

The Analysis of Mars Electrical Power

Team 453, Problem B

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Abstract

In this essay, we investigate the possible minimum mass of a power system on Mars while meeting the energy requirement to sustain a 150kW power output for 2 earth years continuously. Our establishment of the power system model consists of three main parts: power generation, transmission, and energy storage. To further reduce the mass of the system, we exert considerable effort in evaluating and choosing materials. For solar photovoltaic panels, we compare several photovoltaic material, selecting thin-film gallium arsenide material for its lightweight and greater power generation capacity. Large-scale deployment of solar photovoltaic panels also requires sophisticated circuit design, so we further analyzed the impact of different circuit connection methods on transmission efficiency. Finally, after evaluating different energy storage methods, we choose solid-state lithium-ion batteries, which offer higher energy density with a relatively low mass. The minimum mass of the power generation system we ultimately calculate is 71.8t.

Key Words: photovoltaic power generation, minimum mass

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1 Introduction

1.1 Background

Nowadays, the explosive population growth on Earth has led to a series of issues, including resource strain, environmental degradation, etc. Since Mars has a relatively suitable climatic and geological condition, it is an ideal starting point for human's interplanetary exploration.

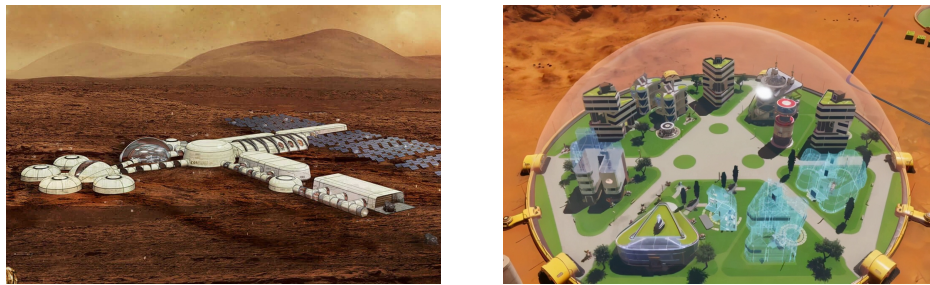


Figure 1: Imaginations of Martian Immigration

To establish a base on Mars, one of the main challenges is how to provide it with stable and sufficient power supply. Previous research has indicated that solar photovoltaic power generation is the most feasible method for power supply on Mars, and some studies have also addressed the effects of dust and temperature fluctuations on solar panels and their solutions. However, research on the lifespan and performance of energy storage technologies in the Martian environment is still insufficient.

Our study has initially constructed a Mars power supply device. Through detailed comparisons, we have further confirmed that compared to chemical batteries and modular nuclear reactors, solar panel photovoltaic power generation remains the optimal method for reducing mass and thereby lowering transportation costs. We have calculated and predicted the extent to which dust coverage weakens the panels' ability to receive sunlight, and have hypothesized crew cleaning scenarios to lay the groundwork for the subsequent design of solar panel layouts. Innovatively, we have explored how to extensively deploy solar panels on the Martian surface, considering factors such as specifications, price, and material performance, to minimize costs and mass while maximizing output power. Additionally, we have constructively determined the use of solid-state lithium-ion batteries as the energy storage device, successfully addressing issues such as safety and transportation costs.

1.2 Problem Restatement

In this study, we aim to construct a power supply system capable of providing 150 kW of continuous electrical energy to a Martian base over a period of two years. To minimize transportation costs, the system's mass should be kept as small as possible. Given the significant differences between the Martian environment and Earth's, such as frequent dust storms, thin atmosphere, and limited direct energy sources, establishing such a power supply system presents numerous challenges. Our system primarily consists of four main components: solar panels for power generation, transmission circuits, DC Switchgear and Inverter, and solid-state lithium-ion batteries for energy storage. For DC Switchgear and Inverter, through calculation and research, we assume its mass to be 0.80 tons. Subsequently, we delved into three other components. We have considered major influencing factors such as dust, Martian surface daylight hours, and thermal losses in the circuits, while neglecting minor factors. Each component is evaluated and compared using various methods to identify the optimal solution with the smallest mass and lowest cost.

2 Assumption and Notation

2.1 Assumptions

- Assumption A

The Martian atmosphere is relatively thin, so the attenuation effect of the Martian atmosphere on solar radiation is not considered.

- Assumption B

Assuming that the location chosen for constructing photovoltaic panels receives half a day of sunlight each day, which is about 12.31 hours.

- Assumption C

The solar radiation received per unit area of solar panels is the same.

- Assumption D

Ignoring the length of wires at corners and connections.

2.2 Notations

Symbols	Description	Value	Unit
W	The total energy required for offering a power of 150KW for 2 years	9.4608×10^9	kJ
F_{max}	The maximum irradiance at a point on the Martian surface in one day (approximately when it is directly hit by the sun)	577	W/m^2
F_{avg}	The average solar radiation intensity on Mars per sol	288.50	W/m^2
t	time	/	s
P'	The power of photovoltaic panels per square meter	83.46	W/m^2
$M_{backsheet}$	The total mass of the backsheet	900	kg
$M_{supportframe}$	The total mass of the support frame	36	t
$M_{additionalbrace}$	The total mass of the additional brace	13.5	t
$M_{totalbracket}$	The total mass of the bracket system	50.4	t
d_0	The average distance between Mars and the Sun	1.52	AU
R_M	The average radius of Mars	3399.2	km
N	The total number of solar panels (156mm $\times$ 156mm)	7.39×10^4	/
S	The total area of the solar panels	1797	m^2
L_1	The estimated length of the whole solar panels array	42.4	m
ρ_{Al}	The electric resistivity of aluminium	2.65×10^{-8}	$\Omega \cdot m$
ρ_{Steel}	The electric resistivity of steel	1.6×10^{-7}	$\Omega \cdot m$
ρ_1	The electric resistivity of ACSR 1/0	4.56×10^{-8}	$\Omega \cdot m$
ρ_2	The electric resistivity of ACSR 54/7	4.18×10^{-8}	$\Omega \cdot m$
η_{Al}	The ratio of aluminium in ACSR 1/0	$\frac{6}{71}$	/
η_{Steel}	The ratio of steel in ACSR 1/0	$\frac{1}{7}$	/
η'_{Al}	The ratio of aluminium in ACSR 54/7	$\frac{54}{61}$	/
η'_{Steel}	The ratio of steel in ACSR 54/7	$\frac{7}{61}$	/
P	The power required to be delivered to the base	150	KW
c	The side length of a panel	156	mm
a	The number of rows of a panel	12	/
b	The number of columns of a panel	6	/
l_t	Total length of wires in the trunk	/	m

