been achieved during the complete discharging process. Hence, the ANSMANN, BAK and YUASA configurations are capable of supplying the DPS ( $P_{\text{Available}} > P_{\text{Load}}$ ) for at least 12 hours. However, in the case of the YUASA battery, it overpasses the permitted weight ([Requirement 3.b](#)). The number of YUASA's unit cannot be reduced as it would not supply enough voltage to follow the voltage specifications ( $12V < 16.5V$ ) and so, this battery configuration is discarded.

Regarding Table 17, we observe that battery configuration in only parallel is not useful as it does not reach the required voltage (16.5V). Adding more branches would not solve this problem <sup>[23]</sup> and so, this type of arrangement is discarded.

From the results of Table 18, we observe that the available power doubles relative to the results from Table 16, while also doubling in weight, cost, and power required from the solar panel. As the available power from the only series configurations was already sufficient to supply the DPS, more power is not required and the 2-branch configuration is, therefore, not beneficial. More than two branches will also provide unnecessary power and add weight, price, and required power from the solar panel. Consequently, any parallel configuration can be discarded. Thus, Table 19 is obtained by discarding both YUASA's battery configuration and any parallel arrangement:

	Units	V <sub>Tot</sub> (V)	V <sub>Discharge</sub> (V)	I <sub>Discharge</sub> (A)	P <sub>Available</sub> (W)	V <sub>Charge</sub> (V)	I <sub>Charge</sub> (A)	P <sub>Solar</sub> (W)	C <sub>Charge</sub> (Ah)	Weight (kg)	Price (£)
VARTA	14	16.8	16.7	0.042	0.70	17.0	0.15	2.55	0.6	0.196	91.56
ANSMAN N	14	16.8	12.6	0.238	2.99	21.0	0.80	16.8	3.2	0.434	135.9
BAK	5	18.5	12.5	0.375	4.69	21.0	1.38	23.1	5.5	0.475	123.6

Table 19: Results from final configurations of the battery selection.

Once we have these results, we can observe that, while having sufficient power available to supply the DPS, the weight does not vary much from one configuration to another. Hence, for now, the weight is not crucial for the decision. In addition, price, while being an important factor to consider and reduce, there is no budget restriction and, consequently, neither is. The most important factor is the power required from the solar panel as it might not be able to supply it, or it might be too expensive or heavy as more solar panels might be required. Having said that, VARTA configuration requires less power, less money and less weight compared to the rest of the configurations. Therefore, it can be concluded that the optimal battery configuration to supply the DPS, consists of 14 1.2V 0.5Ah VARTA rechargeable batteries connected in series. This configuration has a total cost of £91.56, a weight of 0.196kg, a total voltage of 16.8V, an available power of 0.70W, and a required power of 2.55W from the solar panel. The volume of a VARTA battery is 2.42cm x 3.41cm x 0.65cm as indicated on its [datasheet](#) (maximum sizes) and therefore, the configuration's volume is  $7.51 \cdot 10^{-5} \text{m}^3$  (below the permitted range). The configuration is shown in Figure 31.



Figure 31: Configuration of 14 VANTA batteries connected in series.

### *IV.3. End of life, ecological & disposal considerations*

In VARTA's [datasheet](#), the typical life expectancy is said to be 1000 cycles. However, due to the use of accelerated charging instead of normal charging, this expectancy is estimated to be 10% less (900 cycles in total). Assuming one cycle, which consists of a charge and discharge, is carried out each day, then the life expectancy is 900 days, which translates to 2 years, 5 months, and 20 days. After this period, the batteries begin underperforming and need replacement. Therefore, [Requirement 2](#) is not met as the battery configuration will not last for 15 years without replacement.

Regarding the ecological considerations, the VARTA battery does not contain heavy metals as defined by the European directive [2006/66/EC Article 21](#), and therefore, it complies with the chemical composition requirements of this directive. Furthermore, it is considered mercury-free as the mercury content by battery weight is less than 0.0001% [24].

Regarding the disposal considerations, the disposal of batteries is regulated on the basis of the European directive [2006/66/EC Article 12](#). While having to meet certain requirements from this article, each country has its own regulation regarding the disposal of batteries [24]. The directive only states that all member states must ensure an adequate collection scheme for waste portable batteries, and that battery producers must cover any net costs resulting from the collection, treatment, and recycling of all collected waste [25]. In the case of the United Kingdom, if a battery distributor sells or supplies more than 32kg a year, he must offer a free collection of waste or used batteries. The distributor must have a collection point at all premises from where he supplies batteries. Then, a battery compliance scheme will collect those batteries free of charge for their following recycling process [26]. In conclusion, for the system that concerns this paper, the used

batteries should be transported to a collection point offered by the distributor, or any other points offered by the state. The transportation must be appropriate to avoid faults such as a short circuit. Proper measures consist of covering the battery terminals and storing the batteries in their original packaging <sup>[24]</sup>.

## V. SOLAR PANEL SELECTION

In order to charge the battery configuration aforementioned, four different solar panels were considered. In Table 20, the power rating, weight and price of each available solar panel are exposed. Using this and further information from the datasheets, the optimal configuration of solar panels will be found regarding weight, cost, voltage, power and satisfying the constraints.

	Power rating (W)	Voltage at $P_{max}$ (V)	Current at $P_{max}$ (A)	Weight (kg)	Price (£)	Datasheet
Sanyo	0.19	4.60	0.04	0.0086 <sup>[31]</sup>	11.49	<a href="#">Datasheet 1</a> <sup>[27]</sup>
PV Logic 10	10.0	16.8	0.59	1.5	43.72	<a href="#">Datasheet 2</a> <sup>[28]</sup>
PV Logic 60	60.0	17.2	3.49	6.0	194.7	<a href="#">Datasheet 3</a> <sup>[29]</sup>
BP Solar	120	33.7	3.56	13	37.37 <sup>[32]</sup>	<a href="#">Datasheet 4</a> <sup>[30]</sup>

Table 20: Characteristics of the available solar panels.

### V.1. Calculations and results

In order to choose the suitable solar panel configuration, the charge power of the battery needs to be taken into account. This power has a value of 2.55W and must be supplied by the solar panel arrangement. To make the solar panel selection, the solar irradiance in Antarctica must be considered. Solar irradiance is what produces an output in the PV cell. The greater the solar irradiance, the greater the output current is and, as a result, the greater the power generated, *ceteris paribus*<sup>[33]</sup>. The effect of solar irradiance is shown in Figure 32.

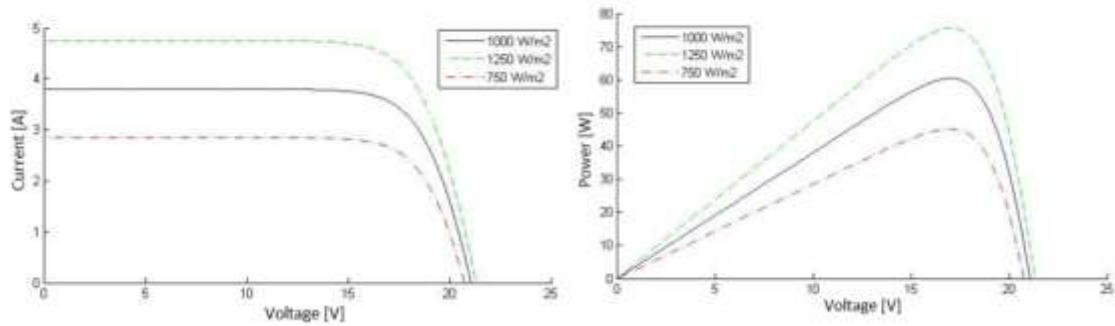


Figure 32: Effects of the solar irradiance in the I-V and P-V curves with permission from the publishers of [33].

The power rating of a solar panel is the maximum power point that can be extracted from the panel under ideal conditions [34]. These ideal conditions are not the case in Antarctica due to the low solar elevation which causes a low angle of incidence [35]. This can be seen in Figure 33 where Antarctica's sun path from December to June is compared to London's.

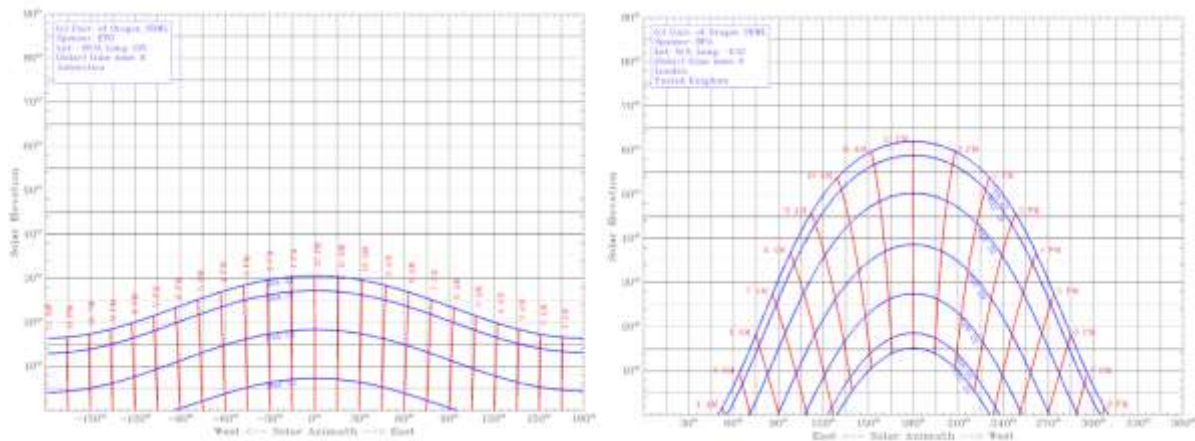


Figure 33: Antarctica's (Left) and London's (Right) sun path from December to June [36].

As it can be seen, during the solar azimuth, the maximum sun elevation is over  $60^\circ$  in London, while it is approximately  $30^\circ$  in Antarctica. One could argue that Antarctica has more hours of light; nonetheless, this is refuted by Antarctica's lack of sunlight during half the year. These inconvenient sunlight conditions must be taken into

consideration when selecting the optimal solar panel configuration as not all the power rating is truly achievable. For future testing, as this shall not take place in Antarctica, a correction factor must be used (depending on the location of testing), to account for the difference in solar irradiance between Antarctica and the testing location. The power obtained from the testing of the solar panel must be multiplied by a correction factor (probably  $<1$  as the testing location is likely to have better sunlight conditions) to simulate Antarctica's conditions.

Continuing with the solar panel selection, Antarctica's solar irradiance has been considered, and it has been estimated that only a 10 % of the output power at the maximum power point (power rating) can be used. This means the maximum power to be extracted from one solar panel is 10% of the power rating. Therefore,

$$Eq. 14 \quad P_{Load_{Bat}} = \frac{P_{Charge_{Bat}}}{10\%} \Rightarrow P_{Solar} = \frac{2.55}{0.1} = 25.5 \text{ W}$$

Similarly to batteries, when solar panels are connected together in series, the total voltage is the sum of the individual voltages. Regarding the current, the resulting current would be the minimum of the individual currents <sup>[37]</sup>. In case the solar panels are from the same model, the voltage is  $n_{Sol} \cdot V$  (where  $n_{Sol}$  is the number of units and  $V$  is the voltage of one solar panel). In contrast, the current would be the individual one <sup>[38]</sup>. The first attempted combinations consist of connecting solar panels from the same model in series. The number of units is the necessary and minimum to supply the battery configuration considering the estimation of the solar irradiance. The number of units needed is the closest integer above the result of the next equation:

$$\text{Eq. 15} \quad n_{Sol} = \frac{P_{Load_{Bat}}}{P_{rating}}$$

For the Sanyo solar panel, 135 units (Eq. 15) are needed to supply, at least, 25.5W (25.6W). In the [datasheet](#), a voltage and a current at  $P_{Max}$  of 4.6V and 41.2mA are shown, respectively. Therefore, the current that flows through the solar panels is 41.2mA and the total voltage of the 135 units is:

$$\begin{aligned} \text{Eq. 16} \quad V_{Tot} &= n_{Sol} \cdot V(P_{Max}) \Rightarrow \\ &\Rightarrow V_{Tot} = 135 \cdot 4.6 = 621 \text{ V} \end{aligned}$$

Then, the total voltage at the maximum power point is 621 V. Similarly to Eq. 12 and Eq. 13, the weight and price are calculated from the number of units used and the individual weight and price of Sanyo's solar panel. It is calculated by Eq. 17 and Eq. 18:

$$\begin{aligned} \text{Eq. 17} \quad Weight_{Tot_{Sol}} &= n_{Sol} \cdot Weight_{Solar} \Rightarrow \\ &\Rightarrow Weight_{Tot_{Sol}} = 135 \cdot 0.0086 = 1.16 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Eq. 18} \quad Price_{Tot_{Sol}} &= n_{Sol} \cdot Price_{Solar} \Rightarrow \\ &\Rightarrow Price_{Tot_{Sol}} = 135 \cdot 11.49 = \text{£}1551 \end{aligned}$$

For the PV Logic 10 solar panel, 3 units (Eq. 15) are needed to supply, at least, 25.5W (30W). In the [datasheet](#), a voltage and a current at  $P_{Max}$  of 16.8V and 0.59A are shown, respectively. Therefore, the current that flows through the solar panels is 0.59A and the total voltage of the 3 units is 50.4V using Eq. 16. Considering the number of used solar panels, the weight and price are 4.5kg and £131.2, respectively (Eq. 17 & Eq. 18).

For the PV Logic 60 solar panel, 1 unit (Eq. 15) is needed to supply, at least, 25.5W (60W). In the [datasheet](#), a voltage and a current at  $P_{Max}$  of 17.2V and 3.49A are



shown, respectively. Therefore, the current that flows through the solar panels is 3.49A and the total voltage is 17.2V using Eq. 16. Considering the number of used solar panels, the weight and price are 6kg and £194.7, respectively (Eq. 17 & Eq. 18).

For the BP solar panel, 1 unit (Eq. 15) is needed to supply, at least, 25.5W (120W). In the [datasheet](#), a voltage and a current at  $P_{Max}$  of 33.7V and 3.56A are shown, respectively. Therefore, the current that flows through the solar panels is 3.56A and the total voltage is 33.7V using Eq. 16. Considering the number of used solar panels, the weight and price are 13kg and £37.4, respectively (Eq. 17 & Eq. 18). All the results from the previous configurations are gathered in Table 21.

	Units	$V_{Tot}$ at $P_{max}$ (V)	$I_{Tot}$ at $P_{max}$ (A)	$P_{max}$ (W)	Weight (kg)	Price (£)
Sanyo	135	621	0.04	25.6	1.16	1551
PV Logic 10	3	50.4	0.59	30.0	4.50	131.2
PV Logic 60	1	17.2	3.49	60.0	6.00	194.7
BP Solar	1	33,7	3.56	120	13.0	37.37

Table 21: Results from combinations of solar panels of the same model connected in series.

We need to consider combinations between different models of solar panels. The only reasonable combinations are using 1 PV Logic 10 with Sanyo's solar panels or using 2 PV Logic 10 with Sanyo's solar panels. The other combinations would just add unnecessary weight, price, and voltage.

For the first mixed combination (1 PV Logic 10 and Sanyo), the current will be the minimum of the individual currents which is, in this case, Sanyo's current (41.2mA). At this current, the PV Logic 10 will supply a power of:

$$Eq. 19 \quad P_{PV10} = n_{PV10} \cdot V_{PV10} \cdot I \Rightarrow$$

$$\Rightarrow P_{PV10} = 1 \cdot 16.8 \cdot 0.0412 = 0.692 W$$

Then, the remaining power ( $P_{\text{LoadBat}} - P_{\text{PV10}} = 24.8\text{W}$ ) must be supplied by Sanyo units. Using Eq. 15, we know that 131 Sanyo units are needed and so, we can say 1 PV Logic 10 accounts for 4 Sanyo solar panels. The total voltage would be 619.4V (Eq. 16) and the weight and price, 2.63kg and £1549, respectively (Eq. 17 & Eq. 18).

For the second mixed combination (2 PV Logic 10 and Sanyo), the current will be the minimum of the individual currents which is, in this case, Sanyo's current (41.2mA). At this current, the PV Logic 10 will supply a power of 1.38W (Eq. 19). Then, the remaining power ( $P_{\text{LoadBat}} - P_{\text{PV10}} = 24.1\text{W}$ ) must be supplied by Sanyo units. Using Eq. 15, we know that 128 Sanyo units are needed. The total voltage would be 622.4V (Eq. 16) and the weight and price, 4.1kg and £1558, respectively (Eq. 17 & Eq. 18). The results from the configurations of different solar panels connected in series are gathered in Table 22.

