# Time Frame

We’ll define four key milestones:

1. **Human Arrival on Mars**: When the first human missions will likely land on Mars.
2. **Start of Infrastructure Building**: When basic infrastructure (e.g., habitats, energy generation, oxygen plants) will be built.
3. **First Civilian Settlements**: When non-astronauts (normal people) will start living on Mars.
4. **Population Growth**: The rate at which the population will grow and the corresponding electricity demand.

## Realistic Projections and Assumptions

### 1. Human Arrival on Mars

**Optimistic Estimate**: SpaceX, NASA, and other space agencies project that humans will land on Mars in the **late 2030s** (e.g., 2037–2040).

* SpaceX plans the first crewed mission within **10–15 years** (2035–2040 range) based on the current pace of Starship development.
* NASA’s Artemis program aims to enable Mars missions post-2030.

### 2. Start of Infrastructure Building

Infrastructure would begin with robotic missions and basic human setups. Key developments:

* Solar panels or nuclear power systems (e.g., Kilopower).
* Habitats with life support (oxygen, water recycling, heating).
* **Time Frame**: Expect basic infrastructure construction to begin **immediately after the first human mission**, around **2040–2045**.

### 3. First Civilian Settlements

A Martian settlement will transition from purely exploratory to semi-permanent as technology and costs improve.

* SpaceX envisions a permanent settlement in **2050 or later**, with hundreds to thousands of residents.
* Expect a slow start with only highly trained personnel (engineers, scientists, technicians).
* By **2060**, small groups of civilians may begin arriving.

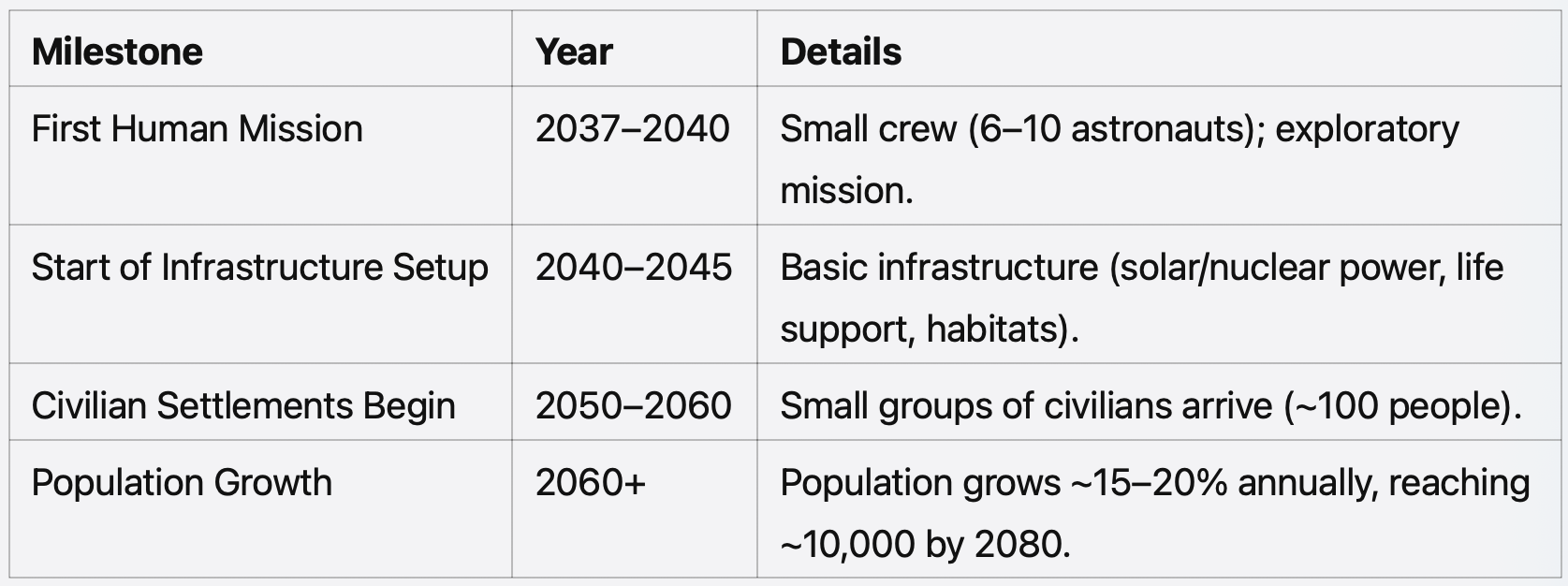
### 4. Population Growth

Population growth will depend on:

* Transport costs dropping (e.g., SpaceX Starship reusability).
* Resource sustainability (e.g., local food and water production).
* Infrastructure capacity (power, housing, medical).

**Assumption**:

* Initial population: ~100 settlers by **2050–2060**.
* Growth rate: ~15–20% annually (a doubling time of ~5 years, comparable to historical colony growth rates on Earth).