Symbols	Description	Value	Unit
l_{1t}	Length of wires in the first trunk	$1.28 \cdot 10^4$	m
l_{2t}	Length of wires in the second trunk	$4.04 \cdot 10^3$	m
H	Height of the solar panel	2	m
D	Distance between neighboring panels	3	m
ρ	The electric resistivity of dual-junction gallium arsenide solar panel	10^{-3}	$\Omega \cdot m$
x	The number of units in one circuit	1	/
y	The number of circuits	1.026×10^3	/
R_0	The resistance of a single dual-junction gallium arsenide solar panel	$2.05 \cdot 10^{-7}$	Ω
R_1	The resistance of a unit	$1.48 \cdot 10^{-5}$	Ω
R_2	The resistance of the wires of a unit	$7.38 \cdot 10^{-3}$	Ω
R_3	The resistance of a micro-inverter connected with a unit	10	$m\Omega$
R_{t_0}	The total resistance of a unit	$1.74 \cdot 10^{-2}$	Ω
R_{t_1}	The resistance of the trunk of a single circuit	$5.24 \cdot 10^{-4} * x$	Ω
P_0	The power that a unit can transfer into electricity	0.146	KW
I	The current inside a unit	/	A
P_1	The output power of a panel unit	$0.146 - I^2 * 1.74 * 10^{-5}$	KW
P_2	The output power of a circuit	$(0.146 - 2.79 * 10^{-4} * I^2)$	KW
P_t	The output power of y such circuits in parallel connection	$1.5 * 10^2 - 1.79 * 10^{-2} I^2 - 2.69 * 10^{-1} * I^2$	KW
U_T	The voltage y circuits output in total	/	V
I_T	The current y circuits output in total	/	A
I_{max}	The total current that y circuits output	0.585	A
m_{1t}	The total mass of the wires in the trunks	$3.34 \cdot 10^3$	kg
m_{2t}	The total mass of the wires in the branches	$4.18 \cdot 10^3$	kg

Symbols	Description	Value	Unit
m_{inv}	The mass of one micro-inverter	1.0	kg
m_{invt}	The total mass of the micro-inverter	$1.03 * 10^3$	kg
M_1	The total mass of wires and micro-inverters	$8.55 * 10^3$	kg
W_1	The energy stored by the storage system in 24 hours	1.296×10^7	kJ
$m_{battery}$	The mass of the solid-state lithium-ion battery used	9000	kg
M	The total mass of the energy storage system	11.250	t
m_{total}	The total mass of reactant that is needed in the model of Hydrogen for electricity generation	595	t
E_0	The amount of energy each uranium-235 atom releases in the nuclear fission reaction	3.204×10^{-17}	KJ
N'	2.953×10^{26}	/	
n	The number of moles of uranium-235 atom	490	mol
m_U	The mass of uranium-235 atom	115.15	kg

Here the main notations are defined while their specific values will be discussed later.

3 Model of the electric power system

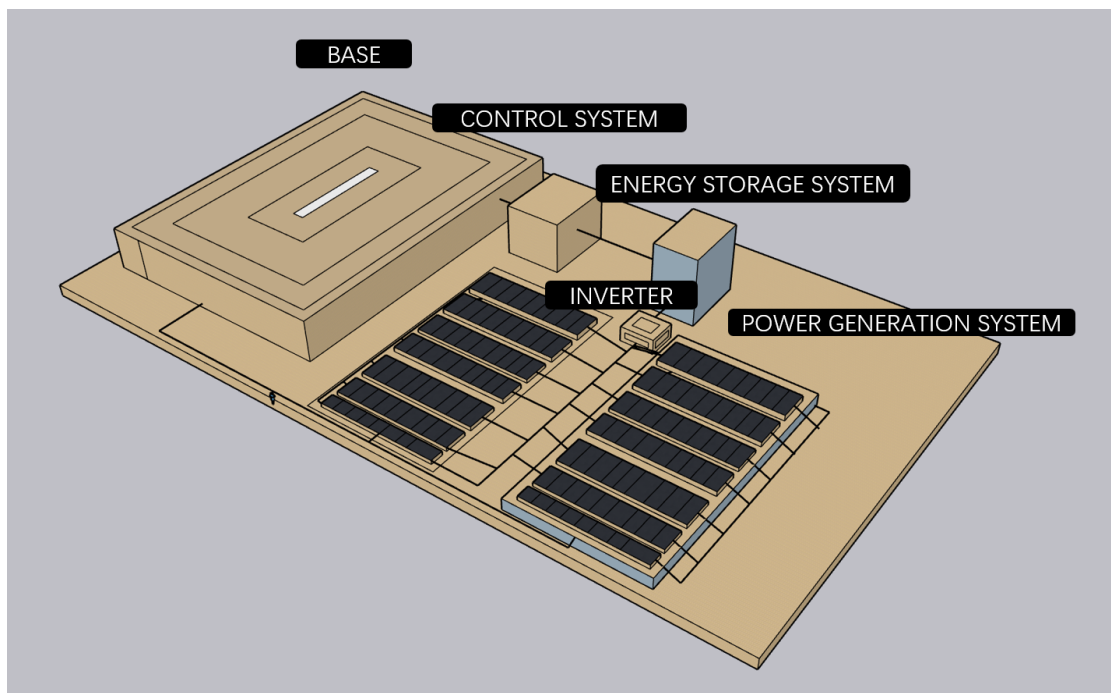
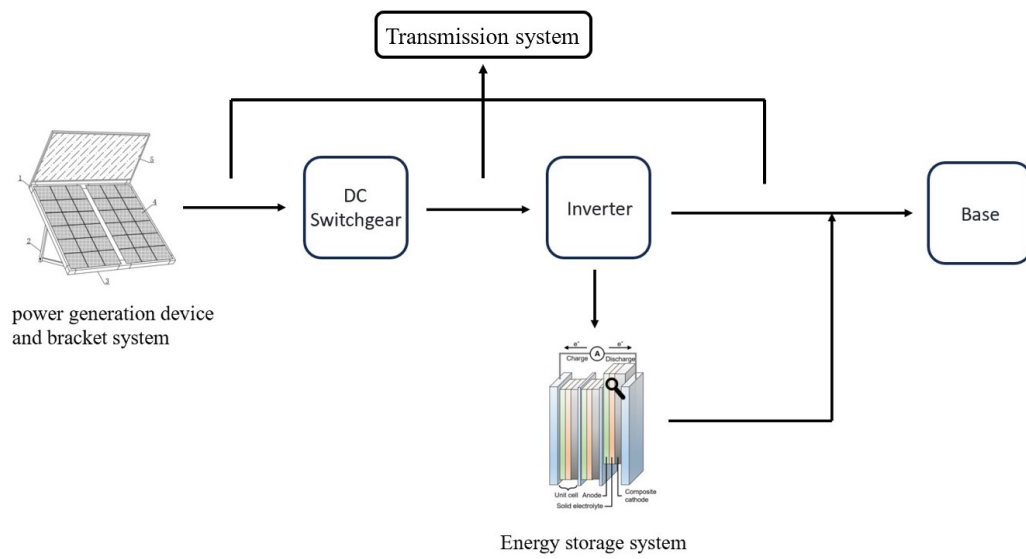
Since minimizing the mass of the power system is our mission with the highest priority, after a general comparison of several power generation methods (chemical reaction power generation, nuclear power generation, and photovoltaic power generation), we believe that photovoltaic power generation can make the total mass of the power generation system the lightest.

Therefore, we decide to adopt this power generation method in our model. The rest estimations of the mass required for the other power generation systems will be mentioned toward the latter part of the essay.

3.1 Power system overview

Four main parts of our power system are as follow: power generation, DC Switchgear and inverter, transmission system and energy storage system.