	$V_{\text{Tot}}$ at $P_{\text{max}}$ (V)	$I_{\text{Tot}}$ at $P_{\text{max}}$ (A)	$P_{\text{max}}$ (W)	Weight (kg)	Price (£)
1 PV Logic 10 + 131 Sanyo	619.4	0.0412	26.0	2.63	1549
2 PV Logic 10 + 128 Sanyo	622.4	0.0412	25.6	4.1	1558

Table 22: Results from mixed solar panels connected in series.

Similarly to batteries, when solar panels are connected together in parallel, the total current is the sum of the individual currents. Regarding the voltage, the resulting voltage would be the minimum of the individual voltages <sup>[37]</sup>. In case the solar panels are from the same model, the current is  $n_{\text{Sol}} \cdot I$  (where  $n_{\text{Sol}}$  is the number of units and  $I$  is the current of one solar panel). In contrast, the voltage would be the individual one <sup>[38]</sup>. The first attempted combinations consist of connecting solar panels from the same model in parallel. The number of units is the necessary and minimum to supply the battery configuration considering the estimation of the solar irradiance.

For the Sanyo solar panel, 135 units (Eq. 15) are needed to supply, at least, 25.5W (25.7W). In the [datasheet](#), a voltage and a current at  $P_{Max}$  of 4.6V and 41.2mA are shown, respectively. Therefore, the voltage of the solar panels is 4.6V and the total current of the 135 units is:

$$Eq. 20 \quad I_{Tot} = n_{Sol} \cdot I(P_{Max}) \Rightarrow$$

$$\Rightarrow I_{Tot} = 135 \cdot 0.0412 = 5.56 A$$

Then, the total current at the maximum power point is 5.56A. Using Eq. 17 and Eq. 18, we obtain a total weight and price of 1.16kg and £1551, respectively.

For the PV Logic 10 solar panel, 3 units (Eq. 15) are needed to supply, at least, 25.5W (30W). In the [datasheet](#), a voltage and a current at  $P_{Max}$  of 16.8V and 0.59A are shown, respectively. Therefore, the voltage of the solar panels is 16.8V and the total current of the 3 units is 1.77A using Eq. 20. Considering the number of used solar panels, the weight and price are 4.5kg and £131.2, respectively (Eq. 17 & Eq. 18).

For the PV Logic 60 solar panel, 1 unit (Eq. 15) is needed to supply, at least, 25.5W (60W). Therefore, it follows the same configuration as in series. For the BP Solar solar panel, 1 unit (Eq. 15) is needed to supply, at least, 25.5W (120W). Thus, it follows the same configuration as in series. The results from the configurations of solar panels from the same model connected in parallel are gathered in Table 23.

	Units	$V_{Tot}$ at $P_{max}$ (V)	$I_{Tot}$ at $P_{max}$ (A)	$P_{max}$ (W)	Weight (kg)	Price (£)
Sanyo	135	4.60	5.56	25.6	1.16	1551
PV Logic 10	3	16.8	1.77	30.0	4.50	131.2
PV Logic 60	1	17.2	3.49	60.0	6.00	194.7
BP Solar	1	33,7	3.56	120	13.0	37.37

Table 23: Results from combinations of solar panels of the same model connected in parallel.

We need to consider combinations between different models of solar panels. The only reasonable combinations are using 1 PV Logic 10 with Sanyo's solar panels or using 2 PV Logic 10 with Sanyo's solar panels. The other combinations would just add unnecessary weight, price, and voltage.

For the first mixed combination (1 PV Logic 10 and Sanyo), the voltage will be the minimum of the individual voltages which is, in this case, Sanyo's voltage (4.6V). At this voltage, the PV Logic 10 will supply a power of:

$$\begin{aligned}
 \text{Eq. 21} \quad P_{PV10} &= n_{PV10} \cdot V \cdot I_{PV10} \Rightarrow \\
 &\Rightarrow P_{PV10} = 1 \cdot 4.6 \cdot 0.59 = 2.71 \text{ W}
 \end{aligned}$$

Then, the remaining power ( $P_{\text{LoadBat}} - P_{PV10} = 22.8\text{W}$ ) must be supplied by Sanyo units. Using Eq. 15, we know that 121 Sanyo units are needed and so, we can say 1 PV Logic 10 in parallel accounts for 14 Sanyo solar panels. The total current would be 5.58A (Eq. 20) and the weight and price, 2.54kg and £1434, respectively (Eq. 17 & Eq. 18).

For the second mixed combination (2 PV Logic 10 and Sanyo), the voltage will be the minimum of the individual voltages which is, in this case, Sanyo's voltage (4.6V). At this voltage, the PV Logic 10 will supply a power of 5.42W (Eq. 21). Then, the remaining power ( $P_{\text{LoadBat}} - P_{PV10} = 20.1\text{W}$ ) must be supplied by Sanyo units. Using Eq. 15, we know that 106 Sanyo units are needed. The total current would be 5.55A (Eq. 20) and the weight and price, 3.91kg and £1305, respectively (Eq. 17 & Eq. 18). The results from the configurations of different solar panels connected in parallel are gathered in Table 24.

	V <sub>Tot</sub> at P <sub>max</sub> (V)	I <sub>Tot</sub> at P <sub>max</sub> (A)	P <sub>max</sub> (W)	Weight (kg)	Price (£)
1 PV Logic 10 // 121 Sanyo	4.6	5.58	25.7	2.54	1434
2 PV Logic 10 // 106 Sanyo	4.6	5.55	25.6	3.91	1305

Table 24: Results from mixed combinations of solar panels connected in parallel.

## V.2. Solar panel selection conclusions

Observing the results from Table 21, we can come to some solutions. All the combinations used are capable of supplying the battery as the power of the solar panel (considering the solar irradiance from Antarctica) is higher than the charge power. However, Sanyo's configuration is unreasonably expensive and BP Solar's configuration overpasses the permitted weight ([Requirement 3.b](#)). Thus, these two configurations are discarded as it violates one of the requirements. Regarding Table 22, the combination that uses 2 PV Logic 10 units, worsens the situation compared to the only Sanyo configuration: adds weight, cost, and voltage. The combination that uses 1 PV Logic 10 unit reduces the cost and voltage by a small amount compared to a fairly high increase in weight. Therefore, these two combinations are also discarded. Regarding the parallel connections, in Table 23 the results are the same as the combinations in series, except for the voltage and current. Thus, a combination of series-parallel can be arranged in order to regulate the voltage and the current while obtaining the same power, weight, and cost. Regarding Table 24, in both configurations, while adding some weight, the price is considerably reduced compared to the only Sanyo configuration. However, the cost is still excessively high for this part of the project and therefore, these are discarded.

Another conclusion drawn from the tables is that combinations between different solar panels are not efficient as they are not delivering their full potential. In the last case, for example, 2 PV Logic with a power rating of 10W and 106 Sanyo solar panels with a

power rating of 0.19W are being used. This gives a total of 40.14W of power rating compared to the 25.6W that can be used. The solar panel is providing 64% of all the rated available power. This is because the parallel connection is limiting the PV Logic 10 voltage (16.8V) to Sanyo's voltage (4.6V). In the case of Table 22, the series connection limits the current from 0.59A (PV Logic 10) to 0.0412A (Sanyo). If different batteries were connected in a series-parallel connection, both the voltage and the current would be limited, and the efficiency would fall drastically, not achieving any beneficial results <sup>[37]</sup>. Therefore, this type of combination is not being considered. Finally, the following solar panel arrangements are obtained:

	Units	$V_{Tot}$ at $P_{max}$ (V)	$I_{Tot}$ at $P_{max}$ (A)	$P_{max}$ (W)	Weight (kg)	Price (£)
PV Logic 10	3	50.4	0.59	30.0	4.50	131.2
PV Logic 60	1	17.2	3.49	60.0	6.00	194.7

Table 25: Possible optimal combinations for the solar panel selection.

The configurations from Table 25 are not restricted to only series. As it was aforementioned, a series-parallel configuration might be beneficial to regulate both voltage and current.

When considering the optimal solar panel it is important to think about the voltage required to charge the battery. It is charged with a voltage of 17V and therefore, it does not seem reasonable to use the PV Logic 60 arrangement as the total voltage at  $P_{max}$  (17.2V) is too close to the output voltage. This means that if one day, the solar panel underperforms (e.g., due to the weather), it will not be able to supply enough voltage. In other words, the solar panel should be operating at almost 100% of its capacity before it will even charge the batteries <sup>[39]</sup>. Consequently, the only possibility left is using the PV Logic 10 configuration. The appropriate arrangement of the PV Logic 10 solar panels will be explained after considering the panel-to-battery circuit.

## VI. PANEL-TO-BATTERY CIRCUIT

### VI.1. Integrated circuit selection

It is essential to take into account the circuit that will be connecting the solar panel to the battery. This circuit will require an integrated circuit (IC) in order to adjust the voltage to the required. The characteristics of the available ICs are exposed in Table 26:

	Max V <sub>cc</sub> (V)	Max V <sub>Output</sub> (V)	Input-to-output V (V)	I <sub>output</sub> (A)	Price (£)	Datasheet
TL071	40	-	-	-	0.45	<a href="#">Datasheet 1<sup>[40]</sup></a>
UA741	15	14	-	-	0.45	<a href="#">Datasheet 2<sup>[41]</sup></a>
MC33063AD	40	-	-	-	0.55	<a href="#">Datasheet 3<sup>[42]</sup></a>
TL317CD	-	32	35	100mA	0.72	<a href="#">Datasheet 4<sup>[43]</sup></a>
UA723CD	40	37	38	150mA	0.68	<a href="#">Datasheet 5<sup>[44]</sup></a>
MC78M05CDTG	35	5	-	-	0.42	<a href="#">Datasheet 6<sup>[45]</sup></a>
MC78M12CDTG	35	12	-	-	0.42	<a href="#">Datasheet 7<sup>[45]</sup></a>

Table 26: Characteristics of the available integrated circuits.

From the previous table, we can discard using the ICs whose output voltage is less than 17 V (UA741, MC78M05CDTG, and MC78M12CDTG). The TL317CD is also discarded due to the lack of information and because it is not modelled in Multisim and, not being able to simulate its operation, is riskier than using an IC which you can simulate. The TL071 and MC33063AD are discarded as well, because, while having the same maximum input voltage and similar cost as the UA723CD, it is an inappropriate option to use ICs of which we do not possess much information about. Thus, the UA723CD is the used IC for the panel-to-battery circuit.

## VI.2. PV Logic 10 solar panels arrangement

The UA723CD has a maximum input voltage of 40V which is lower than the output voltage of the series PV Logic 10 configuration (3 units). In the parallel PV Logic 10 configuration, the voltage is 16.8V and therefore, does not reach the necessary voltage to charge the battery. Consequently, another arrangement must be found to solve these inconveniences. As it was aforementioned, by placing the solar panels in a series-parallel connection, the voltage and current could be regulated. An option is to connect them in two branches; nonetheless, the problem is that the number of used units in the PV Logic 10 configuration is not an even number. This means that a two-branch configuration produces unbalanced branches which is an inefficient arrangement (similar to what happens with the use of different solar panels). Hence, an extra PV Logic 10 solar panel is needed to balance the two branches.

The total voltage is the voltage of one branch which, at the same time, is the voltage of two PV Logic 10 solar panels in series. The total current is the sum of the currents of the branches which, at the same time, are the current of one PV Logic 10. The maximum power is:

$$\text{Eq. 22} \quad V_{Tot} = V_{Branch} = 2 \cdot V_{PV10} \Rightarrow$$

$$\Rightarrow V_{Tot} = 2 \cdot 16.8 = 33.6 \text{ V}$$

$$\text{Eq. 23} \quad I_{Tot} = 2 \cdot I_{Branch} = 2 \cdot I_{PV10} \Rightarrow$$

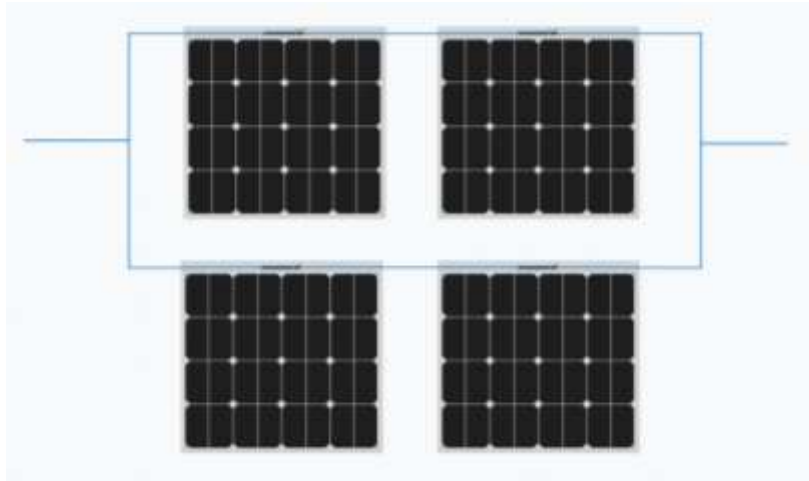
$$\Rightarrow I_{Tot} = 2 \cdot 0.59 = 1.18 \text{ A}$$

$$\text{Eq. 24} \quad P_{Max} = V_{Tot} \cdot I_{Tot} \Rightarrow$$

$$\Rightarrow P_{Max} = 33.6 \cdot 1.18 = 39.7 \text{ W}$$



The maximum power of the series-parallel arrangement is more than enough to charge the battery. The voltage is inside the input voltage limit from the UA723CD integrated circuit. Therefore, we can conclude the optimal solar panel arrangement is to connect two PV Logic 10 (series) in parallel with another two PV Logic 10. This arrangement supplies a maximum of 39.7W with a voltage of 33.6V, a weight of 6kg (Eq. 17), and a cost of £175 (Eq. 18). The volume of a PV Logic 10 solar panel is 39.7cm x 28cm x 2.5cm as indicated on its [datasheet](#) (maximum sizes) and therefore, the configuration's volume is  $2.78 \cdot 10^{-3} \text{m}^3$  (below the permitted range). The arrangement is shown in Figure 34:



*Figure 34: Configuration of PV Logic 10 solar panels connected in series-parallel.*

### *VI.3. UA723CD operation & resistance values*

The UA723CD has several modes of operation which are described in the [datasheet](#). The application mode, that concerns the project, is the Basic high-voltage regulator. This mode is designed for outputs from 7V to 37V (the required output is 17V) and its mode diagram is the following (Figure 35):

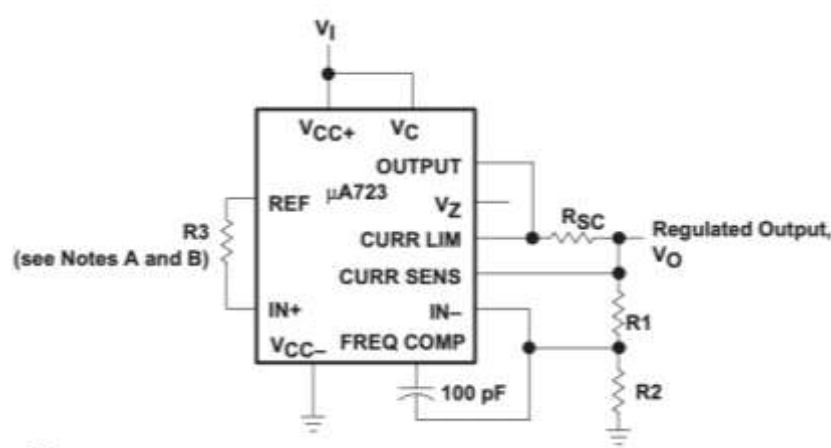


Figure 35: Basic high-voltage regulator mode diagram of the UA723CD <sup>[44]</sup>.