## Electricity Demand Scenarios

Electricity demand will vary depending on the stage of settlement:

1. **Exploratory Phase (2037–2045)**:

* Small demand (e.g., 20–50 kW) for scientific instruments, life support systems, and rovers.

1. **Infrastructure Phase (2045–2050)**:

* Larger demand (~500 kW–1 MW) for resource extraction (water/oxygen), habitat support, and industrialization.

1. **Civilian Settlements (2050–2060)**:

* Medium demand (~5–20 MW) to support a growing settlement of ~100 settlers.

1. **Population Growth (2060–2080)**:

* Large demand scaling with population growth (~1–2 kW/person).
* Demand by 2080: ~20,000 MW for a population of 10,000 settlers.

## Uncertainties

* **Technological Advancements**: Faster rocket development, nuclear reactor miniaturization, and automated construction could accelerate timelines.
* **Funding and Political Support**: Missions depend on government and private funding (e.g., NASA, ESA, SpaceX).
* **Mars Suitability**: Challenges like dust storms, radiation, and resource availability will shape the pace of settlement.

REF:

* (https://www.nasa.gov/humans-in-space/humans-to-mars/)
* (https://nypost.com/2024/09/08/business/elon-musk-predicts-crewed-spacex-flights-to-mars-by-2028-hopes-for-self-sustaining-city/)

# Electricity Demand

## Assumptions

Time Frame

* **Start Year**: 2040 (infrastructure setup begins).
* **End Year**: 2100 (advanced settlement phase with a substantial population).

**Reference**: NASA’s projection for Mars missions and SpaceX’s vision for settlement ([NASA](https://www.nasa.gov/humans-in-space/humans-to-mars), [SpaceX](https://www.nypost.com)).

Phases of Electricity Demand

We’ll divide the years into phases:

1. **2040–2045**: Basic setup for infrastructure (~50–100 kW demand).

**Reference**: Early lunar base power needs as proxies ([NASA Kilopower](https://www.nasa.gov/directorates/spacetech/kilopower)).

1. **2045–2060**: Infrastructure expansion (~500 kW to 20 MW demand).

**Reference**: ISS and Antarctic base power needs as analogs ([NASA ISS](https://science.nasa.gov/)), ([Antarctica](https://www.bas.ac.uk)).

1. **2060–2100**: Population growth, with demand scaling linearly with the population.

* Initial population (~100 settlers): ~5 MW.
* Population of 10,000 by 2100: ~20,000 MW.
* **Assumption**: 2 kW per person (Earth analog adjusted for Martian life support needs).

**Reference**: Per capita electricity consumption on Earth ([Our World in Data](https://ourworldindata.org/energy)).

## Electricity Demand Profile

Electricity demand will follow a daily load profile, similar to Earth but adjusted for Martian conditions:

• **Day/Night Cycle**:

Solar power will dominate initially; nighttime demand will rely on batteries or nuclear power.

Mars has a ~24.6-hour day-night cycle.

• **Seasonal Variations**:

Adjust for solar power efficiency due to the Martian year (~687 Earth days).

**Assumption**: Use Earth-like seasonal variations for simplicity.

• **Hourly Demand**:

Infrastructure phase: Constant demand with minor peaks for operations.

Settlement phase: More varied demand (e.g., morning, evening peaks).

REF:

1. **Mars Mission Timeline**:

• NASA and SpaceX projections ([NASA](https://www.nasa.gov/humans-in-space/humans-to-mars), [SpaceX](https://www.nypost.com)).

2. **Electricity Demand for Bases**:

• Kilopower and ISS analogs ([NASA Kilopower](https://www.nasa.gov/directorates/spacetech/kilopower), [Antarctica](https://www.bas.ac.uk)).

3. **Population Growth**:

• SpaceX vision for Mars settlement ([SpaceX](https://www.nypost.com)).

4. **Per Capita Consumption**:

• Earth analog adjusted for Martian conditions ([Our World in Data](https://ourworldindata.org/energy)).

# Heat Demand

### Phases of Heat Demand

Heat demand evolves across the settlement’s development phases, based on infrastructure needs and population growth:

1. **2040–2045: Basic Infrastructure Phase (~100 kW demand)**:

* Heating is essential during the initial setup for maintaining critical equipment, habitats, and life support systems.

**Reference**: Heating needs for lunar habitats and early research bases ([NASA Kilopower](https://www.nasa.gov/directorates/spacetech/kilopower)).

2. **2045–2060: Infrastructure Expansion (~500 kW to 20 MW demand)**:

* As habitats and industrial facilities expand, heat demand increases proportionally.
* Includes temperature regulation for water recycling, oxygen production, and construction activities.

**Reference**: ISS thermal systems and Antarctic research base heating as proxies ([NASA ISS](https://science.nasa.gov/), [BAS](https://www.bas.ac.uk)).