Here is a diagram of our power supply system design.

**Figure 2: System Model**

3.2 Power generation device and bracket system

In order to reduce the weight of the power generation device as much as possible while ensuring the power generation capacity, we choose to use solar energy to generate electricity on Mars, which is because that after estimation, this method can minimize the quality of the entire power supply system.

3.2.1 photovoltaic panel material choice

After comparing the different materials used in solar photovoltaic panels, we have decided to use dual-junction gallium arsenide due to its relatively high conversion efficiency, better temperature stability, and lighter weight.

Types of photovoltaic panels	Conversion efficiency(%)	Temperature coefficient(%)	Mass per square meter(at typical thickness) (kg/m^2)
Monocrystalline silicon	18-22	0.3-0.4	3-4
Polycrystalline silicon	15-18	0.3-0.4	2-3
Double-junction gallium arsenide(thin film type)	30-33	0.2-0.3	0.05

Table 1: Comparison Table of solar panels made of different materials

We choose to use dual-junction gallium arsenide material for solar panels and the average power generation efficiency of a dual-junction gallium arsenide solar panel is about 31%

3.2.2 The mass of solar photovoltaic panels

Then, let's calculate how many dual-junction gallium arsenide panels we need to meet the need of power generation and calculate the total mass of those panels as well.

First, let's calculate the average light intensity received by the photovoltaic panel per day. Considering the distance from Mars to the Sun to be 1.52AU, the radius of the Mars to be 3396.2km. Since the radius of the Mars is much less than the distance from Mars to the Sun, we can calculate the peak irradiance at a certain point on the surface of Mars

per sol by the function

$$F_{max} = L \times \frac{1}{4 \times \pi \times d^2} \quad (1)$$

where

F_{max} refers to the maximum irradiance at a point on the Martian surface in one day (approximately when it is directly hit by the sun)

L refers to solar luminosity

d refers to the distance between Mars and the Sun

$$F_{max} = 3.74 \times 10^{26} \times \frac{1}{4 \times \pi \times (1.52AU)^2} \approx 577W/m^2 \quad (2)$$

Since Mars has a rotation period of approximately 24 hours and 37 minutes, assuming the duration of sunlight at the location of the photovoltaic panel is half of the day, then by the integral function We can get the average solar radiation intensity on Mars per sol is

$$F_{avg} = \frac{1}{24.62} \int_0^{24.62} \left(\int_{x_0}^{x_0+12.31} \int_0^{577} I(t, x, y), dy, dx \right) dt \approx 288.50W/m^2 \quad (3)$$

where

$$I = y \times \sin(\pi \times t/x)^2 \quad (4)$$

x refers to time

y refers to the instantaneous irradiance

t refers to Illumination time

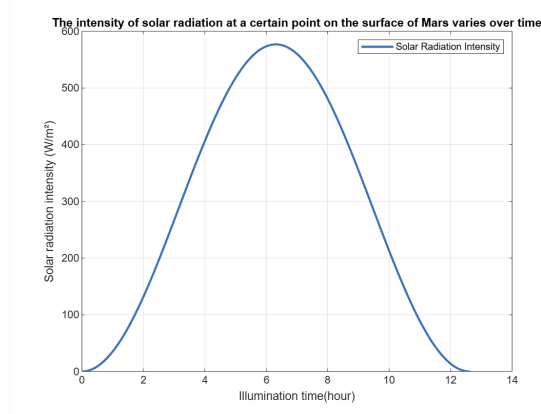


Figure 3: The variation of instantaneous light intensity with time throughout a day

Next, let's consider the impact of dust cover on solar panels.

D. Crisp, A. Pathare, R.C. Ewell(2004)[1] simulated a situation where solar panels on the surface of Mars are covered in dust, finding out that the power losses associated

with dust accumulation are near 0.4–0.5%/sol. After that, the power losses fell below 0.1%/sol. We assume that the crew will clear the dust every month. So the effective power generation efficiency of photovoltaic panels is about $270.1W/m^2$

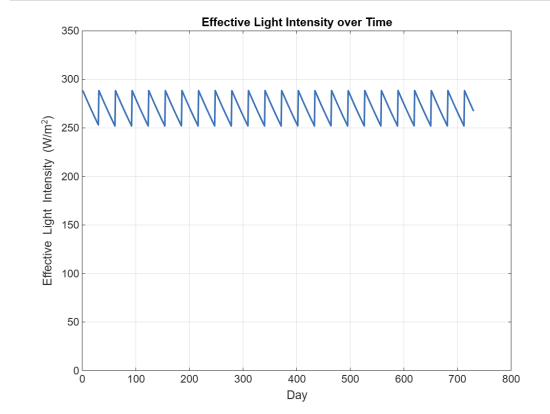


Figure 4: Power decrease curve

The power of photovoltaic panels per square meter is

$$270.1W/m^2 \times 30.9\% = 83.46W/m^2 \quad (5)$$

And the area of solar photovoltaic panels we need is

$$S = 150kW \div 83.46W/m^2 \approx 1797m^2 \quad (6)$$

Let's approximately assume that the mass of the photovoltaic panels per square is 0.05kg, with the thickness of $5\mu m$, then the total mass of photovoltaic panels we need are

$$1797m^2 \times 0.05kg/m^2 = 89.86kg \quad (7)$$

3.2.3 The mass of bracket system

As we have already estimated the total mass of photovoltaic panels, let's estimate the total mass of other equipment that may be used to build a solar photovoltaic panel system.

We adopt an adjustable skeleton support structure in the power supply system. The entire structure consists of a backsheet supporting the solar panels and a single-axis adjustable system.

Firstly, we choose to use TPT solar backsheet. Then, let's choose the material of the adjustable system. By contrast we see that magnesium alloys have relatively strong strength as well as a lower density. So we are going to choose magnesium alloys.

The type of the material	Density($10^3 kg/m^3$)	Tensile Strength(Mpa)
Aluminum Alloy	2.7	110-270
Magnesium Alloy	1.8	250-343
Titanium Alloy	4.5	580-1646

Table 2: Comparison Table Of Three Materials

The mass of the TPT solar backsheet is approximately 0.5 kilograms per square meter, assuming the area of the alloy backsheet is slightly larger than the total area of the photovoltaic panels. The total mass of the backsheet is

$$M_{backsheet} = 0.5 kg/m^2 \times 1800 m^2 = 900 kg$$

Assuming that for each solar panel with dimensions of 1 m by 2 m (we need 1000 such panels in total), we use one magnesium alloy support frame with a cross-sectional area of 0.1 m by 0.1 m and a height of 2 meters, and an additional brace with a cross-sectional area of 0.05 m by 0.05 m and a length of approximately 3 meters to reinforce between the frames. Then the total mass of this part is

$$\begin{aligned}
 M_{bracket} &= M_{support frame} + M_{additional brace} \\
 &= 1000 \times (0.1 \times 0.1 \times 2 + 0.05 \times 0.05 \times 3) \times 1.8 \times 10^3 \\
 &= 49.5 t
 \end{aligned}$$

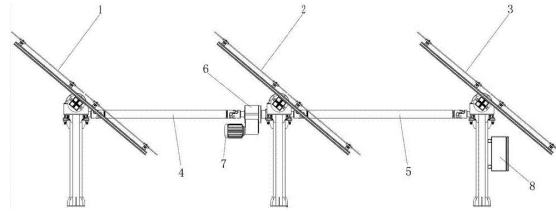


Figure 5: Bracket System

So the total mass of the bracket system should be

$$M_{total bracket} = 900 kg + 49.5 t = 50.4 t \quad (8)$$

3.2.4 Total mass of the power generation system

We need at least about $2000 m^2$ magnesium alloy bracket, assuming its thickness is then the total weight of the equipment we need is approximately

$$89.96 kg + 50.4 t \approx 50.5 t \quad (9)$$

In this case, we only need about 50.5t of power generation device!