The voltage from the solar panel would be connected to the IC's input ( $V_1$  or  $V_{CC+}$ ). The [datasheet](#) describes the relationship between the different resistances using the following equations:

$$\text{Eq. 25} \quad V_O = V_{Ref} \cdot \frac{R_1 + R_2}{R_2}$$

$$\text{Eq. 26} \quad R_3 = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

$$\text{Eq. 27} \quad I_{Limit} = \frac{0.65 \text{ V}}{R_{SC}}$$

The reference voltage  $V_{Ref}$  is said to typically be 7.15V (6.8V – 7.5V). Therefore, if the output voltage must be 17V, the relationship between resistors 1 and 2 ( $R_1/R_2$ ) is 1.38, using Eq. 25. Then, using Eq. 26, the relationship between resistors 1 and 3 ( $R_3/R_2$ ) is 0.579. Finally, the current limit is not necessary (no short circuit requirement), and it is set to 0.65A with a  $R_{SC}$  of 1 $\Omega$  (Eq. 27). If we use 1.1k $\Omega$  as resistor 2, then, resistor 1 must be 1.51k $\Omega$  and resistor 3, 637 $\Omega$ . Moreover, to replicate the charging process of the battery, a load resistor must be added that provides 150mA (charging current) when the voltage is 17V. This resistor is calculated using Ohm's Law (Eq. 1) and the result is 113 $\Omega$ . With these resistance values and following the mode diagram from Figure 35, the

hereafter Multisim model is built. In the simulation, we can observe the measures of the output current, output voltage, and reference voltage:

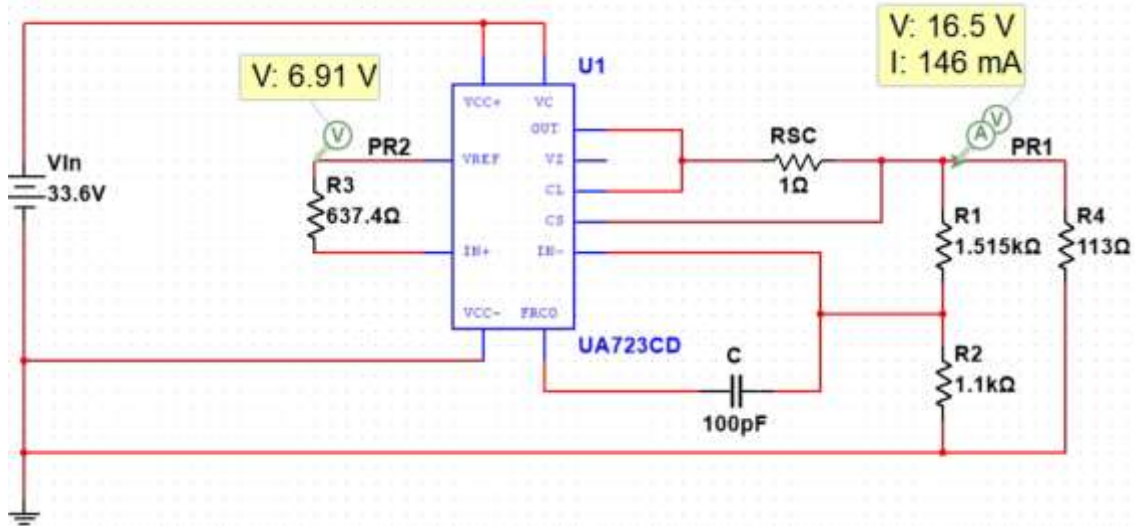


Figure 36: Multisim simulation of the panel-to-battery circuit with the theoretical resistance values using typical reference voltage.

As it can be seen in Figure 36, the output voltage is not the desired and neither is, the output current. This is due to the fact that the reference voltage is not the predicted, it is not the typical value. Instead, it is 6.91V which is indeed within the range of the reference voltage (6.8V – 7.5V). If we adjust the calculations, we find the relationship between resistors 1 and 2 ( $R1/R2$ ) is 1.46 (Eq. 25); the relationship between resistors 1 and 3 ( $R3/R2$ ) is 0.593 (Eq. 26); the value of  $R_{SC}$  does not change. If we use 1.1k $\Omega$  as resistor 2, then, resistor 1 must be 1.61k $\Omega$  and resistor 3, 653 $\Omega$ .

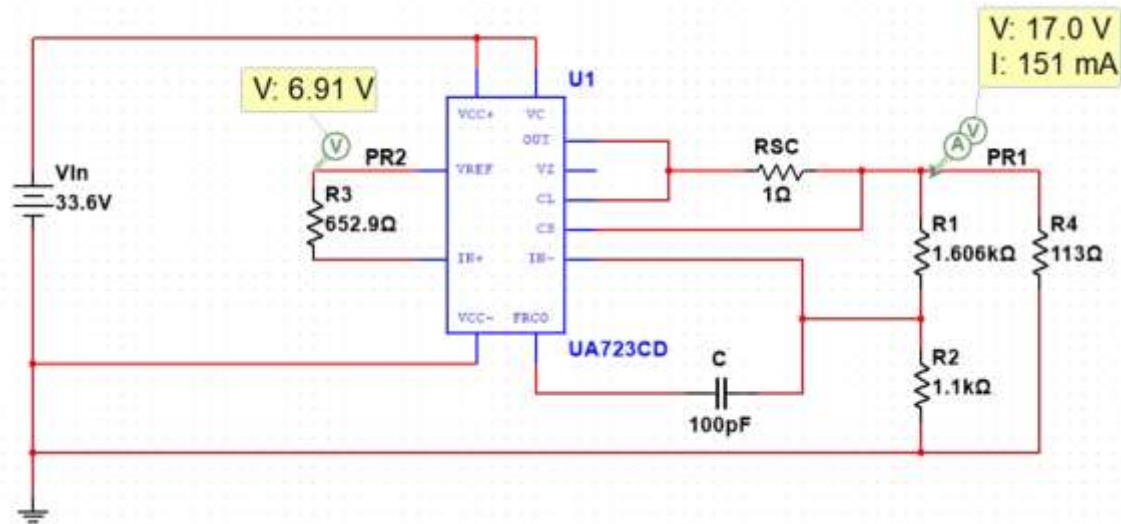


Figure 37: Multisim simulation of the panel-to-battery circuit with the theoretical resistance values using 6.91 V as the reference voltage.

As can be seen in Figure 37, the desired output is obtained. Nevertheless, those resistor values must be adjusted to the available resistance values from the [Component List](#). The closest values are the following: 1.6kΩ, 1.1kΩ, 680Ω, and 1Ω for R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, and R<sub>sc</sub>, respectively. With these values, simulation from Figure 38 is obtained:

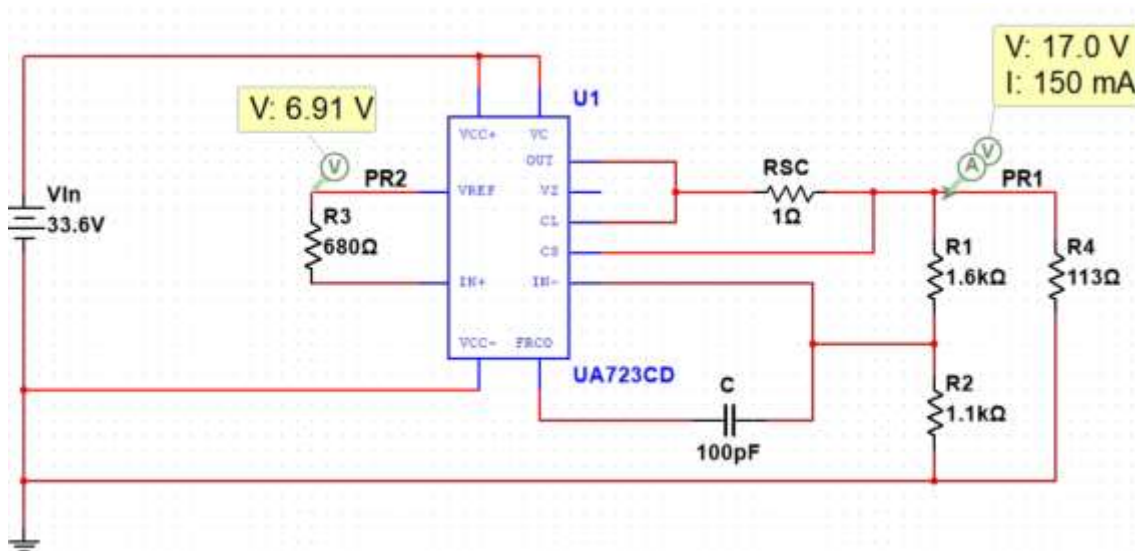


Figure 38: Multisim simulation of the panel-to-battery circuit with the real resistance values.

With this resistance configuration, the desired output voltage (17V) and current (150mA) are obtained. Therefore, we can conclude that, with the aforementioned solar panel configuration connected to this circuit through the input and, at the same time, connected to the battery arrangement through the output, the charging process can be carried out.

#### VI.4. Worst-case scenario

##### a. Calculations and results

Each component from the circuit has a certain tolerance which defines what range of values may the component take. For example, for a  $1\text{k}\Omega$  5% may take values from  $950\Omega$  to  $1050\Omega$ . Therefore, all the possible combinations of resistance and capacitance values must still follow the voltage specifications. As there are no defined voltage specifications, it will be assumed that if it is within  $\pm 10\%$  of the desired voltage (17V), the device will perform correctly. To find out if it does, the worst-case scenario has to be carried out. If this extreme point complies with the specifications, then any other point will do as well. In Figure 39, the Multisim model has been adjusted so that the resistors and capacitors have their respective tolerances specified in the [Component List](#).

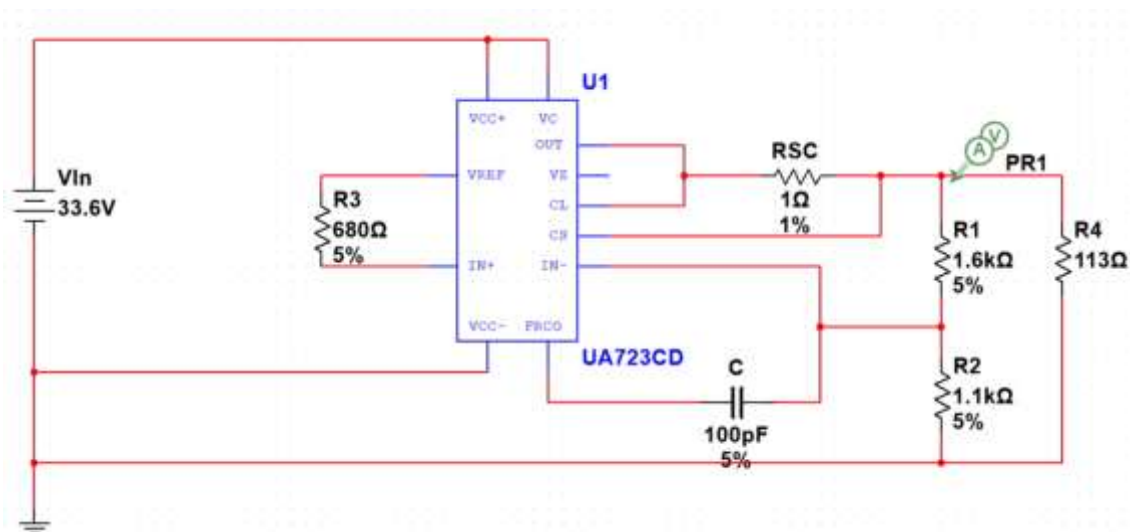


Figure 39: Multisim model of the panel-to-battery circuit with tolerances.

V(PR 1), Nominal Run	16.98571	V(PR 1), Nominal Run	16.98571
V(PR 1), Worst Case Run	18.04670	V(PR 1), Worst Case Run	16.03066
Worst Case Run		Worst Case Run	
DC operating point for all devices: 1.06099, (6.24638% of nominal)		DC operating point for all devices: -0.955048, (5.62265% of nominal)	
Tolerance changes needed to achieve worst case:		Tolerance changes needed to achieve worst case:	
rr3 resistance decreased to 646		rr3 resistance increased to 714	
cc capacitance unchanged from 1e-10		cc capacitance unchanged from 1e-10	
rr1 resistance increased to 1680		rr1 resistance decreased to 1520	
rr2 resistance decreased to 1045		rr2 resistance increased to 1155	
rrsc resistance decreased to 0.99		rrsc resistance increased to 1.01	

Figure 40: Multisim worst-case scenario for both over (left) and below (right) the output voltage.

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To desired V	V <sub>Ref</sub> (V)	R <sub>1</sub> (Ω)	R <sub>2</sub> (Ω)	R <sub>3</sub> (Ω)	R <sub>Sc</sub> (Ω)	C (pF)
Maximum	18.05	159.7	6.25	6.91	1680	1045	646	0.99	100
Minimum	16.03	141.9	-5.62	6.91	1520	1155	714	1.01	100

Table 27: Results from Multisim's worst-case scenario.

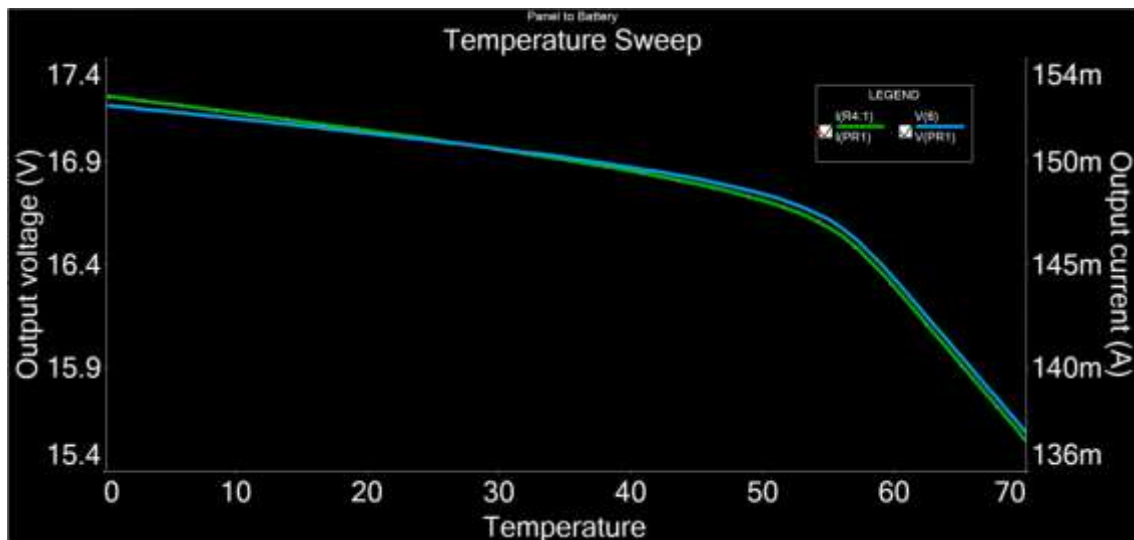
In Figure 40, the worst-case scenario for both the maximum and minimum output voltage is run by Multisim, taking into account the component tolerances. These results are gathered in Table 27.

Nevertheless, Multisim has an established value for the reference voltage (6.91V) and therefore, in the worst-case scenarios, it is not considering the different values  $V_{Ref}$  may take. In the UA723CD's [datasheet](#), the reference voltage is stated to be within 6.8V – 7.5V. Therefore, using MATLAB, a worst-case scenario has been developed in order to know which is the minimum and maximum of both the voltage (using Eq. 25) and current (using Ohm's Law: Eq. 1). Once the MATLAB [code](#) has been run, it delivers the solution presented in Table 28:

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To desired V	V <sub>Ref</sub> (V)	R <sub>1</sub> (Ω)	R <sub>2</sub> (Ω)	R <sub>3</sub> (Ω)	R <sub>Sc</sub> (Ω)	C (pF)
Maximum	19.56	173.1	15.0	7.5	1680	1045	680	1	100
Minimum	15.75	139.4	-7.36	6.8	1520	1155	680	1	100

Table 28: MATLAB's worst-case scenario for both the maximum and the minimum output voltage.

Apart from the tolerances, another factor that affects the output voltage is the temperature. The greater the temperature is, the greater the resistance is <sup>[46]</sup>. Therefore, the effect of the temperature in the circuit must be simulated and, again, a worst-case scenario must be carried out. To do so, Multisim offers a temperature sweep analysis, in which it goes through a range of temperatures simulating the output voltage. In our case, following [Requirement 1.b.i](#), the range of temperature in which the device must follow the specifications is 0 – 70°C. To know how resistors and capacitors change with temperature, the temperature coefficient of resistance (TCR) and of capacitance (TCC) must be specified. These TCR and TCC can be found on the 0805 resistor's [datasheet](#) <sup>[47]</sup>, and on the 0805 capacitor's [datasheet](#) <sup>[48]</sup>. Once these values are specified in Multisim, the next results are obtained:



*Graph 11: Multisim's temperature sweep analysis of the output voltage (blue) and current (green) in the panel-to-battery circuit.*

As can be observed in Graph 11, the voltage is maximum, when the temperature is minimum and vice versa. Multisim also provides the exact values of these maximum and minimum points which are gathered in Table 29:

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To desired V	T (°C)
Maximum	17.17	152.0	1.11	0
Minimum	15.59	137.9	-8.24	70

Table 29: Output voltage results from Multisim's temperature sweep analysis.

Nonetheless, these corner-case scenarios are not complete, until all the variables, tolerances, reference voltage, and temperature coefficients, are analysed together: a complete worst-case scenario analysis must be carried out. Multisim does not produce such analysis and therefore, we, again, reside in MATLAB's help. This program considers the resistor tolerances and the reference voltage's range of values and using Eq. 25, the output voltage is calculated. However, the IC's output voltage also varies with its own temperature coefficient (0 – 0.015%/°C) which can be found on its [datasheet](#) and can take a range of values. In addition the resistors vary, at the same time, with temperature following the next equation <sup>[46]</sup>:

$$Eq. 28 \quad R(T) = R(T_0) \cdot (1 + TCR \cdot (T - T_0))$$

The TCR is defined in the [datasheet](#) to be 100ppm/°C for a resistance >10Ω and 200ppm/°C for <10Ω. The ambient temperature is also specified to be 25°C. As R<sub>3</sub>, R<sub>SC</sub>, and C, do not appear in Eq. 25, they are not present in the results. With all this in mind, the MATLAB [program](#) is run and the results are gathered in Table 30:

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To desired V	T (°C)	IC temperature coefficient (%/°C)	V <sub>Ref</sub> (V)	R <sub>1</sub> (Ω)	R <sub>2</sub> (Ω)
Maximum	19.69	174.2	15.8	70	0.015	7.5	1688	1050
Minimum	15.64	138.4	-7.98	70	-0.015	6.8	1527	1160

Table 30: MATLAB's complete worst-case scenario for both the maximum and the minimum output

voltage.



### *b. Conclusions*

As was stated earlier, the voltage specifications have been assumed to be a fixed value of +/-10% of the desired voltage. Given that, it can be observed in Table 27 that if we vary the resistors and capacitors values within their tolerance range, the specifications will still be followed ( $6.25\% < 10\%$  and  $-5.62\% > -10\%$ ). However, the possibility that the reference voltage is not 6.91V (as established in Multisim) has to be considered. If this factor is considered, the results from Table 28 are obtained. Now, the maximum voltage is over the permitted limit ( $15\% > 10\%$ ) which is obtained with the maximum possible reference voltage. This stands to reason as the output voltage follows Eq. 25 and is, therefore, directly proportional to the reference voltage. To prevent overpassing the limit, several ICs' reference voltages can be tested. Thus, the IC that delivers the closest voltage to 6.91V (voltage at which the circuit has been designed) is chosen. This testing method, however, will increase the cost of manufacturing as more ICs will need to be wasted or resold (the cost analysis will be discussed later on in the paper).

In Graph 11, a voltage vs. temperature graph of the panel-to-battery circuit is represented. It can be observed that while the temperature is close to the reference one ( $25^{\circ}\text{C}$ ), the voltage does not vary greatly. However, once it reaches a certain temperature around  $55^{\circ}\text{C}$  the curve gets steeper, and the voltage varies greatly. In Table 29, the results from the aforementioned graph are presented, and as it was predicted, the highest temperature means the highest difference from the desired voltage. Still, in both cases (maximum and minimum voltage), the specifications are met.

Nevertheless, as much as possible, the DPS should be maintained at a temperature close to  $25^{\circ}\text{C}$  to lower the voltage difference.

Finally, a complete worst-case scenario considering temperature, tolerances and reference voltage is shown in Table 30. These results show that the maximum voltage is over the permitted range ( $15.8\% > 10\%$ ) while the minimum meets the specifications ( $-7.98\% > -10\%$ ). There is a clear difference with the previous temperature sweep analysis as when all variables are considered, the maximum voltage happens at the highest temperature. In contrast, when only the temperature is considered, this happens at the lowest temperature. This is due to the fact that Multisim's temperature sweep analysis does not take into account the IC's temperature coefficient. Therefore, the situation worsens with the highest difference in temperature relative to reference temperature ( $25^{\circ}\text{C}$ ) which is obtained with  $70^{\circ}\text{C}$  rather than  $0^{\circ}\text{C}$ . Ultimately, it can be concluded that, as it is said previously, to lower the percentage to the desired voltage, an IC with a reference voltage close to  $6.91\text{V}$  must be used, and the temperature must be kept low.

### VI.5. Sensitivity analysis

Additionally, a sensitivity analysis is studied to find out which component affects the output voltage the most. In the analysis, the component is varied by one unit and the output voltage is measured. Multisim's simulation is shown in Figure 41, and the results are gathered in Table 31:

Panel to Battery Sensitivity Analysis	
Variable	Sensitivity
rr1	6.28322 m
rr2	-9.13769 m
rr3	-1.76898 u
rrsc	-148.26855 u
vvin	362.13488 u

Figure 41: Multisim's sensitivity analysis of the output voltage.

	Sensitivity
R <sub>1</sub>	6.28 mV/Ω
R <sub>2</sub>	-9.14 mV/Ω
R <sub>3</sub>	-1.77 μV/Ω
R <sub>SC</sub>	-148 μV/Ω
V <sub>in</sub>	362 μV/V
V <sub>Ref</sub>	2.45 V/V

Table 31: Results from the sensitivity analysis.

First of all, the results presented show that R<sub>3</sub>, R<sub>SC</sub>, and V<sub>in</sub> changes in the output voltage are negligible which stands to reason as they are not part of Eq. 25, which is the equation the IC follows to deliver the output voltage. Furthermore, from the parameters that are in the equation, it can be seen that varying the value of resistors 1 and 2 does affect notably the output voltage. Of these two, the second one is the component that affects the most the outcome of the voltage (-9.14mV/Ω). Moreover, the reference voltage has been added to the analysis because, despite the fact that it cannot be changed the same way a resistor can be changed, it is a crucial factor to consider when choosing an IC. To support that argument, it can be seen the reference voltage affects enormously the outcome of the voltage.

### VI.6. DipTrace layout

Following the same steps as with the DPS, after the appropriate Multisim simulations which simulate the performance requirements, it is time to design the PCB layout using DipTrace considering the physical requirements from the [Requirement List](#). In this case, the board is a square of 3.5cm x 3.5cm as required in [Requirement 5.a](#). Due to the fact that fewer components are required for this PCB, it is able to fit on a smaller board (3.5cm square compared to 4.5cm from the DPSs). Furthermore, the printed circuit board must follow the constraints from [Requirement 5.b](#) to facilitate its construction.

Hereafter, the DipTrace layout and its respective physical form are shown Figure 42 and Figure 43. In this layout design, apart from meeting the requirements, any unnecessary unconnected copper islands have been eliminated, and any oblique lines that might harden the construction or worsen the connectivity have been eliminated.

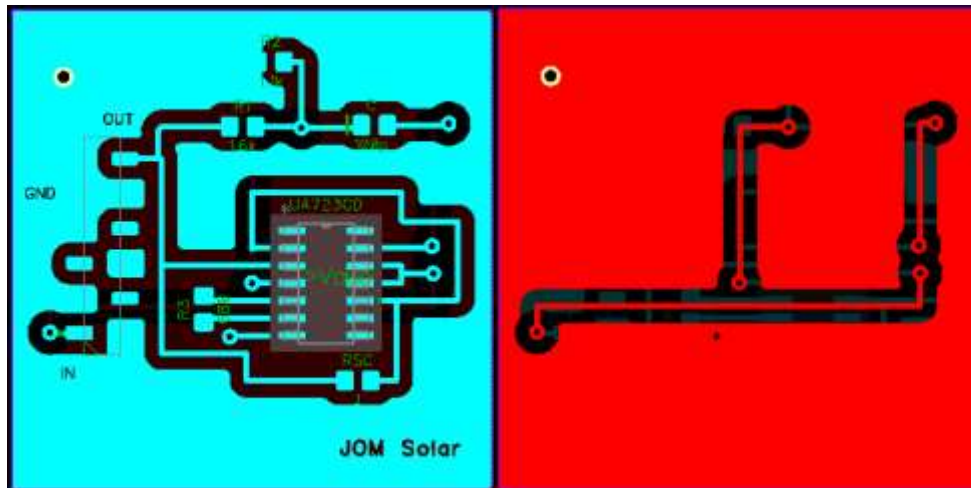


Figure 42: PCB layout from the panel-to-battery circuit. Top view on the left and bottom view on the right.

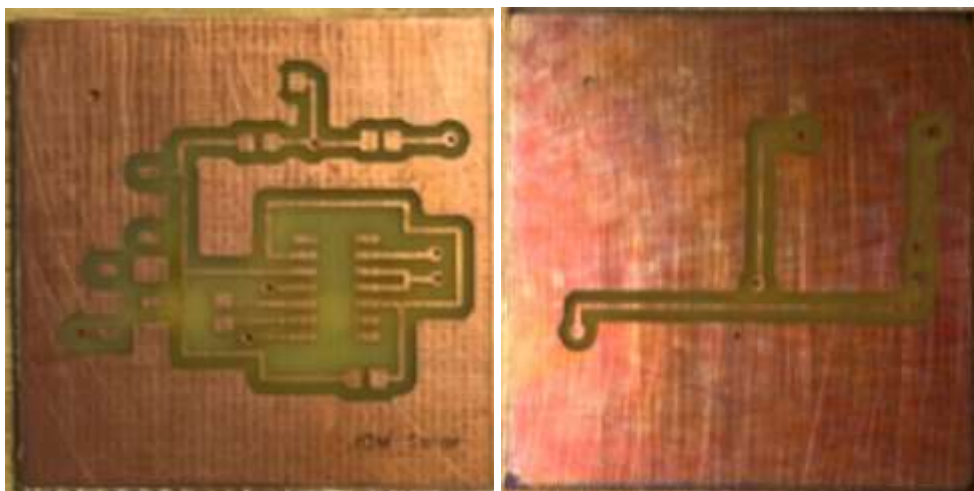
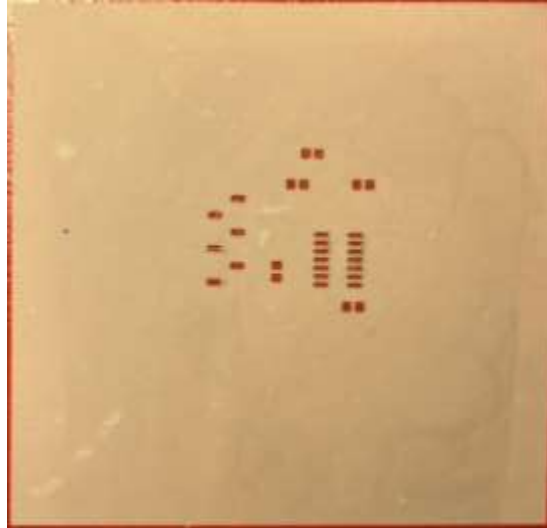


Figure 43: Built PCB from the panel-to-battery circuit. Top view on the left and bottom view on the right.

### VI.7. Population of the PCB

Once the board has been manufactured, it is populated using a stencil to facilitate the soldering. In this case, the stencil is fairly simple and therefore, it could be done by hand without the need for one. However, it is likely it will provide a better result when a stencil is used due to human error. This design's stencil is shown in Figure 44.



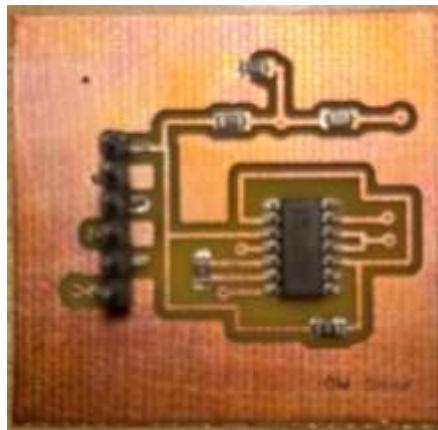
*Figure 44: Stencil from the panel-to-battery circuit.*

Again, the stencil is accurately placed on top of the PCB and a thin layer of solder paste is added to the stencil as shown in Figure 24 (Digital Power Supply). In this case, sorting out the components before applying the solder paste loses importance due to the simplicity. However, it can always prevent errors and inconveniences. One more time, once the solder paste is added to the PCB, the components are placed, and the device is deposited in the furnace.

### *VI.8. Verification Plan of the panel-to-battery circuit*

After the population and soldering of the PCBs (Figure 45), the boards are tested following the Verification Plan in order to guarantee they still meet the requirements as, despite having proven it in the simulations, results change when testing in practice (compared to theoretical results). This plan consists of certain tests that assure proper

performance. First of all, the panel-battery charging system must not suffer damage at temps down to  $-40^{\circ}\text{C}$  ([Requirement 1.a.ii.1](#)) and must maintain voltage specifications at a temperature range of  $0 - 70^{\circ}\text{C}$  ([Requirement 1.b.ii.1](#)); therefore, all the selected components including solar panels and batteries have a minimum storage temperature of at least  $-40^{\circ}\text{C}$  and an operating temperature range of at least  $0 - 70^{\circ}\text{C}$ . Note that a test on how the panel-to-battery circuit physically responds to temperature and long-lasting operations (12 hours run) should have been done. However, due to lack of equipment and time these tests have not been carried out.



*Figure 45: Top view of the populated panel-to-battery PCB.*

During the testing of the battery system, no solar panels were used as these were not available in the laboratory. To simulate the solar panel operation, a DC power supply was used to supply the circuit. As it was calculated, the solar panel configuration supplies  $33.6\text{V}$  and therefore, the DC power supply is set to  $33.6\text{V}$ . Likewise, the batteries were not available in the laboratory and hence, some resistors were used. In order to simulate the charging of the battery ( $17\text{V}$   $150\text{mA}$ ), a resistance of  $113\Omega$  (Ohm's law – Eq. 1) should be used. However, the resistors in the laboratory have a maximum power of  $0.25\text{W}$  and consequently, the power should be calculated.

Eq. 29

$$P_{Load} = \frac{V_{Output}^2}{R_{Load}} \Rightarrow$$

$$\Rightarrow P_{Load} = \frac{17^2}{113} = 2.56W$$

This value exceeds the power limit and therefore, the resistor would malfunction, or it could even melt. To operate inside the limit, the resistance should be higher than  $1156\Omega$  (Eq. 29). The output voltage is dependent on the current and vice versa (Ohm's law); therefore, any resistance can be used as long as the output voltage is the desired. Thus, an arbitrary value of  $1800\Omega$  was used to test the PCB. Using this resistor, the following results are obtained when the input is  $33.6V$ :

	Voltage (V)	Current (mA)
Input	33.6	17.0
Output	17.7	9.73

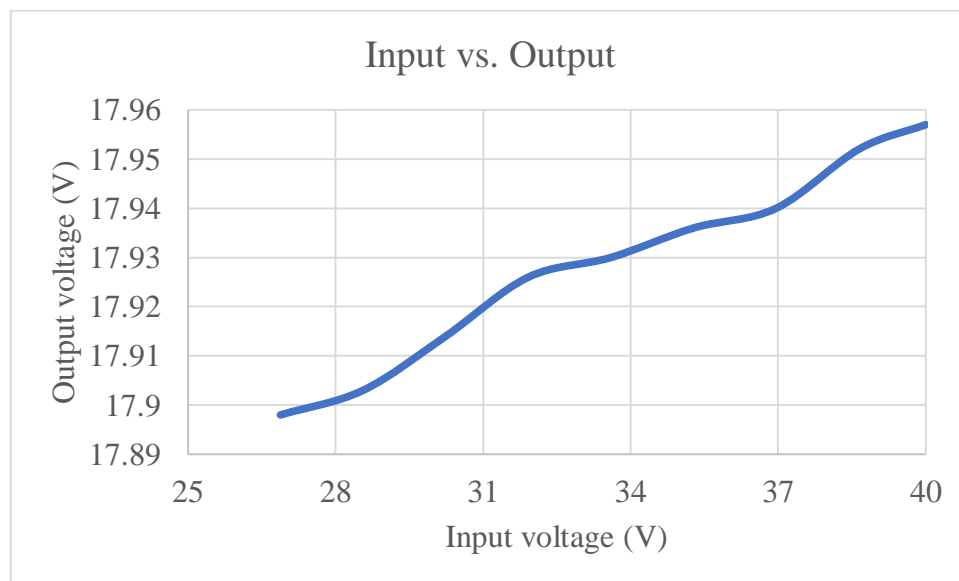
Table 32: Output voltage and current from the panel-to-battery circuit at an input voltage of  $33.6V$  with a load of  $1800\Omega$

As it can be observed, the output voltage is higher than expected (4.11% higher). With the previous values and, despite not having much sense (not using adequate resistance) and not being questioned, an efficiency of 30.2% is obtained (Eq. 3). Then, similar to [Requirement 4.e](#), when the panel-to-battery circuit is brought under +/-20% input voltage conditions (26.9V and 40.3V), it shall still maintain voltage specifications which, in this case, will be set to +/-5% of the desired output (16.15V – 17.85V). When testing for +20%, the input voltage is set to 40.0V as in the [UA723CD's datasheet](#) is recommended not to surpass 40.0V. Following these conditions, the resulting voltages are shown in Table 33. In addition, in Graph 12, the evolution of output voltages when

the input voltage goes from -20% to +20% is represented. The curve has been produced with points each of 5%.

	-20% (V)	+20% (V)
Input	26.90	40.00
Output	17.69	17.76

Table 33: Voltage from the panel-to-battery circuit at a +/-20% input voltage.



Graph 12: Evolution of the output voltage when varying the input voltage from -20% to +20% of nominal voltage of the panel-to-battery circuit.

Finally, the output current is measured under short-circuit conditions. While not being any short circuit requirements, the current should be below 0.65A (Eq. 27). The results are exposed in Table 34.

	Current (mA)
Output	613.4

Table 34: Output current of the panel-to-battery circuit under short-circuit conditions.