3.3 Transmission system

3.3.1 The choice of wire

Wires are an essential part of the entire electric power system. It connects electrical appliances to ensure their normal operation. Meanwhile, the thermal loss on wires also contribute to the total cost of a system, especially in our situation where we consistently require plenty of stable electricity. Hence, there's mounting significance of figuring out and choosing the most suitable wires for specific systems.

Copper and aluminium are two frequently-used materials for wires. In our situation, they're both not very suitable as copper's heavy weight adds to the cost of transportation while aluminium is easily subject to spacial radiation, which is a main characteristic of the environment on Mars. Larruskain et al.(2007)[2] propose that aluminium conductor steel reinforced (ACSR) combines the properties of the lightweight aluminium with the high tensile strength of steel.

Material	Copper	Aluminium	ACSR
Density [g/cm ³]	8.96	2.70	3.0 – 3.5
$\frac{\text{Price}}{\text{Mass}}$ [\$/kg]	10 – 12	2.5 – 3.5	1.5 – 2.5

Table 3: Density and $\frac{\text{Price}}{\text{Mass}}$ of the three materials for wires

From the table above, we can see ACSR has a ratio of $\frac{\text{Price}}{\text{Mass}}$ lower than aluminium and significantly lower than copper, while its density is significantly lower than copper and approximate to aluminium. Besides, ACSR has stronger capabilities to defend radiation and low temperatures. Other materials mentioned in Larruskain et al.(2007)'s essay, like High Temperature Low Sag(HTLS), are much more expensive, thus have a higher ratio of $\frac{\text{Price}}{\text{Mass}}$. Meanwhile, their main advantage lies in the greater ability to defend high temperatures. As Mars has an average temperature of -63°C and a highest temperature in summer of roughly 35°C , this advantage of resisting high temperatures is not our main concern. Then, let's consider another property of wires:the current capacity. Let's first estimate the current of an electrical machine with a power of roughly 150KW. Taha El Hajji et al. (2024)[6] conduct research about a 150kW V-shaped PMSM, where they set the voltage at 400V and get a max phase current of 850A [2], which equals to an effective current of 600A. It's approximate to ACSR's normal current capacity of about 600-800A. Though it's less than copper's 800-1000A, it's enough for the generator we have now and we still have about 200A for consideration of the loss of electricity during transition. Considering that we should pay attention to the sustainable usage of 2 years and the the actual current capacity needed, and our top priority is to lower the ratio ratio of $\frac{\text{Price}}{\text{Mass}}$ as much as possible, it's more favorable to choose ACSR as our wires.

3.3.2 The length of wires

Step 1: To Minimize the Thermal Heat Loss

There are mainly two connecting models for our panels: series connection and parallel connection. Compared with parallel connection, series connection is known for its ability to lower the current and elevate the voltage, thus minimizing the Joule heat loss transition process and increasing the energy efficiency. The higher the energy efficiency is, the less energy we need solar panels to generate, and therefore the fewer solar panels we require. This is important for us to reduce the number of solar panels and then lower the total mass of our devices and their prices. However, every panel on one series arm can only work together when they're are in good conditions. To ensure quick maintenance and guarantee temporary energy supply when power failure happens in part of the circuit, we decide to adopt an array with a combination of series and parallel connection to utilize their respective advantages to a full extent. Meanwhile, we'll also use micro-inverters to improve efficiency. The following is a diagrammatic sketch of this idea that we adopt from greensarawak[4]:

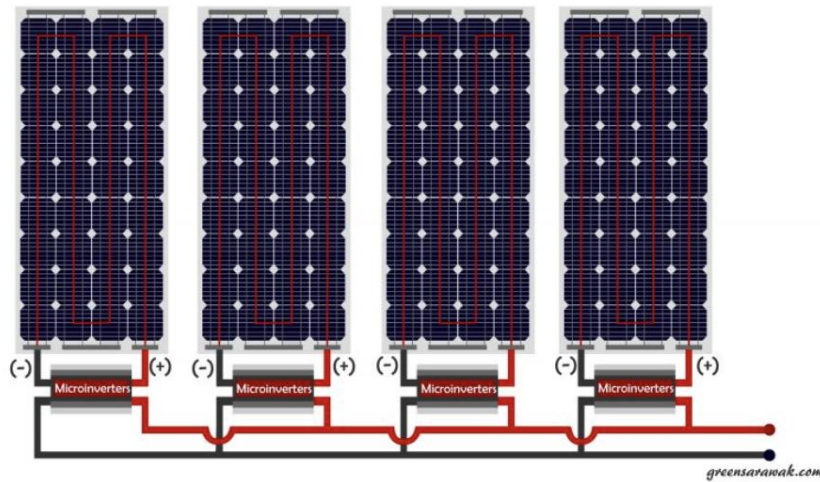


Figure 6: solar PV panel array with micro-inverters

A certain amount of solar panels form a rectangle large unit in series connection. Each unit is in parallel connection with a micro-inverter. The micro-inverters makes every unit work separately and insusceptibly. The micro-inverters regulate and control their respective unit to maximize and stabilize energy output by using algorithm. Then we use this model to design the actual arrangement of solar panels. The average distance between the Mars and the sun is $d_0 = 1.52AU = 1.5 * 10^{11}m$. The average radius of Mars

$$R_M = 3399.2km \ll L_0 = 1.5 * 10^{11}m \quad (10)$$

So the sunlight can be considered parallel on Mars.

The total number of solar panels is N . The distance between each unit d_1 is the same inside the panel array. Since the total area of the solar panels is $S = 1797m^2$, the length of a side L_1 is approximately the same order of magnitude to

$$\sqrt{S_2} = 42.4m = 4.24 * 10^{-2}km \ll R_M = 3399.2km \quad (11)$$

So We can generally consider all the solar panels have the same solar elevation angle and the distance d_1 between each unit is not much larger than the length of a side L_1 . Thus, we assume that all the panels accept an amount of sunlight the same as the panel in the center during half a day when they can receive sunlight.

We don't consider the edge effect, namely when the panels initially begin to receive or start to not receive sunlight, that leads to a broader distance between the neighbouring unit and a greater length of wires due to elevated panels to avoid being shaded by neighbouring units, which has a negligible effect on our result.

Then we'll figure out the choice of which specific type of ACSR is more suitable in different parts of the circuit. The following shows the electric resistivity of the composition of ACSR cables.