Once all the charging system has been selected and tested, it is time to calculate the total weight of the panel-to-battery system and prove it does not surpass the weight



limit from [Requirement 3.b](#). First of all, the solar panel arrangement which consists of 4 PV Logic 10 solar panels (1.5kg per solar panel) has a total weight of 6kg and a volume of  $2.78 \cdot 10^{-3} \text{m}^3$ . Using a scale, the panel-to-battery circuit's weight, while negligible, is measured to be 4g (3g before population). Using a ruler, the panel-to-battery circuit's size is 3.5cm x 3.5cm x 1cm which gives a total volume of  $1.23 \cdot 10^{-5} \text{m}^3$ . The battery configuration which consists of 14 VARTA batteries (0.014kg per battery) has a total weight of 0.196kg and a volume of  $7.51 \cdot 10^{-5} \text{m}^3$ . Therefore, the total weight and volume of the panel-battery charging system are 6.196kg and  $2.87 \cdot 10^{-3} \text{m}^3$ . Overall, the mass and volume of the battery charging system and the DPS together are 6.202kg and  $2.89 \cdot 10^{-3} \text{m}^3$  (assuming the different parts are cuboids and neglecting connection between parts).

### *VI.9. Conclusions*

First of all, it should be clarified that the requirements to be met for the battery charging system were designed to be for the DPS. However, for the sake of the project, these requirements have been adapted and reused. Having said this, it can be seen that the desired output voltage is reasonably acquired being 4.11% higher. This increase will simply raise the current (Ohm's law – Eq. 1) as the resistance does not notably vary. As the increment is not high, the current stays within the permitted charging current range specified in the [datasheet](#), and the charging is still feasible (actually, it will be even faster). Moreover, as aforementioned, the efficiency, apart from not being questioned, does not show much due to the fact the resistor used does not accurately represent the battery system. Furthermore, when the input voltage is brought to +/-20%, the output voltage does not vary considerably, and it remains in the permitted range (+/-5%). This is coherent as the equation used to calculate the output voltage (Eq. 25) from the [UA723CD's datasheet](#) is not a function of the input voltage, and therefore it should not be dependent on it. In addition, the output current when tested under short-circuit conditions is indeed

below the 0.65A current limit. The weight of the complete battery charging system is within the permitted range (below 10 kg) and the total weight and volume of the device are below 10kg and below 1m<sup>3</sup> following [Requirement 3](#).

## VII. MANUFACTURING PLAN, COSTING, AND RISK MANAGEMENT

### *VII.1. Manufacturing Plan*

A manufacturing plan is a series of tests that must be carried out before a product can be submitted. It may require modifications, or replacement of components and therefore requires an estimate of the cost of skilled labour time <sup>[49]</sup>. Before being sent to the customer from the factory, the board needs to go through 4 inspection steps. These steps have already been successfully tested on the prototypes and therefore, any incoming issues must be caused by the sample tested, in particular. Hence, these tests are no proof of flaws in the design.

**Step 1:** Check that the exterior of the device is not worn.

If there is wear on the exterior of the circuit, repair (sand, polish, clean, or other embellishment procedures) if it is easily repairable and recycle if not.

**Step 2:** Run the device and check the loaded output voltage and current are the nominal values.

Check for soldering, connection (continuity testing), or component issues if the device does not perform correctly.

- a. If there are soldering issues with the components, check for the possibility of resoldering. If not, replace the component.
- b. If there are connection issues on the PCB, recycle components and build a new board.
- c. If there are connection issues between the subsystems of the device, enhance connection points. If it is not possible, change the wiring.

- d. If there are component issues, dissolve the solder and replace the component.

**Step 3:** Run the device short-circuiting the output and check the current is within the permitted range.

Check for soldering, connection (continuity testing), or component issues if the device does not perform correctly.

- a. If there are soldering issues with the components, check for the possibility of resoldering. If not, replace the component.
- b. If there are connection issues on the PCB, recycle components and build a new board.
- c. If there are connection issues between the subsystems of the device, enhance connection points. If it is not possible, change the wiring.
- d. If there are component issues, dissolve the solder and replace the component.

**Step 4:** Run the device continuously at room temperature for 12 hours to check whether it has excessive heat generation and whether temperature variation is within the normal range of fluctuation. Also, check the output is maintained in nominal values.

If the device performance or temperature is inadequate, find the source of the problem (component) and look for further damage. Replace the component that caused the issues.

- a. If the PCB connections have been damaged, recycle components and build a new board.

- b. If the connections between the subsystems have been damaged, enhance connection points. If it is not possible, change the wiring.
- c. If any other components have been damaged, dissolve the solder and replace the component.

**Step 5:** Using the temperature chamber, run the device at different temperatures and check the output is maintained in nominal values.

If the device performance is inadequate, find the source of the problem (component) and look for further damage. Replace the component that caused the issues.

- a. If the PCB connections have been damaged, recycle components and build a new board.
- b. If the connections between the subsystems have been damaged, enhance connection points. If it is not possible, change the wiring.
- c. If any other components have been damaged, dissolve the solder and replace the component.

**Expected time frame<sup>1</sup>:**

- a) If the exterior is worn, it is expected that professional staff can repair the exterior within half an hour.
- b) If there are soldering issues, it is expected that professional staff can resolder within half an hour.
- c) If there are connection issues on the PCB, it is expected that professional staff can remove and recycle the components within half an hour.
- d) If there are connection issues between the subsystems, it is expected that professional staff can adjust the connections within half an hour.

- e) If there are component issues, it is expected that professional staff can remove and replace the component within an hour.

<sup>1</sup>The above scenarios all assume one staff member.

## *VII.2. Cost*

This part will describe a cost analysis of the final device. The final device consists of the initial group PCB (DPS) and the battery charging system put together. The analysis will consist of studying the cost of manufacturing 10, 100, and 1000 devices. To do so, several assumptions must be made. There are various aspects to consider when estimating the cost of the device. First of all, it is essential to distinguish between recurring and non-recurring costs. On the one hand, recurring costs consist of component, PCB fabrication, PCB assembly, testing, and packaging costs. On the other hand, non-recurring costs consist of design, product-specific manufacturing equipment, test equipment, “pick and place” machinery, computer systems, and support staff costs. These two types of costs also include the salaries of technicians, engineers, and other personnel for their labour <sup>[49]</sup>.

### *a. Recurring costs*

First, the component cost of the device is carried out. It is divided into two parts, the DPS and the battery charging system. In the [Component List](#), a full display of the components used is shown. The DPS has a total cost, considering resistors, capacitors, ICs, transistors, and header pins of £2.73 per PCB. On the other hand, the battery charging system's total cost is also calculated. The solar arrangement accounts for £174.8 (£43.7 per solar panel). The circuit has a total cost, considering resistors, capacitors, an integrated circuit, and a header pin, of £1.07. The 14-battery configuration accounts for £91.56 (£6.54 per battery). All added together, gives a total cost of the panel-battery charging system of £267.43. An extra £0.03 is added for the wires that connect the different

subsystems together. Therefore, the device's total cost is £270.19 (10 devices for £2701.90). In the case of building 100 and 1000 devices, it has been estimated that the components cost would be reduced by 25% (£202.64/device) and 30% (£189.13/device), respectively, due to bulk purchasing <sup>[49]</sup>. The shipping cost has been assumed to be included in the previous figures.

Secondly, manufacturing the PCBs represents an additional cost. It will be assumed that this process is outsourced. For this cost, a PCB manufacturer firm called [Techbridge Circuits](#) will be taken as a reference <sup>[51]</sup>. On their website, by entering the size, the number of layers, quantity and other secondary parameters, different prices are offered depending on delivery time. In this case, it will be assumed that time is not in play; therefore, the cheapest option will be taken (the maximum delivery time for the number of PCBs in question is 15 days). The price for 10 DPS boards (45mm x 45mm) is £88.90 and for 10 panel-to-battery boards (35mm x 35mm) is £87.00. Therefore, for 10 devices (two different PCBs), the manufacturing costs will be £175.90 (£17.59/device). For 100 printed circuit boards, the unitary price lowers to £1.54 per large board and £1.24 per small board which makes a total of £2.78 per device (£278 for 100 devices). For 1000 printed circuit boards, the unitary price lowers even more to £0.60 per large board and £0.42 per small board which makes a total of £1.02 per device (£1020 for 1000 devices). The boards are sent back with a cost also specified on the website of £9.49 (10 devices – £0.95/device), £9.99 (100 devices – £0.10/device), and £10.49 (1000 devices – £0.10/device). It is important to bear in mind it has been assumed that manufacturing and shipping take place in the United Kingdom (prices may vary from one country to another). In addition, it is important to consider that first, a prototype (three to assure performance) must be constructed and tested (Verification Plan) and, once this has proven to be adequate, mass production can start. Therefore, before producing 10, 100,

or 1000 devices, 3 must be produced. As the prototype costs do not depend on the number of units, these costs will be reviewed in the non-recurring costs.

The mass assembly process is assumed to be outsourced and it will not be manual (as in the prototype done in this project) but will be carried out by a “pick and place” machine. It will cost 10p per component <sup>[49]</sup> (shipping costs included) with an automated machine and it will be assumed it doesn’t vary depending on the number of components. Hence, if there are 16 components in the DPS and 7 in the panel-to-battery circuit. The cost of 10, 100, and 1000 devices is £23, £230, and £2300, respectively. Nevertheless, for this assembly process, the components have to be manually selected and tested. This requires a technician whose salary is assumed to be £20 per hour including tax, pension, and overheads such as the cost of his desk, heating, and lighting <sup>[49]</sup>. It has been estimated that a professional technician can select and test 500 components per hour. It also has been assumed that the salary is based on an integer number of hours. Having said this, the cost to select and test the components necessary to build 10, 100 and 1000 devices is £20 (1 hour – £2/device), £100 (5 hours – £1.00/device), and £920 (46 hours – £0.92/device), respectively.

Once the PCBs are built, they need to be tested, calibrated, and put together. However, a distinction must be done between the verification and the manufacturing plan. The former is more detailed testing which is done on a prototype device. The latter is more reduced but is done on all the samples <sup>[49]</sup>. The latter will require again the labour of a technician whose salary is the aforementioned. In this case, it has been estimated that a technician is capable of testing, calibrating, and putting together 4 devices per hour. Then, the cost of this process for 10, 100, and 1000 devices is £60 (3 hours – £6/device), £500 (25 hours – £5/device), and £5,000 (250 hours – £5/device), respectively. Finally, the device has to be packaged and sent away. It will be assumed that the PCBs, when



delivered to the customer, are well wrapped in, for example, bubble wrap to prevent any damage in the delivery. Furthermore, the device will not have any casing that covers the PCBs. It has been estimated that 100 metres of bubble wrap cost £12 <sup>[52]</sup>. Nonetheless, for bulk purchasing, it has been estimated a discount of 10% (over 5 rolls) and of 25% (over 50 rolls) <sup>[50]</sup>. With a 100m roll of bubble wrap, 15 devices can be wrapped. Therefore, the packaging of 10, 100, and 1000 devices cost £12 (1 roll – £1.2/device), £75.6 (7 rolls – £0.76/device), and £603 (67 rolls – £0.60/device), respectively. For the shipping, a price comparator website of delivery services has been used <sup>[53]</sup>. On the website, the weight of the package is entered, and the lowest price is shown. For 10 devices (100kg) the cost is £107.69; for 100 devices (1 tonne) the cost is £147.65; for 1000 devices (10 tonnes) the cost is £1055. All the previous recurring costs are gathered in Table 35 where the total recurring cost is calculated.

Recurring costs	10 devices	100 devices	1000 devices
Component purchase	£2,701.90	£20,264.25	£189,133
PCB manufacturing	£175.90	£278	£1,020
PCB delivery	£9.49	£9.99	£10.49
Component selection and testing	£20	£100	£920
PCB assembly	£23	£230	£2300
Device testing and construction	£60	£500	£5,000
Device packaging	£12	£75.60	£603
Device delivery to customer	£107.69	£147.65	£1,055
Total	£3,109.98	£21,605.49	£200,041.49
Total/device	£311.00/device	£216.05/device	£200.04/device

*Table 35: Total recurring costs for 10, 100, and 1000 devices.*

b. *Non-recurring costs*

First of all, the design, simulation, and documentation (datasheets, application notes, video tutorials) represent a non-recurring cost as it is reusable. The design and simulation are carried out by an electronic engineer whose salary is £40 per hour including tax, pension, and overheads such as the cost of his desk, heating, and lighting (assumption) <sup>[44]</sup>. A professional engineer is estimated to take about 14 hours to make the DPS design and another 12 hours for the battery charging system (5 for the circuit and 7 for the battery and solar panel selection). The simulation of both designs takes 4 hours. The datasheets and any application notes take an extra 4 hours. Hence, the engineer would work a total of 34 hours, representing a cost of £1,360. Furthermore, the design and simulation will be carried out using certain computer software: Multisim, DipTrace, and Matlab. Of these, the only non-free license is Matlab's, which annually costs £760 and will be added to the costs <sup>[54][55][56]</sup>. Also, a technician must create the video tutorials which it has been estimated it takes him 1 hour (£20).

Moreover, a computer engineer will be needed to develop a website with customer support (helpdesk), video tutorials, and other services. This computer engineer is estimated to take about 24 hours to develop the website in question. At the same rate as the electronic engineer, it represents an additional cost of £960. A customer support operator must be any queries from calls, emails, and other sources, supposing another cost. Estimating the operator works 6 hours a day, 3 days a week at a rate of £10 per hour (including additional costs); the customer support staff costs £8,640 annually.

As PCB manufacturing is outsourced, no product-specific equipment, such as photomasks, is needed. However, the testing equipment does represent a non-recurring cost. This equipment is formed by a DC power supply of at least 40V (maximum voltage

used in the testing), two multimeters (to accelerate the testing process), several resistors (working as the load in the tests), and other testing materials, such as cables, crocodile clips... The following prices are extracted from Farnell.com (Electronic components distributor): the DC power supply (two-channel 30V – short-circuit both channels to get over 40V) costs £166.84 <sup>[57]</sup>; the multimeters cost £13.14 each (£26.28 for two) <sup>[58]</sup>; the resistors come in a kit with 31 different values (100 resistors per value) that costs £46.99 <sup>[59]</sup>; 12 crocodile clips for £3.01 <sup>[60]</sup>; and £10 for any extra material. The resistors should be renewed often to assure accurate results and therefore, it is convenient to have extra ones. All this testing equipment together, we obtain a total of £253.12.

In addition, the manufacturing, assembly, and testing of the prototypes represent a non-recurring cost. To begin with, the component cost for three devices is £810.57 (as seen previously), the PCB production costs £176.98 (including delivery) <sup>[51]</sup>, and the assembly is £6.90 (£2.30 per device) <sup>[49]</sup>. The detailed testing (Verification Plan) must be done by an engineer, and it has been estimated that the testing and construction of the prototypes take 2 hours. Therefore, the engineer's work costs £80 <sup>[49]</sup>. Summing up the prototype costs, we obtain a non-recurring cost of £1,074.45. It should be taken into account that the prototypes are not sold to any of the customers and therefore, in the case of selling one device, an extra one must be produced. Overall, the total non-recurring costs are gathered in Table 36.

	Non-recurring costs
Design, simulation, datasheets, and application notes	£1,360
Software license	£760 (annually)
Video tutorials	£20
Website development	£960
Customer support	£8,640 (annually)
Testing equipment	£253.12
Prototype manufacturing, assembly, verification plan, and construction	£1,074.45
<b>Total</b>	<b>£13,067.57</b>

Table 36: Total non-recurring costs of the project.

c. Total cost

Once the non-recurring and recurring costs have been calculated, the total costs can be determined. The unitary costs are exposed in Table 37, calculated using Eq. 30 where the recurring costs are added to the unitary non-recurring <sup>[49]</sup>.

Eq. 30 
$$\text{Unitary cost} = \text{Recurring cost} + \frac{\text{Non-recurring costs}}{\text{Number of units}}$$

	10 devices	100 devices	1000 devices
Recurring costs	£311.00/device	£216.05/device	£200.04/device
Non-recurring costs	£13,067.57	£13,067.57	£13,067.57
Unitary non-recurring costs	£1,306.76/device	£130.68/device	£13.07/device
Unitary total cost	£1,617.76/device	£346.73/device	£213.11/device
Total cost	£16,177.57 <sup>1</sup>	£34,672.57 <sup>1</sup>	£213,107.57 <sup>1</sup>

Table 37: Total and unitary costs for 10, 100, and 1000 devices.

<sup>1</sup>All the product prices include the VAT.

### VII.3. Risk management

The previous costing plan only considers the cost of the used components, the manufacturing cost, and the testing cost (i.e., the cost if every step goes as expected). However, it is crucial to include any risks that can affect project performance, timescales, cost overrun, or safety <sup>[56]</sup>. These risks represent a financial cost that can be measured. First, they have to be identified and therefore, it is essential to consider both the plausible risks that cover the complete lifecycle of the project and the requirements that cover the entire lifecycle of the product (design, construction, installation, operation, and, eventually, disposal of the product) <sup>[62]</sup>. Then, these risks are categorized by their impact and probability of occurrence, and the optimal approach and actions to take are described. The possible values for the impact, probability and approach are exposed in Table 38, Table 39, and Table 40. The identified risks are shown in Table 41 where they have been categorized and ranked by impact multiplied by probability <sup>[61]</sup>.

Probability (%)	Description
0 – 10 (1)	Remove
20 – 40 (2)	Unlikely
40 – 60 (3)	Possible
60 – 80 (4)	Probable
80 – 100 (5)	Highly probable

Table 38: Description and possible probabilities of occurrence.

Impact	Description
1	Insignificant
2	Minor
3	Moderate
4	Major
5	Catastrophic

Table 39: Description and possible values for the impact of occurrence.

Approach	Description
Avoid (Av)	Change or abandon the objective associated with the risk; or choose alternative actions that make the risk irrelevant.
Transfer (T)	Transfer liability and ownership by financial means or by contractual terms or share the risk.
Mitigate (M)	Mitigate the possibility of the risk occurring by modifying the causes of the risk; limit the risk's impact to an acceptable level.
Accept (Ac)	Control and manage residual risks.
Contingency (C)	Contingency plans developed in response to a risk if it cannot be avoided, transferred, reduced, or accepted.

*Table 40: Description of the different approaches towards risk <sup>[64]</sup>.*

Rank	Risk title	Impact	Probability	Approach	Actions taken
1	Damage to the device caused by transportation.	4	3	M	Improve the packaging (e.g., bubble wrap) of the vulnerable items. Increase the number of samples.
2	Performance requirements not being satisfied in the testing.	5	2	C	Redesign the device considering all possible corner-case scenarios.
3	Lack of power supplied by the solar panels or malfunction due to meteorological conditions.	4	2	T	Establish a high correction factor in case meteorological conditions are not optimal.
4	Connection issues in the cooper of the PCBs during manufacturing or due to any posterior damage.	3	2	M	Widen the connection lines and avoid oblique lines. Increase the number of samples.
5	Malfunction or incorrect placement of the electronic components from the PCBs during manufacturing and testing.	2	3	M	Test every component and carefully sort them before soldering. Replace the damaged or incorrect components.
6	Lack of power supplied by the solar panels due to dust or shadowing.	3	2	T	Find a suitable place for the device where shadow and dust interference are minimal and have a regular maintenance.
7	Damage to the device due to low-temperature issues.	5	1	M	Avoid placing the device in such conditions. Improve casing and heat transfer of the device.
8	Considerable delay in the delivery of the final product.	5	1	C	Investigate the root cause of the problem and take immediate action.
9	Malfunction of the device due to the entry of water in the device.	4	1	T	Improve casing of the device to avoid water entry.
10	Considerable delay in the delivery of the components or the PCBs.	2	2	Av	Find alternative suppliers.
11	Malfunction of the device due to high-temperature issues.	2	2	M	Avoid placing the device in such conditions. Improve casing and heat transfer of the device.
12	Components from the Component List are not available.	1	4	Av	Find alternative suppliers.
13	Considerable cost excess compared to the cost.	3	1	Av	Find alternative suppliers, outsource/insource processes.
14	Incorrect PCB size or weight.	2	1	M	Redesign the model.

Table 41: Risk identification, categorization, and ranking.

Once the risks have been identified and categorized, a risk matrix can be carried out. This matrix is a more visual representation of the previous risks and their criticality [63]. The criticality index and the matrix are represented in Table 42.

<b>LIKELIHOOD</b>	5					
	4	12				
	3		5		1	
	2		10,11	4,6	3	2
	1		14	13	9	7,8
<b>Criticality</b>		1	2	3	4	5
High						
Medium	<b>IMPACT</b>					
Low						

*Table 42: Risk matrix of the project and criticality index.*

These risks have to be considered in the cost analysis as they represent possible outcomes that ought to be fixed in case of happening and therefore, imply extra financial costs. These extra costs are included in the Contingency Table exposed hereafter (Table 43). In this table, only the top 5 risks are taken into account as the rest are considered negligible in financial terms [61]. For the former, the financial impact and probability have been estimated.



Rank	Risk title	Actions	Financial impact (F) <sup>1</sup>	Probability (P)	Contingency (F·P)
1	Damage to the device caused by transportation.	Improve the packaging (e.g., bubble wrap) of the vulnerable items. Increase the number of samples.	£9,500 <sup>2,3,4</sup>	55%	£5,225
2	Performance requirements not being satisfied in the testing.	Redesign the device considering all possible corner-case scenarios.	£2,434 <sup>5,6</sup>	40%	£974
3	Lack of power supplied by the solar panels or malfunction due to meteorological conditions.	Establish a high correction factor in case meteorological conditions are not optimal.	Transferred risk	25%	Transferred risk
4	Connection issues in the cooper of the PCBs during manufacturing or due to any posterior damage.	Widen the connection lines and avoid oblique lines. Increase the number of samples.	£4,580 <sup>3,7</sup>	20%	£916
5	Malfunction or incorrect placement of the electronic components from the PCBs during manufacturing and testing.	Test every component and carefully sort them before soldering. Replace the damaged or incorrect components.	£20-£3,220 <sup>8</sup>	40%	£1,288 (worst-case)
				<b>Total</b>	<b>£8,403</b>

Table 43: Contingency table to account for the financial impact of the top 5 risks.

<sup>1</sup>The financial impact has been estimated from the production of 1000 devices.

<sup>2</sup>£5,000 for the testing of the devices (Manufacturing Plan).

<sup>3</sup>£4,000 for adding extra devices (20 more devices).

<sup>4</sup>£500 for better packaging (double the actual packaging).

<sup>5</sup>£1,360 for new design (electronic engineer salary).

<sup>6</sup>£1,074 for prototype production and testing.

<sup>7</sup>£80 to redesign with wider lines (it is estimated that it would take the engineer less than two hours).

<sup>8</sup>Depending on the quantity of PCBs and components that have been affected, the preselection and assembly of new components can vary. £20 for one component in one PCB. £3,220 (component testing and assembly) for all the components in 1000 PCBs.

The total contingency must be added to the costs, to gain a more realistic view of the cost of the project. The contingency may not be spent but helps to be prepared for uncertain events. Therefore, the more realistic unitary cost follows Eq. 31 <sup>[61]</sup> and it is gathered in Table 44.

$$\text{Eq. 31} \quad \text{Unitary cost} = \text{Recurring cost} + \frac{\text{Non recurring costs} + \text{Contingencies}}{\text{Number of units}}$$

	10 devices	100 devices	1000 devices
Recurring costs	£311.00/device	£216.05/device	£200.04/device
Non-recurring costs	£13,067.57	£13,067.57	£13,067.57
Unitary non-recurring costs	£1,306.76/device	£130.68/device	£13.07/device
Contingency	£8,403	£8,403	£8,403
Contingency per unit	£840.30/device	£84.03/device	£8.40/device
Unitary total cost	£2,458.06/device	£430.76/device	£221.51/device
Total cost	£24,580.57 <sup>1</sup>	£43,075.57 <sup>1</sup>	£221,510.57 <sup>1</sup>

Table 44: Total costs of 10, 100, and 1000 devices taking into account the contingency.

## VIII. DATASHEET

### **Solar Panel Battery-charging Supply to a 5V and 12V Digital Power Supply**

#### **Model number**

SP2BDPS5V12V

#### **Features**

- Auto charging batteries with solar power.
- 50.1% efficiency from the batteries input to 5V and 12V terminal outputs at 20mA current load.
- Light (6.2kg) and compact ( $3 \cdot 10^{-3} \text{m}^3$ ) device.
- Device characterised for operation from 0°C to 70°C.
- Capability to be stored at -40°C.
- Maximum output current below 35mA under short circuit conditions.
- Long-lasting batteries.

#### **Applications**

- Logic 5V power supply for the sensors and processor of the Power and Environmental Control Unit of a weather station.
- Non-volatile 12V power supply for the flash memory of the Power and Environmental Control Unit of a weather station.

#### **Description**

The SP2BDPS5V12V is a device composed of 4 solar panels, 14 batteries, a panel-to-battery circuit (SP2B) which obtains power from the solar panels and charges

the batteries, and a digital power supply (DPS) which obtains power from the batteries and delivers a 5V and a 12V output.

The solar panels used are PV Logic 10W Polycrystalline solar panels and are connected 2 panels in series paralleled with another 2 panels in series. The batteries used are VARTA's 1.2V nickel metal hydride 510mAh rechargeable batteries and are connected in series.

Schematics

- Device

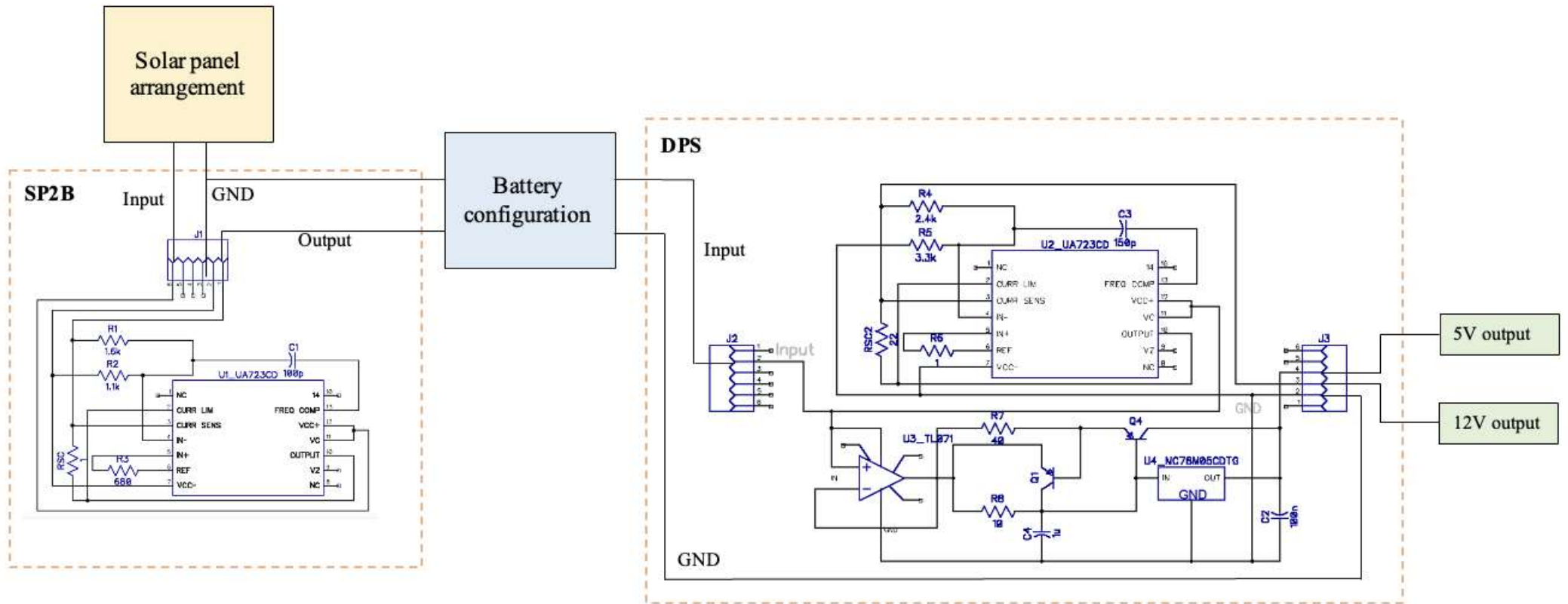
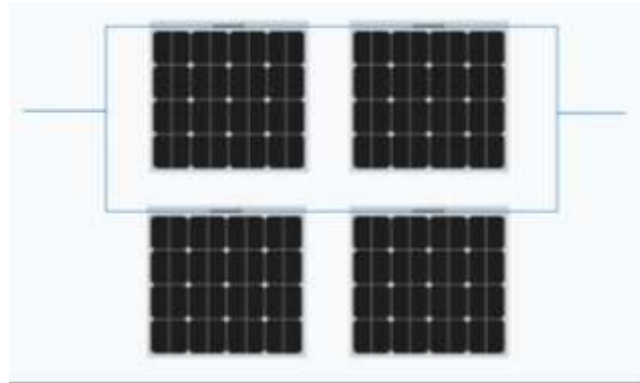


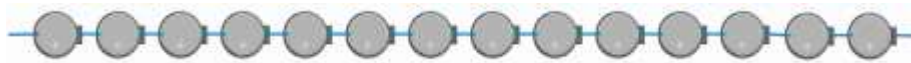
Figure 46: Schematic of the entire device SP2BDPS5V12V.

- Solar panel arrangement



*Figure 47: Solar panel arrangement formed by 4 PV Logic 10 connected in series-parallel.*

- Battery configuration



*Figure 48: Battery configuration formed by 14 VARTA batteries in series.*

**Maximum ratings** ( $T_A = 25^\circ\text{C}$ , unless otherwise noted) (See Note 1)

Rating	Symbol	Value	Unit
Input voltage	$V_I$		Vdc
SP2B		50	
DPS		35	
Operating temperature range	$T_{op}$		$^\circ\text{C}$
SP2B		+150	
DPS		+150	
Battery		0 to +85	
Solar panel		-40 to +85	
Device		0 to +85	
Storage temperature range	$T_{stg}$		$^\circ\text{C}$
SP2B		-65 to +150	
DPS		-65 to +150	
Battery (less than 30 days)		-40 to +85	
Solar panel		-40 to +85	
Device (less than 30 days)		-40 to +85	

*Table 45: SP2BDPS5V12V maximum ratings at a 25°C temperature.*

Stresses exceeding those listed in the Maximum ratings (Table 45) may damage the device. If any of these limits are exceeded, device functionality should not be assumed, damage may occur, and reliability may be affected.

Notes:

1. More specific maximum ratings from the solar panel can be seen in its [datasheet](#).

More specific maximum ratings from the battery can be seen in its [datasheet](#).

**Recommended operating conditions** ( $T_A = 25^\circ\text{C}$ , unless otherwise noted)

Rating	Symbol	MIN MAX	Unit
Input voltage	$V_I$		Vdc
SP2B		9.5    40	
DPS		9.5    35	
Operating temperature range	$T_{op}$		$^\circ\text{C}$
SP2B		0    70	
DPS		0    70	
Device		0    70	

Table 46: SP2BDPS5V12V recommended operating conditions at a  $25^\circ\text{C}$  temperature.



**Electrical characteristics at specified free air temperature** (See Note 2, 3,4, and 5)

Parameter	Test conditions	T <sub>A</sub> (°C)	MIN	TYP	MAX	UNIT
Output voltage						V
SP2B	V <sub>I</sub> = 33.6V R <sub>Load</sub> = 1800Ω	25	16.03	17.7	18.05	
SP2B	V <sub>I</sub> = 33.6V R <sub>Load</sub> = 113Ω	0 to 70	15.64		19.69	
DPS 5V	V <sub>I</sub> = 16.7V R <sub>Load</sub> = 250Ω	25	5.003	4.98*	5.003	
DPS 5V	V <sub>I</sub> = 16.7V R <sub>Load</sub> = 250Ω	0 to 70	4.991		5.003	
DPS 12V	V <sub>I</sub> = 16.7V R <sub>Load</sub> = 599Ω	25	11.48	11.9	12.49	
DPS 12V	V <sub>I</sub> = 16.7V R <sub>Load</sub> = 599Ω	0 to 70	10.94		12.09	
Output current						mA
SP2B	V <sub>I</sub> = 33.6V R <sub>Load</sub> = 1800Ω	25	8.90		10.03	
SP2B	V <sub>I</sub> = 33.6V R <sub>Load</sub> = 113Ω	0 to 70	138.4	9.73	174.2	
DPS 5V	V <sub>I</sub> = 16.7V R <sub>Load</sub> = 250Ω	25		20.0		
DPS 5V	V <sub>I</sub> = 16.7V R <sub>Load</sub> = 250Ω	0 to 70	19.96		20.01	
DPS 12V	V <sub>I</sub> = 16.7V R <sub>Load</sub> = 599Ω	25		19.8		
DPS 12V	V <sub>I</sub> = 16.7V R <sub>Load</sub> = 599Ω	0 to 70	18.26		20.18	
Short circuit current						mA
SP2B	V <sub>I</sub> = 33.6V V <sub>O</sub> = 0V	25	608.0		620.3	
SP2B	V <sub>I</sub> = 33.6V V <sub>O</sub> = 0V	0 to 70	526.6	613.0	667.2	
DPS 5V	V <sub>I</sub> = 16.7V V <sub>O</sub> = 0V	25	26.7		27.7	
DPS 5V	V <sub>I</sub> = 16.7V V <sub>O</sub> = 0V	0 to 70	25.9	26.3*	32.4	
DPS 12V	V <sub>I</sub> = 16.7V V <sub>O</sub> = 0V	25	28.2		28.2	
DPS 12V	V <sub>I</sub> = 16.7V V <sub>O</sub> = 0V	0 to 70	30.4	32.6*	24.4	
Input regulation						mV/V
SP2B	V <sub>I</sub> = 27V to 40V	25	2.4	4.0	5.4	
DPS 5V	V <sub>I</sub> = 13V to 20V	25	2.7	4.9	6.0	
DPS 12V	V <sub>I</sub> = 13V to 20V	25	4.1	82	344	

*Table 47: SP2BDPS5V12V electrical characteristics at specified test conditions and free air temperature.*

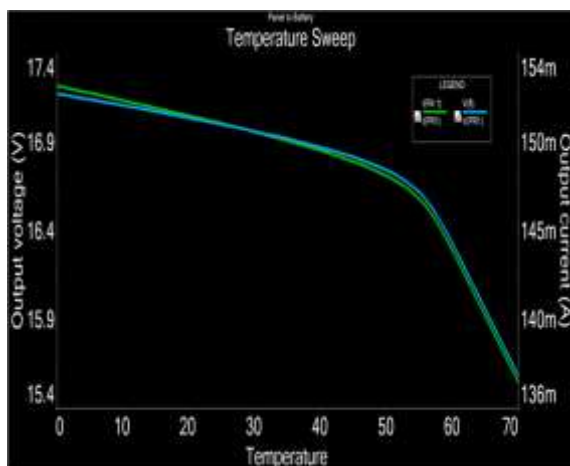
Notes:

- The typical values are obtained in the prototype testing.