Properties	Aluminium	Steel
Electric resistivity (ρ) [$*10^{-8}\Omega \cdot m$]	2.65	16

Table 4: Electric resistivity of aluminium and steel

Denote the electric resistivity of aluminium, steel, and the ACSR cable as ρ_{Al} , ρ_{Steel} , and ρ_i ($i = 1, 2$). Denote the ratio of aluminium and steel in a type of ACSR cable as η_{Al} , η_{Steel} , and η'_{Al} , η'_{Steel} . Then by the table below, we can calculate the electric resistivity of two types of ACSR cables.

The electric resistivity of ACSR 1/0:

$$\rho_1 = \rho_{Al} * \eta_{Al} + \rho_{Steel} * \eta_{Steel} = 2.65 * 10^{-8} * \frac{6}{7} + 16 * 10^{-8} * \frac{1}{7} \Omega \cdot m = 4.56 * 10^{-8} \Omega \cdot m \quad (12)$$

The electric resistivity of ACSR 54/7:

$$\rho_2 = \rho_{Al} \cdot \eta'_{Al} + \rho_{Steel} \cdot \eta'_{Steel} = 2.65 \times 10^{-8} \cdot \frac{54}{61} + 16 \times 10^{-8} \cdot \frac{7}{61} \Omega \cdot m = 4.18 \times 10^{-8} \Omega \cdot m \quad (13)$$

Properties	Aluminium	Steel	price	current capacity
Composition in ACSR 1/0	6	1	200	1.5-2.0
Composition in ACSR 54/7	54	7	600	6.0-7.0

Table 5: The composition of aluminium and steel in two types of ACSR cables

As we can see, ACSR 54/7 excels at accommodating large current and greater strength, so it's suitable for being circuit trunk wires as they have larger current for linking branches and should be resistant to the frequent sandstorms on Mars. On the other hand, ACSR 54/7 has the advantage of lower prices, which is suitable for connecting plenty of branches that has a current smaller than 200A. Therefore, by using ACSR 54/7 in trunks and ACSR 1/0 in branches, we manage to deal with the issue of high current capacity in trunk wires and minimize the cost under normal operation at the same time.

After that, we'll calculate the optimal arrangement of the solar panel array. The power delivered to the base is $P = 150KW$. Every panel has a size of $156mm * 156mm$ (denote as $c = 0.156m$), and the total area of solar panels is $S = 1797m^2$, so the number of solar panels needed is

$$N = \frac{S}{l_0^2} = \frac{1797}{(156 * 10^{-3})^2} \approx 7.384 * 10^4. \quad (14)$$

So we choose $N = 7.39 * 10^4$ to cover that amount.

There is one common design of solar panels. In this model, a unit consist of 72 pieces ($6*12$), forming an area of $1.638m^2$ ($0.992m*1.652m$). Denote the rows of a unit as $a = 12$ and the columns of a unit as $b = 12$. Suppose that we have x such units in every circuit and there are y such circuits.

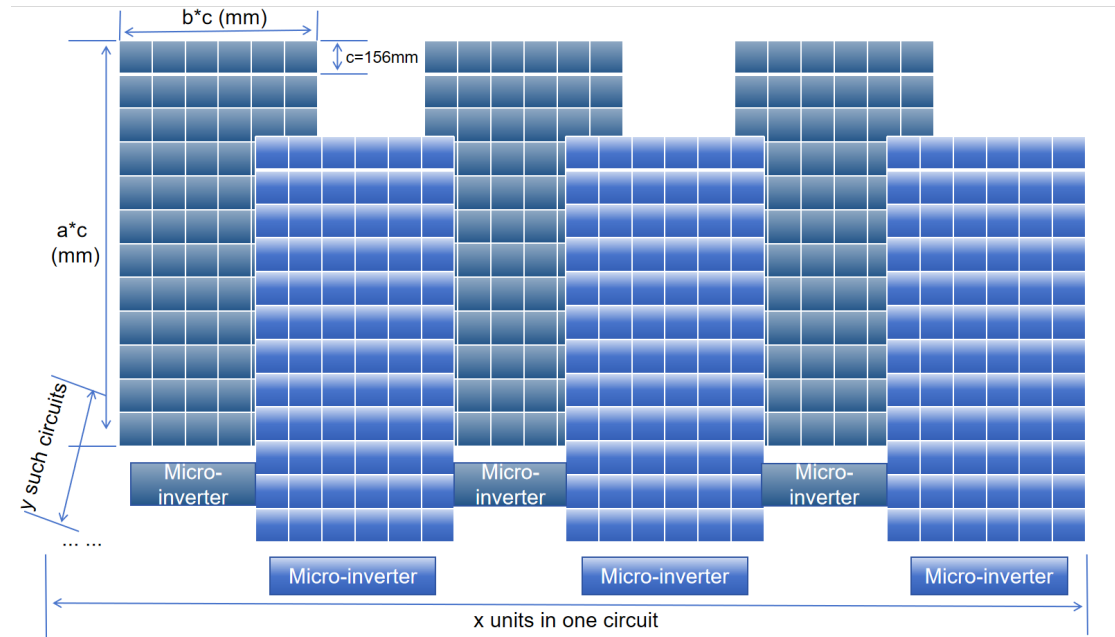


Figure 7: Instruction figure of a, b, c, x, y

We don't consider the length of wires that connect the transformer or that link every

row to a nearby energy storage system, as this part of length is relatively small compared with that in other parts of trunks and branches. The total length of wires in one row is l_t , which is composed of l_{1t} in the branches and l_{2t} in the trunk. We then assume that the wires link the center of each panel in a unit except the two ones that connects the micro-inverter, and the height (H) of a solar panel is 2m. Here the height means the vertical distance of the center of the solar panel to the ground. Considering the unfavorable weather on Mars, we set the distance between neighbouring panels(D) to be 1.5 times of the height of solar panel, that means the distance

$$D = 1.5 * H = 1.5 * 2 = 3m \quad (15)$$

We put parallel wires in columns and make turns in the outmost circle to change columns. In this case, the length of wires in the branch of a unit is

$$l_1 = (b * (a - 0.5) + a - 0.5 * 2) * c = (6 * 11.5 + 12 - 1) * 0.156m = 80 * 0.156m = 12.48m \quad (16)$$

The electric resistivity of dual-junction gallium arsenide solar panel(ρ_0) is about $10^{-3}\Omega \cdot m$. The resistance of a single dual-junction gallium arsenide solar panel(156mm*156mm)

$$R_0 = \rho_0 * \frac{D_0}{c^2} = 10^{-3} * \frac{5 * 10^{-6}}{(156 * 10^{-3})^2} \Omega = 2.05 * 10^{-7} \Omega \quad (17)$$

The resistance of a unit

$$R_1 = R_0 * a * b = 2.05 * 10^{-7} * 12 * 6 = 1.48 * 10^{-5} \Omega \quad (18)$$

The resistance of the wires of a unit

$$R_2 = \rho_1 * \frac{l_1}{\pi * r_1^2} = 4.56 * 10^{-8} * \frac{12.48}{\pi * (4.955 * 10^{-3})^2} = 7.38 * 10^{-3} \gg R_1 \quad (19)$$