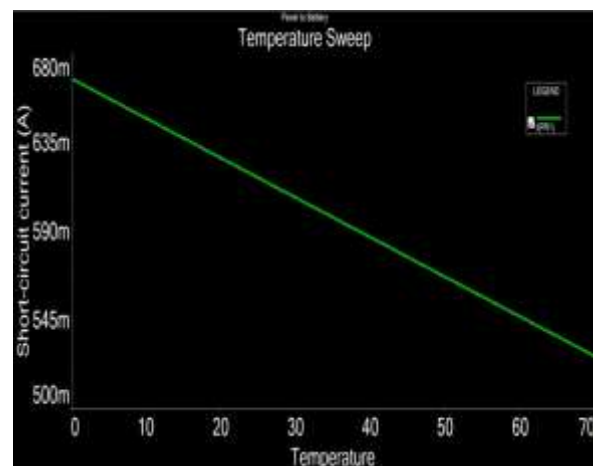
3. The minimum and maximum values are obtained from simulations in Multisim which can be found in the graphs exposed hereafter and in the [Annex](#). At 25°C, the values are extracted from the worst-case scenario of resistance tolerances. From 0 to 70°C, the values are extracted from the temperature sweep analysis.
4. As simulations and testing results may vary, it may happen that the typical value is not within the minimum-maximum range. These cases are indicated with ‘\*’.
5. The input regulation values are obtained from the prototype testing where the input was varied +/-20% from nominal. The values have been calculated using Eq. 32 and extracting the minimum, maximum, and average values.

### Output performance in terms of temperature

- SP2B

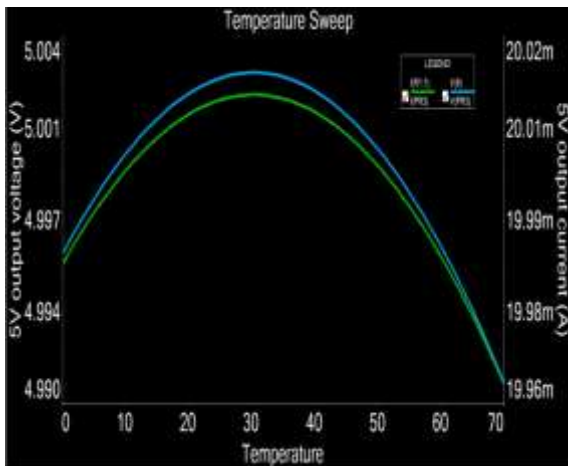


Graph 13: Relationship between the output and temperature in the SP2B.

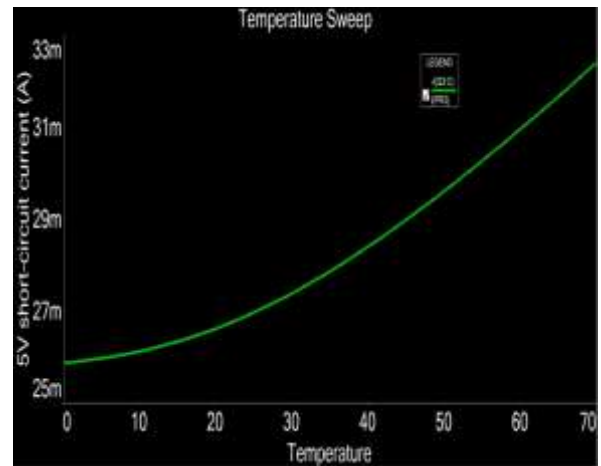


Graph 14: Relationship between the short-circuit current and temperature in the SP2B.

- 5V DPS output:

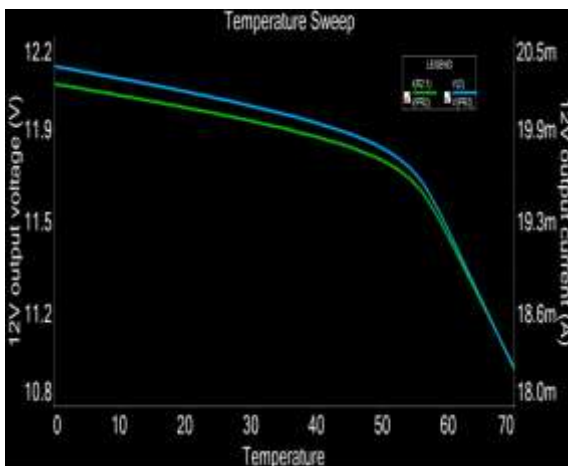


Graph 15: Relationship between the output and temperature in the 5V output of the DPS.

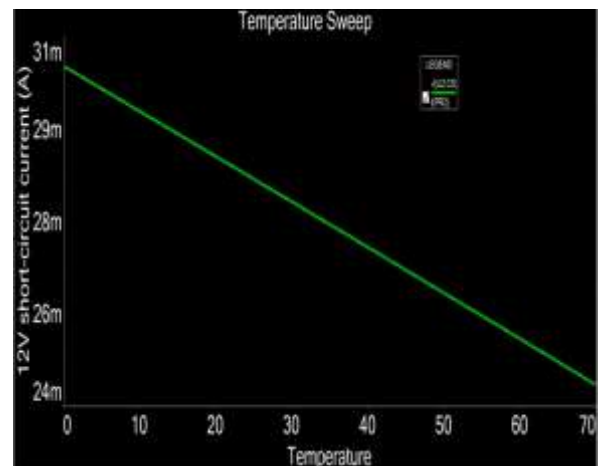


Graph 16: Relationship between the short-circuit current and temperature in the 5V output of the DPS.

- 12V DPS output:



Graph 17: Relationship between the output and temperature in the 12V output of the DPS.



Graph 18: Relationship between the short-circuit current and temperature in the 12V output of the DPS.

**PCB layout**

- SP2BGraph 18:

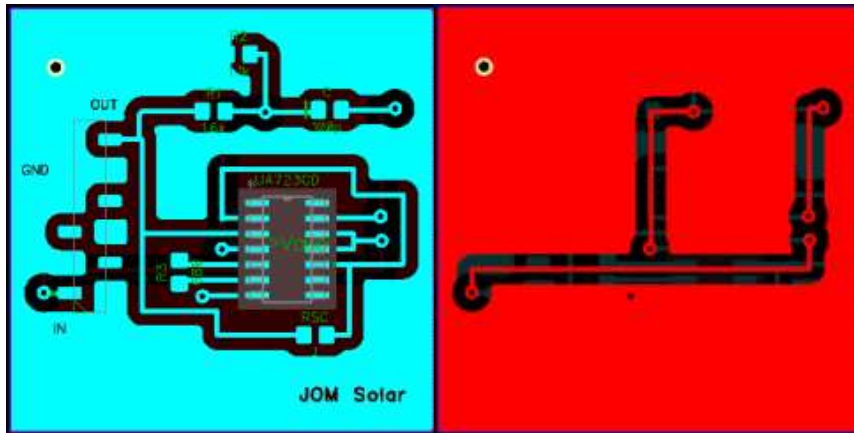


Figure 49: PCB layout from the SP2B. Top view on the left and bottom view on the right.

- DPS:

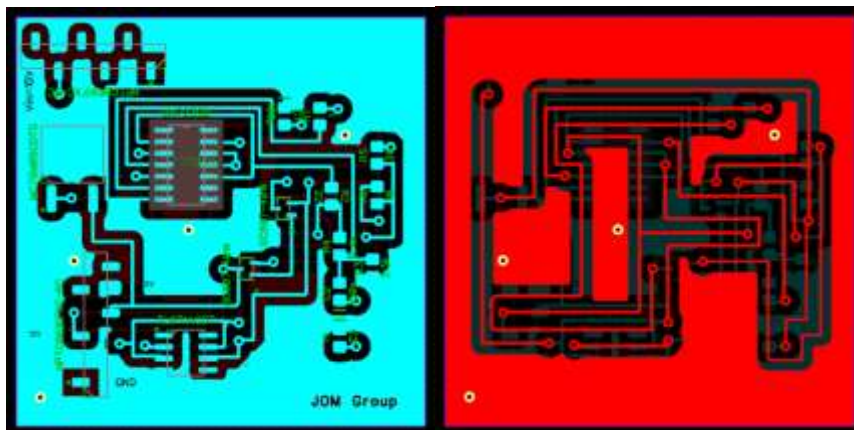


Figure 50: PCB layout from the DPS. Top view on the left and bottom view on the right.

### Pin configuration

- SP2B

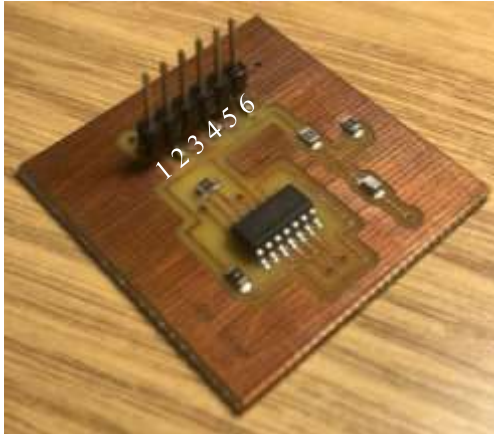


Figure 51: Pin configuration of the SP2B.

- DPS

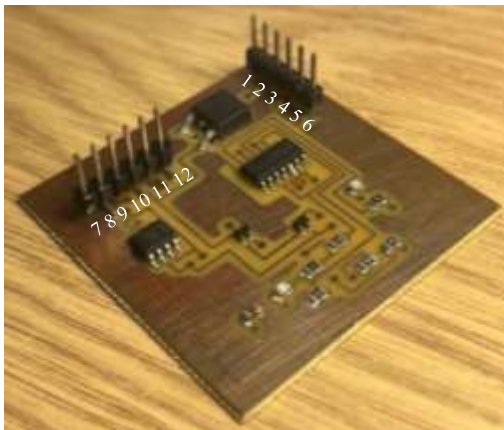


Table 49: Pin configuration of the DPS.

Pin number	Pin function
1	Input
2, 3, and 4	No connection
5	Ground
6	Output

Table 48: Description of the SP2B's pin configuration.

Pin number	Pin function
1, 3, 4, 5, 6, 7, 11, and 12	No connection
2	Input
8	Ground
9	12V output
10	5V output

Table 50: Description of the DPS's pin configuration.

## Component list

Component name	Pattern/Range	Value	Manufacturer	Quantity
Resistor	0805	1 $\Omega$	Not unique	2
Resistor	0805	10 $\Omega$	Not unique	1
Resistor	0805	22 $\Omega$	Not unique	1
Resistor	0805	39 $\Omega$	Not unique	1
Resistor	0805	680 $\Omega$	Not unique	1
Resistor	0805	1.1k $\Omega$	Not unique	1
Resistor	0805	1.6k $\Omega$	Not unique	1
Resistor	0805	2.4k $\Omega$	Not unique	1
Resistor	0805	3.5k $\Omega$	Not unique	1
Capacitor	0805	100pF	Not unique	1
Capacitor	0805	150pF	Not unique	1
Capacitor	0805	100nF	Not unique	1
Capacitor	0805	1 $\mu$ F	Not unique	1
BC807-40W	SOT-323	No value	Not unique	2
TL071	SOIC-8	No value	Texas Instruments	1
UA743CD	SOIC 14	No value	Texas Instruments	2
MC78M05CDTG	TO-252-3	No value	On Semiconductor	1
M20-8770646	6 contacts, 1 row	No value	Harmin	3
Rechargeable Ni-MH Button	55750201501	1.2V	Varta	14
PV Logic 10	STP010P	10W	PV Logic	4

Table 51: Component list from the SP2BDPS5V12V.

## IX. ANNEX

*IX.1. Component List*

RESISTORS ( $\Omega$ )	PATTERN/IMAGE	QUANTITY PER DEVICE	COST PER UNIT (£)
0.2 1%	0805	2	£0.01
1 1%	0805		£0.01
10 5%	0805	1	£0.01
11 5%	0805		£0.01
12 5%	0805		£0.01
15 5%	0805		£0.01
16 5%	0805		£0.01
18 5%	0805		£0.01
20 5%	0805		£0.01
22 5%	0805	1	£0.01
24 5%	0805		£0.01
27 5%	0805		£0.01
30 5%	0805		£0.01
33 5%	0805		£0.01
36 5%	0805		£0.01
39 5%	0805	1	£0.01
43 5%	0805		£0.01
47 5%	0805		£0.01
51 5%	0805		£0.01
56 5%	0805		£0.01
62 5%	0805		£0.01
68 5%	0805		£0.01
75 5%	0805		£0.01
82 5%	0805		£0.01
91 5%	0805		£0.01
100 5%	0805		£0.01
110 5%	0805		£0.01
120 5%	0805		£0.01
150 5%	0805		£0.01
160 5%	0805		£0.01
180 5%	0805		£0.01

200 5%	0805		£0.01
220 5%	0805		£0.01
240 5%	0805		£0.01
270 5%	0805		£0.01
300 5%	0805		£0.01
330 5%	0805		£0.01
360 5%	0805		£0.01
390 5%	0805		£0.01
430 5%	0805		£0.01
470 5%	0805		£0.01
510 5%	0805		£0.01
560 5%	0805		£0.01
620 5%	0805		£0.01
680 5%	0805	1	£0.01
750 5%	0805		£0.01
820 5%	0805		£0.01
910 5%	0805		£0.01
1K0 5%	0805		£0.01
1K1 5%	0805	1	£0.01
1K2 5%	0805		£0.01
1K5 5%	0805		£0.01
1K6 5%	0805	1	£0.01
1K8 5%	0805		£0.01
2K0 5%	0805		£0.01
2K2 5%	0805		£0.01
2K4 5%	0805	1	£0.01
2K7 5%	0805		£0.01
3K0 5%	0805		£0.01
3K3 5%	0805	1	£0.01
3K6 5%	0805		£0.01
3K9 5%	0805		£0.01
4K3 5%	0805		£0.01
4K7 5%	0805		£0.01
5K1 5%	0805		£0.01
5K6 5%	0805		£0.01
6K2 5%	0805		£0.01
6K8 5%	0805		£0.01



7K5 5%	0805		£0.01
8K2 5%	0805		£0.01
9K1 5%	0805		£0.01
10K 5%	0805		£0.01
11K 5%	0805		£0.01
12K 5%	0805		£0.01
15K 5%	0805		£0.01
16K 5%	0805		£0.01
18K 5%	0805		£0.01
20K 5%	0805		£0.01
22K 5%	0805		£0.01
24K 5%	0805		£0.01
27K 5%	0805		£0.01
30K 5%	0805		£0.01
33K 5%	0805		£0.01
36K 5%	0805		£0.01
39K 5%	0805		£0.01
43K 5%	0805		£0.01
47K 5%	0805		£0.01
51K 5%	0805		£0.01
56K 5%	0805		£0.01
62K 5%	0805		£0.01
68K 5%	0805		£0.01
75K 5%	0805		£0.01
82K 5%	0805		£0.01
91K 5%	0805		£0.01
100K 5%	0805		£0.01
110K 5%	0805		£0.01
120K 5%	0805		£0.01
150K 5%	0805		£0.01
160K 5%	0805		£0.01
180K 5%	0805		£0.01
200K 5%	0805		£0.01
220K 5%	0805		£0.01
240K 5%	0805		£0.01
270K 5%	0805		£0.01
300K 5%	0805		£0.01

330K 5%	0805		£0.01
360K 5%	0805		£0.01
390K 5%	0805		£0.01
430K 5%	0805		£0.01
470K 5%	0805		£0.01
510K 5%	0805		£0.01
560K 5%	0805		£0.01
620K 5%	0805		£0.01
680K 5%	0805		£0.01
750K 5%	0805		£0.01
820K 5%	0805		£0.01
910K 5%	0805		£0.01
1M 5%	0805		£0.01

Table 52: Available resistors characteristics and units used.

CAPACITORS	PATTERN	QUANTITY PER DEVICE	COST PER UNIT (£)
10pF COG 5% 50V	0805		£0.03
15pF COG 5% 63V	0805		£0.03
22pF COG 5% 63V	0805		£0.03
33pF COG 5% 63V	0805		£0.03
47pF COG 5% 63V	0805		£0.03
68pF COG 5% 63V	0805		£0.03
100pF COG 5% 50V	0805	1	£0.05
150pF COG 5% 63V	0805	1	£0.05
220pF COG 5% 63V	0805		£0.05
330pF COG 5% 63V	0805		£0.05
470pF COG 5% 63V	0805		£0.05
680pF COG 5% 63V	0805		£0.05
1nF X7R 10% 63V	0805		£0.05

1.5nF X7R 10% 63V	0805		£0.05
2.2nF X7R 10% 63V	0805		£0.05
3.3nF X7R 10% 63V	0805		£0.05
4.7nF X7R 10% 63V	0805		£0.05
6.8nF X7R 10% 63V	0805		£0.05
10nF 10% 50V	0805		£0.05
15nF X7R 10% 63V	0805		£0.05
100nF 10% 50V	0805		£0.05
1µF 10% 50V	0805	1	£0.05
10µF 10% 16V	0805		£0.10
150µF 20% 16V	<a href="http://www.farnell.com/datasheets/2151198.pdf">http://www.farnell.com/datasheets/2151198.pdf</a>	1	£0.10
330µF 20% 16V	<a href="https://www.farnell.com/datasheets/3486024.pdf">https://www.farnell.com/datasheets/3486024.pdf</a>		£0.10

Table 53: Available capacitors characteristics and units used.

INDUCTORS	PATTERN (Note: non-standard pattern)	QUANTITY PER DEVICE	COST PER UNIT (£)
47µH 20% 0.25A 1Ω	<a href="https://www.we-online.com/katalog/datasheet/744031470.pdf">https://www.we-online.com/katalog/datasheet/744031470.pdf</a>		£0.44
82µH 20% 0.59A 552mΩ	<a href="https://docs-emea.rs-online.com/webdocs/1662/0900766b81662b7e.pdf">https://docs-emea.rs-online.com/webdocs/1662/0900766b81662b7e.pdf</a>		£0.44
150µH 20% 0.48A 905mΩ	<a href="https://docs-emea.rs-online.com/webdocs/1662/0900766b81662b7e.pdf">https://docs-emea.rs-online.com/webdocs/1662/0900766b81662b7e.pdf</a>		£0.55
220µH 20% 0.37A 1.48Ω	<a href="https://docs-emea.rs-online.com/webdocs/1662/0900766b81662b7e.pdf">https://docs-emea.rs-online.com/webdocs/1662/0900766b81662b7e.pdf</a>		£0.55
330µH 20% 0.32A 2.16Ω	<a href="https://docs-emea.rs-online.com/webdocs/1662/0900766b81662b7e.pdf">https://docs-emea.rs-online.com/webdocs/1662/0900766b81662b7e.pdf</a>		£0.44

Table 54: Available inductors characteristics and units used.

DIODES	PATTERN	QUANTITY PER DEVICE	COST PER UNIT (£)
1N4148	SOD-123		£0.15

1N5819HW	SOD-123		£0.15
SD103AW-E3-08	SOD-123		£0.21
PMEG4010EGWX	SOD-123		£0.21
RS2B	SMB		£0.19

Table 55: Available diodes characteristics and units used.

LEDs	PATTERN	QUANTITY PER DEVICE	COST PER UNIT (£)
LTST-C171KRKT	0805		£0.10
LTST-C171KGKT	0805		£0.10

Table 56: Available LEDs characteristics and units used.

TRANSISTORS	PATTERN	QUANTITY PER DEVICE	COST PER UNIT (£)
BJT			
NPN			
BC817-40W	SOT-323		£0.13
PNP			
BC807-40W	SOT-323	2	£0.16
MOSFET			
N-Channel			
MCH3478-TL-H	SOT-323		£0.32
P-Channel			
DMP2160UW-7	SOT-323		£0.30

Table 57: Available transistors characteristics and units used.

ICs	PATTERN	QUANTITY PER DEVICE	COST PER UNIT (£)
TL071	SOIC-8	1	£0.45
UA741	SOIC-8		£0.45
MC33063AD	SOIC-8		£0.55
TL317CD	SOIC-8		£0.72
UA723CD	SOIC-14	2	£0.68
MC78M05CDTG	TO-252-3	1	£0.42
MC78M12CDTG	TO-252-3		£0.42

Table 58: Available integrated circuits characteristics and units used.

HEADER PINS	PATTERN	QUANTITY PER DEVICE	COST PER UNIT (£)
6 contacts, 1 row	<a href="https://onecall.farnell.com/harwin/m20-8770646/connector-header-6pos-2-54mm-1row/dp/3225973">https://onecall.farnell.com/harwin/m20-8770646/connector-header-6pos-2-54mm-1row/dp/3225973</a>	3	£0.30

Table 59: Available header pins characteristics and units used.

## IX.2. Matlab coding

### Worst-case scenario

```

t=0.05
VD=17
R1=1600*(1-t):1:1600*(1+t)
R2=1100*(1-t):1:1100*(1+t)
Vref=6.8:0.01:7.5
maxV=VD
minV=VD
for i=1:length(R1)
    for j=1:length(R2)
        for k=1:length(Vref)
            V0=Vref(k)*(R1(i)+R2(j))/R2(j)
            I0=V0/113
            if V0>maxV
                maxV=V0
                maxVI=I0
                maxVR1=R1(i)
                maxVR2=R2(j)
                maxVVref=Vref(k)
            end
            if V0<minV
                minV=V0
                minVI=I0
                minVR1=R1(i)
                minVR2=R2(j)
                minVVref=Vref(k)
            end
        end
    end
end

```

```

        end
    end
end

maxVP=(maxV/VD-1)*100
minVP=(minV/VD-1)*100

```

### Complete worst-case scenario

```

t=0.05;
TCR1=0.0001;
TCR2=0.0001;
Tamb=25;
VD=17;
R1=1600*(1-t):1:1600*(1+t);
R2=1100*(1-t):1:1100*(1+t);
Vref=6.8:0.01:7.5;
T=0:1:70;
TCIC=-0.015:0.001:0.015;
maxV=VD;
minV=VD;
for i=1:length(R1)
    for j=1:length(R2)
        for k=1:length(Vref)
            for l=1:length(T)
                for m=1:length(TCIC)
                    R1T=R1(i)*(1+TCR1*(T(l)-Tamb));
                    R2T=R2(j)*(1+TCR2*(T(l)-Tamb));
                    V0=Vref(k)*(R1T+R2T)/R2T;
                    V0T=V0*(1+(TCIC(m)*(T(l)-Tamb))/100);
                    I0T=V0T/113;
                    if V0T>maxV
                        maxV=V0T;
                        maxVI=I0T;
                    end
                end
            end
        end
    end
end

```

```
maxVR1=R1T;
maxVR2=R2T;
maxVVref=Vref(k);
maxT=T(1);
maxTCIC=TCIC(m);
end
if V0T<minV
    minV=V0T;
    minVI=I0T;
    minVR1=R1T;
    minVR2=R2T;
    minVVref=Vref(k);
    minT=T(1);
    minTCIC=TCIC(m);
end
end
end
end
end
end
maxVP=(maxV/VD-1)*100;
minVP=(minV/VD-1)*100;
```

IX.3. Other tables, equations, figures, and graphs

V(PR3), Nominal Run	5.00255	V(PR3), Nominal Run	5.00255
V(PR3), Worst Case Run	5.00255	V(PR3), Worst Case Run	5.00255
Worst Case Run		Worst Case Run	
DC operating point for all devices: -2.46035e-06, (-4.91819e-05% of nominal)		DC operating point for all devices: 2.46046e-06, (4.91842e-05% of nominal)	
Tolerance changes needed to achieve worst case:		Tolerance changes needed to achieve worst case:	
cc2 capacitance unchanged from 1e-06		cc2 capacitance unchanged from 1e-06	
cc1 capacitance unchanged from 1e-07		cc1 capacitance unchanged from 1e-07	
r3 resistance unchanged from 22		r3 resistance unchanged from 22	
r13 resistance increased to 42		r13 resistance decreased to 38	
r5 resistance increased to 10.5		r5 resistance decreased to 9.5	
r8 resistance unchanged from 3300		r8 resistance unchanged from 3300	
r7 resistance unchanged from 2400		r7 resistance unchanged from 2400	
cc4 capacitance unchanged from 1.5e-10		cc4 capacitance unchanged from 1.5e-10	
r6 resistance unchanged from 2		r6 resistance unchanged from 2	

Figure 52: Multisim worst-case scenario for both below (left) and over (right) the 5V output voltage.

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To desired V	T (°C)
Maximum	5.003	20.01	0.05	30
Minimum	4.991	19.96	-0.18	70

Table 60: 5V output results from Multisim's temperature sweep analysis.

V(PR2), Nominal Run	11.95680	V(PR2), Nominal Run	11.95680
V(PR2), Worst Case Run	11.47923	V(PR2), Worst Case Run	12.48829
Worst Case Run		Worst Case Run	
DC operating point for all devices: -0.477563, (3.99407% of nominal)		DC operating point for all devices: 0.531498, (4.44515% of nominal)	
Tolerance changes needed to achieve worst case:		Tolerance changes needed to achieve worst case:	
cc2 capacitance unchanged from 1e-06		cc2 capacitance unchanged from 1e-06	
cc1 capacitance unchanged from 1e-07		cc1 capacitance unchanged from 1e-07	
r3 resistance increased to 23.1		r3 resistance decreased to 20.9	
r13 resistance unchanged from 40		r13 resistance unchanged from 40	
r5 resistance unchanged from 10		r5 resistance unchanged from 10	
r8 resistance increased to 3465		r8 resistance decreased to 3135	
r7 resistance decreased to 2280		r7 resistance increased to 2520	
cc4 capacitance unchanged from 1.5e-10		cc4 capacitance unchanged from 1.5e-10	
r6 resistance increased to 2.02		r6 resistance decreased to 1.98	

Figure 53: Multisim worst-case scenario for both below (left) and over (right) the 12V output voltage.

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To desired V	T (°C)
Maximum	12.1	20.2	0.75	0
Minimum	10.9	18.3	-8.83	70

Table 61: 12V output results from Multisim's temperature sweep analysis.



I(PR1), Nominal Run	612.89958 m	I(PR1), Nominal Run	612.89958 m
I(PR1), Worst Case Run	608.08872 m	I(PR1), Worst Case Run	620.31536 m
Worst Case Run		Worst Case Run	
DC operating point for all devices: -0.00481086, (0.784934% of nominal)		DC operating point for all devices: 0.00741578, (1.20995% of nominal)	
Tolerance changes needed to achieve worst case:		Tolerance changes needed to achieve worst case:	
rr3 resistance increased to 714		rr3 resistance decreased to 646	
cc capacitance unchanged from 1e-10		cc capacitance unchanged from 1e-10	
rr1 resistance decreased to 1520		rr1 resistance increased to 1680	
rr2 resistance decreased to 1045		rr2 resistance increased to 1155	
rrsc resistance increased to 1.01		rrsc resistance decreased to 0.99	

Figure 54: Multisim’s worst-case scenario for both below (left) and over (right) the short circuit current in the panel-to-battery circuit.

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To nominal I	T (°C)
Maximum	0	667.2	8.84	0
Minimum	0	526.6	-14.1	70

Table 62: Panel-to-battery’s short circuit current results from Multisim’s temperature sweep analysis.

I(PR3), Nominal Run	27.12971 m	I(PR3), Nominal Run	27.12971 m
I(PR3), Worst Case Run	26.71100 m	I(PR3), Worst Case Run	27.65863 m
Worst Case Run		Worst Case Run	
DC operating point for all devices: -0.000418708, (1.54336% of nominal)		DC operating point for all devices: 0.00052892, (1.9496% of nominal)	
Tolerance changes needed to achieve worst case:		Tolerance changes needed to achieve worst case:	
cc2 capacitance unchanged from 1e-06		cc2 capacitance unchanged from 1e-06	
cc1 capacitance unchanged from 1e-07		cc1 capacitance unchanged from 1e-07	
rr3 resistance unchanged from 22		rr3 resistance unchanged from 22	
rr13 resistance decreased to 38		rr13 resistance increased to 42	
rr5 resistance increased to 10.5		rr5 resistance decreased to 9.5	
rr8 resistance unchanged from 3300		rr8 resistance unchanged from 3300	
rr7 resistance unchanged from 2400		rr7 resistance unchanged from 2400	
cc4 capacitance unchanged from 1.5e-10		cc4 capacitance unchanged from 1.5e-10	
rr6 resistance unchanged from 2		rr6 resistance unchanged from 2	

Figure 55: Multisim’s worst-case scenario for both below (left) and over (right) the short circuit current in the 5V output.

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To maximum I	T (°C)
Maximum	0	32.40	8.00	70
Minimum	0	25.87	-13.8	0

Table 63: 5V short circuit current results from Multisim’s temperature sweep analysis.

I(PR2), Nominal Run	28.13641 m	I(PR2), Nominal Run	28.13641 m
I(PR2), Worst Case Run	28.19478 m	I(PR2), Worst Case Run	28.19478 m
Worst Case Run		Worst Case Run	
DC operating point for all devices: 5.83623e-05, (0.207426% of nominal)		DC operating point for all devices: 5.83623e-05, (0.207426% of nominal)	
Tolerance changes needed to achieve worst case:		Tolerance changes needed to achieve worst case:	
cc2 capacitance unchanged from 1e-06		cc2 capacitance unchanged from 1e-06	
cc1 capacitance unchanged from 1e-07		cc1 capacitance unchanged from 1e-07	
r3 resistance unchanged from 22		r3 resistance unchanged from 22	
r13 resistance increased to 42		r13 resistance decreased to 38	
r5 resistance decreased to 9.5		r5 resistance increased to 10.5	
r8 resistance unchanged from 3300		r8 resistance unchanged from 3300	
r7 resistance unchanged from 2400		r7 resistance unchanged from 2400	
cc4 capacitance unchanged from 1.5e-10		cc4 capacitance unchanged from 1.5e-10	
r6 resistance unchanged from 2		r6 resistance unchanged from 2	

Figure 56: Multisim's worst-case scenario for both below (left) and over (right) the short circuit current in the 12V output.

	V <sub>Out</sub> (V)	I <sub>Out</sub> (mA)	% To maximum I	T (°C)
Maximum	0	30.45	1.50	0
Minimum	0	24.41	-18.6	70

Table 64: 12V short circuit current results from Multisim's temperature sweep analysis.

Eq. 32 
$$\text{Input regulation} = \frac{V_O - V_{ONom}}{V_I - V_{INom}}$$

#### IX.4. Chronogram

- **January**
  - 01 – 21: Complete a detailed requirement specification – Group
  - 22 – 31: Sketch the printed circuit board designs and layouts – Individual
- **February**
  - 01 – 11: Simulation and selection of the best two designs – Group
  - 12 – 18: Population and baking of the printed circuit board – Group
  - 19 – 28: Testing and data capture of the six samples – Group
- **March**
  - 01 – 15: Decision on the final design, verification plan and datasheet elaboration.
  - 16 – 31: Battery and solar panel selection.
- **April**

- Battery and solar panel selection – Individual
- 01 – 12: Solar power battery charging circuit design and layout.
- 13 – 20: Cost per unit and bulk production cost analysis.
- 21 – 30: Risk matrix elaboration
- **May**
  - 01 – 12: Solar power battery charging circuit design and layout.
  - 13 – 20: Individual PCB design and simulation – Individual
  - 21 – 31: Individual PCB layout – Individual
- **June**
  - 01 – 15: Laboratory work: Construction and testing of the individual, group, and battery charging PCBs – Individual
  - 16 – 30: Worst-case scenario, sensitivity analysis – Individual
- **July**
  - 01 – 10: Manufacturing plan, cost, and risk – Individual
  - 11 – 20: Datasheet – Individual
  - 21 – 31: Revision and formatting – Individual

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<p>[59] )