Since the resistance of a micro-inverter connected with a unit $R_3 = 10m\Omega$, so we may only take the resistance of wires and micro-inverters into account when calculating the thermal heat loss in the transmission system. Hence, the total resistance of a unit

$$R_{t_0} = R_2 + R_3 = 7.38 * 10^{-3} + 0.01\Omega = 1.74 * 10^{-2} \Omega \quad (20)$$

The resistance of the trunk

$$R_{t_1} = \rho_2 * \frac{(b * c + D)}{\pi * r_2^2} * x = 4.18 * 10^{-8} * \frac{6 * 156 * 10^{-3} + 3}{\pi * (10 * 10^{-3})^2} * x = 5.24 * 10^{-4} * x \Omega \quad (21)$$

The power that a unit can transfer into electricity

$$P_0 = P' * ac * bc = 83.46 * (12 * 6 * 0.156^2) = 146.24W = 0.146KW \quad (22)$$

Assume that the current inside a unit is I , then the current of a circuit is xI . The output power of a panel unit

$$P_1 = P_0 - I^2 * R_{t_0} = 0.146 - I^2 * 1.74 * 10^{-5} KW \quad (23)$$

The output power of a circuit

$$P_2 = x * P_1 - 0.5 * (xI)^2 * R_{t_1} = (0.146 - 1.74 * 10^{-5} * I^2)x - 2.62 * 10^{-4} * I^2 * x^3 \quad KW \quad (24)$$

The output power of y such circuits in parallel connection

$$P_t = P_2 * y = ((0.146 - 1.74 * 10^{-5} * I^2)x - 2.62 * 10^{-4} * I^2 * x^3) * y \quad KW \quad (25)$$

while the total number of solar panels

$$72xy \geq 7.39 * 10^4 \quad (26)$$

Substitute y with $\frac{7.39*10^4}{72x} = \frac{1.026*10^3}{x}$ Then we have The output power of y such circuits in parallel connection

$$\begin{aligned} P_t &= P_2 * y = ((0.146 - 1.74 * 10^{-5} * I^2)x - 2.62 * 10^{-4} * I^2 * x^3) * \frac{1.026*10^3}{x} KW \\ &= 1.5 * 10^2 - 1.79 * 10^{-2} I^2 - 2.69 * 10^{-1} * I^2 * x^2 KW \end{aligned} \quad (27)$$

Assume that we have a fixed voltage at the terminal of the wire and that our transformer has a fixed ratio of voltage elevation, then the voltage U_T y circuits output in total should be the same. Therefore, for fixed required output power $P = 150KW$, the current I_T y circuits output in total is the same. Since

$$I_T = y * xI = 1.026 * 10^3 I \quad (28)$$

I is the same regardless of x, y .

Hence, to achieve maximum output power, we only need to consider $\frac{dP_t}{dx}$.

$$\frac{dP_t}{dx} = -5.38 * 10^{-1} * I^2 * x < 0 \quad (29)$$

for all $x > 0$

This means the maximum output of the whole transmission system before the transformer decreases as the number of parallel circuits increases.

In the former part, we discuss that the current I_T (which is an effective value) that y circuits output in total should be no more than 600A. This leads to

$$I_{max} = \frac{I_T}{xy} = \frac{600}{1.026 * 10^3} = 0.585A \quad (30)$$

This result is smaller than the rated current of solar panels (about 0.714A) and the micro-inverter(about 15A), and shows its feasibility.

Step 2: To Calculate the length

When $x = 1$, each circuit has exactly one solar panel unit and all the circuits are in parallel connection with one another. This is equivalent to all units are in one circuit and they are in parallel connection with each other. To reduce the effect of the increase of length on the validation of our assumption that all the solar panels have the same solar elevation angle, we'll put our circuit in a snake-like way, namely their actual arrangement looks similar to a rectangle, such that $\max\{x', y'\}$ is the smallest. Here, x', y' is the number of rows and columns of "the solar panel array" we mention above.

The total length l_{1t} in the trunk is

$$l_{1t} = l_1 * y = 12.48 * 1.026 * 10^3 = 1.28 * 10^4 m \quad (31)$$

Its mass m_{1t} can be calculated by

$$m_{1t} = \rho_3 * l_{1t} * (\pi * r_1^2) = 3.38 * 10^3 * 1.28 * 10^4 * \pi * (4.955 * 10^{-3})^2 kg = 3.34 * 10^3 \quad kg \quad (32)$$

The total length of wires in one row is l , which is composed of l_1 in the trunk and l_2 in the branches.

The total length l_{2t} in the trunk is

$$l_{2t} = l_2 * y = (bc + D) * y = (6 * 156 * 10^{-3} + 3) * 1.026 * 10^3 = 4.04 * 10^3 m \quad (33)$$

Its mass m_{2t} can be calculated by

$$m_{2t} = \rho_4 * l_{2t} * (\pi * r_2^2) = 3.29 * 10^3 * 4.04 * 10^3 * \pi * (10 * 10^{-3})^2 kg = 4.18 * 10^3 \quad kg \quad (34)$$

Besides, a common micro-inverter weighs between $0.5kg - 1.5kg$, we'll choose its average and sets the mass m_{inv} of the micro-inverter we use in this model as $m_{inv} = 1kg$. Then the total mass of the micro-inverter

$$m_{invt} = m_{inv} * y = 1 * 1.026 * 10^3 kg = 1.03 * 10^3 \quad kg \quad (35)$$

Therefore, the total mass of wires and micro-inverters in this part is

$$M_1 = m_{1t} + m_{2t} + m_{invt} = 3.34 * 10^3 + 4.18 * 10^3 + 1.03 * 10^3 = 8.55t \quad (36)$$

3.4 Energy storage system

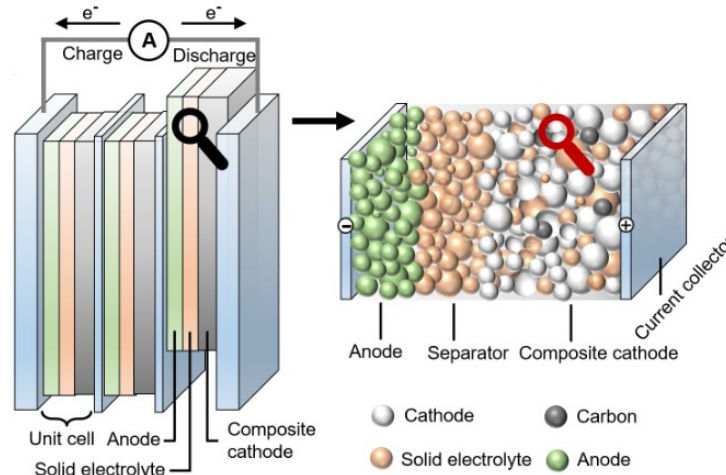


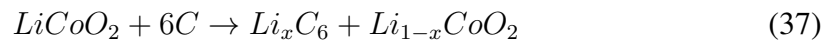
Figure 8: Schematic diagram of a solid lithium battery

Due to the day-night cycle and seasonal variations on Mars, an efficient energy storage system is required to store energy generated during the day for use at night. To minimize mass and maximize energy density, we choose to use solid-state lithium-ion batteries among the options of latent heat storage systems, solid-state lithium-ion batteries, and capacitors. We connect the solid-state lithium-ion battery in series with the solar metal plate system, first inputting the electrical energy generated by the solar metal plates into the energy storage system, and then directly supplying power to our base from it.

First, let's introduce the traditional lithium-ion battery. It consists of a positive electrode, a negative electrode, a separator, and an electrolyte. Typically, the positive electrode uses lithium compound oxides (such as LiCoO_2 , LiMn_2O_4 , LiFePO_4 , etc.) as active materials, and the negative electrode usually uses lithium-containing materials such as graphite and silicon as active materials. The lithium ions in the positive electrode material move back and forth between the positive and negative electrodes, enabling the charging and discharging of the battery. The medium for the movement of lithium ions is liquid electrolyte.

During the charging process, by applying an external voltage to the lithium battery, the lithium originally at the anode loses an electron to become a lithium ion, which moves towards the cathode under the driving force of the potential difference, eventually combining with the cathode material. The released electrons flow from the positive electrode to the negative electrode through the external circuit, replenishing an electron to the negative electrode. During discharge, the process is exactly the reverse.

discharging of solid lithium-ion battery:



charging of solid lithium-ion battery:



The traditional lithium-ion battery has already been applied in various fields, including but not limited to consumer electronics, electric vehicles and so on. However, if it is to be used as an energy storage system on Mars, more tricky factors have to be considered.

Firstly, as the electrolyte used in these batteries often contains highly flammable components. If it leaks accidentally, it can lead to fire or explosion, especially when overheated. During transportation or while operating on the Martian surface, the external environment may be extremely unstable, making liquid lithium-ion batteries highly susceptible to fire or explosion. This not only prevents energy from being stored but also affects other equipment or poses a danger to the crew. Secondly, the mass of liquid electrolyte is very big, and transporting enough of it for two years of use would significantly increase the labor and material costs of transportation.

Therefore, we consider retaining lithium, for its molar mass is relatively small, and replacing the liquid electrolyte. We decide to adopt solid lithium-ion battery, which employ solid electrolytes (typically ceramic or polymer materials). It is non-flammable and less prone to leakage or explosion during transportation, thereby ensuring the safety of crew members and equipment. Additionally, since solid electrolytes do not degrade easily, solid-state lithium-ion batteries have a longer cycle life.

For example, $Li_7La_3Zr_2O_{12}$ (LLZO) is often used as the conductive medium of solid lithium-ion battery.

	interfacial resistance with metallic lithium	fracture toughness	lattice energy
LLZO	$5 \times 10^{-2} cm^2 \cdot \Omega$	$2 - 3 MPam^{0.5}$	$1500 kJ/mol$

The table shows that the lattice energy of LLZO is very high, so it's much more stable than the molecular crystal Ethylene Carbonate, which is often used as the medium in the traditional lithium-ion battery. Also, the relatively high fracture toughness indicates that LLZO is capable of withstanding significant mechanical stress, which makes it very suitable for being transported a long way to Mars.

This allows us to carry a smaller amount of electrolyte, thus reducing transportation costs.

Now, let's calculate the mass of the energy storage system. Previously, we have assumed that the solar photovoltaic system can receive 12 hours of sunlight per day. This means that to ensure a continuous power supply of at least 150 kW to our Mars base, the energy storage system needs to be capable of storing enough power to keep

the base operational for 12 hours. To account for unforeseen circumstances, we assume that the energy storage system should store enough power to keep the base operational for at least 24 hours, that is,

$$W_1 = 150 \times 10^3 \times 24 \times 3600 = 1.296 \times 10^7 kJ \quad (39)$$

Then, to determine the energy density of the solid-state lithium battery, let's look into some of the examples that have already existed

	energy density(Wh/kg)
Lithium Iron Phosphate (LFP) Batteries	100-160
Ternary Lithium Batteries	150-250
NIO Semi-Solid State Battery	360
IM L6 Battery	368
Amprius (American Company) Batteries	450

Table 6: energy density of some existed solid batteries

From the data in the table, we assume that the solid-state lithium-ion battery used has a density of 400 Wh/kg.

$$W_0 = \frac{1.296 \times 10^7}{3.6} = 3.6 \times 10^6 Wh \quad (40)$$

$$m_{battery} = \frac{3.6 \times 10^6}{400} = 9000 kg \quad (41)$$

Next, let's consider the mass of other battery components such as the casing, electrolyte, current collectors, and separator. We assume these parts account for twenty percent of the total mass.

So the total mass of the energy storage system is

$$M = \frac{m_{battery}}{0.8} = 11250 kg = 11.25 t \quad (42)$$

4 Other Models

Solar energy is already the most commonly used form of energy. We initially sought to find a lighter and more efficient energy-generating device. Consequently, we explored various methods, including traditional hydrogen-oxygen fuel cells, innovative approaches that utilize the existing carbon dioxide on Mars in combination with self-carried aluminum powder to generate heat, and modular nuclear reactors for power generation. However, upon comparison, the mass required for these methods far exceeds

that needed for solar photovoltaic power generation. Below are other several assumptions and calculations we have made.

Note that we need a power system that can continuously provide 150 Kw for at least 2 years, the total energy that is required is

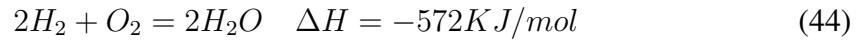
$$W = 150 \times 10^3 \times 2 \times 365 \times 24 \times 3600 = 9.4608 \times 10^9 kJ \quad (43)$$

(we assume that there are 365 days each year, without considering leap years.)

4.1 Hydrogen for electricity generation

For fuels that can generate power through combustion reactions, Davood Zivar(2020)[1] has proposed that "hydrogen has 2.5-3 times more energy content than natural gas, making it the fuel with the most energy"[23439], so we begin with analyzing the mass of fuel that is needed to generate the required amount of energy.

As there's little oxygen and hydrogen on Mars, liquid oxygen and liquid hydrogen must be brought from Earth to Mars.



$$m(O_2) = \frac{9.4608 \times 10^9}{|-572|} \times 32 \approx 529t \quad (45)$$

$$m(H_2) = \frac{9.4608 \times 10^9 \times 2}{|-572|} \times 2 \approx 66t \quad (46)$$

Therefore, the total mass of reactant that is needed is

$$m_{total} = m(O_2) + m(H_2) = 529 + 66 = 595t \quad (47)$$

Obviously, If we use this method, we need to carry lots of reactants, which will lead to inconvenience and high transportation costs. Therefore, we turn to look for reactants that are easy to carry.

4.2 Aluminium for electricity generation

Considering that aluminum has a relatively small atomic mass, aluminum powder is very convenient to carry. It can react with carbon dioxide to release a certain amount of heat. Plus, there exists considerable amount of carbon dioxide on Mars, so we initially reckon that bringing aluminium powder to Mars and collect carbon dioxide to react with it is a feasible choice. The thermochemical equation for this reaction is as follows



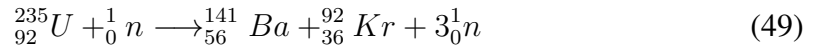
However, later we found out that this reaction requires an electrolyte solution or extremely high temperatures to proceed. Since the highest temperature on Mars is generally around 20 degrees Celsius, and it is also difficult to find a suitable electrolyte solution as the reaction environment, therefore, this plan is still not feasible.

4.3 Nuclear energy for electricity generation

Our thinking extended to newer forms of energy, such as nuclear power.

Based on the concept of modular data centers adopted by Huawei, we constructed a model of small modular nuclear reactor.

A typical nuclear fission reaction equation for uranium-235 is:



Each uranium-235 atom releases approximately 200 MeV of energy during fission. Therefore,

$$E_0 = 200 \times 1.602 \times 10^{-16} = 3.204 \times 10^{-17} \text{ KJ} \quad (50)$$

$$N' = \frac{9.4608 \times 10^9}{3.204 \times 10^{-17}} \approx 2.953 \times 10^{26} \quad (51)$$

$$n = \frac{N}{N_A} = \frac{2.953 \times 10^{26}}{6.02 \times 10^{23}} = 490 \text{ mol} \quad (52)$$

$$m_U = n \times 235 = 115.15 \text{ kg} \quad (53)$$

so only 115.15kg of uranium-235 can already meet our need.

However, to shield against radiation, we need a containment structure made of concrete. Such a containment structure can be 1-2 meters thick and weigh several hundred to several thousand tons, which undoubtedly significantly increases the difficulty and cost of transportation.

(54)

5 Model Evaluation

5.1 Strengths

1. When calculating the actual amount of solar panels needed, we referenced experimental results from the literature on the changing conditions of dust coverage on the Martian surface over dates, taking into account the impact of dust on the photovoltaic panel power generation efficiency. This makes the calculated required photovoltaic panel mass more closely approximate the real value.

2. After comparing various energy storage devices, such as biological batteries and latent heat storage systems, we ultimately selected solid-state lithium-ion batteries as the energy storage method. Though solid-state lithium-ion batteries have not yet been widely deployed and represent a relatively new type of energy storage battery. They can minimize the mass of the energy storage device while being easy to transport and offering high safety.

5.2 Weaknesses

1. In this system, several components used have immature manufacturing processes, which may lead to difficulties in processing and poor quality. For example, the magnesium alloy backing plate has a high processing cost and may risk separating from the battery panel after exposure to heat or cold. In addition, although the high mechanical strength of solid-state lithium-ion batteries makes them easy to transport, it also makes them prone to cracking, which can affect battery life.
2. Due to time constraints, we did not incorporate an intelligent control system into the device. If an intelligent control system were added, it could enable real-time adjustments to the device. For example, it could dynamically adjust the orientation and elevation of each solar panel based on light intensity or angle, maximizing the efficiency of each square meter of solar panel and producing the required energy with the fewest number of panels. This approach could reduce the overall mass of the device by decreasing the number of solar panels. Additionally, an intelligent control system could use algorithms to regulate micro-inverters in the circuit, ensuring that the output of each branch reaches its maximum simultaneously without interfering with each other.

6 Conclusion

	mass(t)(approximate)
power generation device and bracket system	50.50
DC Switchgear and Inverter	0.80
transmission system	8.55
energy storage system	11.25
total	71.10

Table 7: The mass of each component and the total mass of the aforementioned models

The total mass of our electrical power system is approximately 71,10t. For the power generation system, we adopted solar energy to generate electricity and chose

magnesium alloys as the material of the bracket system. Concerning the transmission system, Due to the susceptibility of microwave transmission to interference and the significant propagation loss, coupled with the heavy equipment requirements, we opted for traditional overhead electrical conductors, whose material is ACSR. With regard to the energy storage system, solid-state lithium-ion battery is used because of its relatively light weight and stable performance.

Under the premise of using solar photovoltaic power generation, we have tried our best to use the lightest possible components in each part to reduce transportation costs. In the future, if humans were to massively migrate to Mars and need to transport a large number of power supply systems to the planet, we would still need to fundamentally research new power generation technologies, significantly reduce the mass of nuclear reactors, or adopt other new energy sources to make power supply on Mars more widespread and affordable.

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- [2] D.M. Larruskain, I. Zamora, O. Abarrategui, A. Iraolagoitia, M. D. Gutiérrez, E. Loroño and F. de la Bodega, Power transmission capacity upgrade of overhead lines, *RE&PQJ*, Vol. 1, No.4, April, <https://doi.org/10.24084/repqj04.296>
- [3] T. El Hajji, A. Lehtikoinen, A. Hemeida and A. Belahcen, "Optimal Design of Cost-effective E-Machines for Traction: A Case Study of 150kW V-shaped PMSM," 2024 International Conference on Electrical Machines (ICEM), Torino, Italy, 2024, pp. 1-5, doi: 10.1109/ICEM60801.2024.10700405
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A Intensity1.m

This code is used for the calculation and visualization of instantaneous light intensity and average light intensity over the course of a day.

```
1  # This is a sample for Matlab
2  function calculate_average_sunlight_intensity()
3
4  A = 577;
5  duration = 1231;
6
7
8  time_hours = 0:0.01:duration;
9
10
11  I = A * sin(pi * time_hours / duration).^2;
12
13
14  total_sunlight_intensity = trapz(time_hours, I);
15
16  average_sunlight_intensity = total_sunlight_intensity / duration;
17
18  fprintf('The average intensity of sunlight received by a fixed
19  point on the surface of Mars per day is %.2f W/²m\n',
20  average_sunlight_intensity);
21
22  figure;
23  plot(time_hours, I, 'LineWidth', 2);
24  title('The intensity of solar radiation at a certain point on the
25  surface of Mars changes with time');
26  xlabel('time (hrs)');
27  ylabel('solar radiation intensity(W/²m)');
28  grid on;
29  hold on;
30
31  plot([0 duration], [0 0], 'r--', 'LineWidth', 1);
32  legend('solar radiation intensity');
33
34  end
```

B Intensity2.m

We used this code to calculate and visualize the changes in light intensity received by the photovoltaic panel over time under the influence of dust.

```
1      % This is a sample for Matlab
2
3      initial_light_intensity = 288.5;
4      total_days = 365 * 2;
5      dust_loss_rate = (0.4 + 0.5) / 2 / 100; (0.4-0.5% per day)
6      cleaning_interval_days = 2;
7
8      light_intensities = zeros(total_days, 1);
9      effective_light_intensities = zeros(total_days, 1);
10     light_intensities(1) = initial_light_intensity;
11     effective_light_intensities(1) = initial_light_intensity;
12
13
14     for day = 2:total_days
15
16         light_loss = light_intensities(day-1) * dust_loss_rate;
17
18
19         light_intensities(day) = light_intensities(day-1) - light_loss;
20
21
22         if mod(day, cleaning_interval_days) == 0
23             light_intensities(day) = initial_light_intensity;
24         end
25
26
27         effective_light_intensities(day) = light_intensities(day);
28     end
29
30     average_light_intensity = mean(effective_light_intensities);
31
32
33     figure;
34     plot(1:total_days, effective_light_intensities, 'LineWidth', 1.5);
35     title('Effective Light Intensity over Time');
36     xlabel('Day');
37     ylabel('Effective Light Intensity (W/m^2)');
38     grid on;
39
40
41     ylim([0 max(effective_light_intensities)]);
42
43
44     fprintf('Average Effective Light Intensity: %.2f W/m^2\n',
```

```
45 |         average_light_intensity);
```