3. **2060–2100: Population Growth (~10 kW/person)**:

* Heat demand scales linearly with population, accounting for habitat temperature regulation and industrial heat.

Example:

* ~100 settlers in 2060: ~1 MW heat demand.
* ~10,000 settlers by 2100: ~100 MW heat demand.
* **Assumption**: 10 kW per person (adjusted from Earth analogs to account for Mars’ colder climate and life support systems).

**Reference**: Per capita heating demand in cold Earth environments ([Our World in Data](https://ourworldindata.org/energy)).

### Heat Demand Profile

**Martian Environment**:

* Mars’ average surface temperature is ~-60°C, with significant daily and seasonal variations.
* Local heating requirements will vary based on habitat insulation and geographical location (e.g., equatorial regions vs. polar regions).

**Day/Night Cycle**:

* Temperature drops dramatically at night due to Mars’ thin atmosphere.
* Nighttime heating demand is higher than daytime.

**Seasonal Variations**:

* Mars’ elliptical orbit results in greater temperature swings during its **687-day year** compared to Earth.
* Assumption: Heating demand is higher during colder Martian seasons, especially for polar and mid-latitude settlements.

### Integration of Heat Demand

Heat demand on Mars will rely on the following sources:

1. **Nuclear Reactors**:

* Waste heat from nuclear reactors can be directly utilized for habitat heating and industrial processes.

**Reference**: Reactor thermal management systems on Earth and space missions ([NASA Kilopower](https://www.nasa.gov/directorates/spacetech/kilopower)).

2. **Geothermal Sources**:

* Volcanic regions can provide localized heat, reducing dependency on other energy sources.

**Reference**: Geothermal potential studies ([USGS Mars Geology](https://pubs.er.usgs.gov/publication/70041187)).

3. **Electric Heating**:

* Powered by solar or nuclear energy, this will serve as a backup or supplemental heating method.

REF:

1. **Mars Mission Timeline**:

• NASA and SpaceX projections ([NASA](https://www.nasa.gov/humans-in-space/humans-to-mars), [SpaceX](https://www.nypost.com)).

2. **Heating Demand for Bases**:

• Lunar and Antarctic base analogs ([NASA Kilopower](https://www.nasa.gov/directorates/spacetech/kilopower), [BAS](https://www.bas.ac.uk)).

3. **Population Growth**:

• SpaceX vision for Mars settlement ([SpaceX](https://www.nypost.com)).

4. **Per Capita Heating**:

• Earth analogs for cold regions ([Our World in Data](https://ourworldindata.org/energy)).

5. **Geothermal Studies**:

• Volcanic region potential ([USGS Mars Geology](https://pubs.er.usgs.gov/publication/70041187)).

# Power Generation Options

## 1. Solar Power

**Solar power is the most straightforward option on Mars, but with some caveats.**

**Solar Irradiance:**

* Mars receives about **43% of the solar irradiance** compared to Earth due to its greater distance from the Sun.
* On Earth: ~1361 W/m² (average).
* On Mars: ~590 W/m² (average).

**Advantages:**

* Solar panels are a proven technology and can be deployed relatively easily.
* Abundance of silicon on Mars could allow for the **in-situ production of solar panels** in the future.

**Challenges:**

* **Dust storms**:

Can last for months, significantly reducing solar output.

Fine dust can cover panels, requiring periodic cleaning.

* **Day-night cycle**:

Martian day (~24.6 hours) requires energy storage for nighttime use (e.g., batteries).

**Optimal Usage:**

Solar power is feasible for early missions with **low-energy needs** but will require robust **energy storage systems** (e.g., lithium-ion batteries) or backup systems.

## 2. Nuclear Power

**Nuclear energy is a highly promising option for Mars.**

If water is unavailable for a steam cycle, nuclear power plants can still generate electricity using **alternative cooling and power conversion systems**. These systems bypass the need for traditional water-based Rankine (steam) cycles. Here are viable approaches:

**1. Closed Brayton Cycle**

The **Brayton cycle**, typically used in gas turbines, can be adapted for nuclear applications. Instead of using steam, it relies on a **gas** as the working fluid.

**Working Fluids**:

* **Helium**: Inert, high thermal conductivity, and works well at high temperatures.

**CO₂ (Supercritical)**: Compact and efficient at transferring heat.

**Process**:

* Heat from the reactor core transfers to the gas.
* The heated gas expands through a turbine, driving a generator to produce electricity.
* The gas is then cooled and recompressed before returning to the cycle.

**Advantages**:

* No need for water or steam.
* High efficiency at temperatures over 800°C.
* Compact systems suitable for Mars’ limited resources.

**Applications**:

* NASA’s Kilopower project explores this concept for space and planetary applications.

**References:**

• NASA Kilopower Reactor Systems ([NASA Kilopower](https://www.nasa.gov/directorates/spacetech/kilopower)).

• Studies on Supercritical CO₂ Brayton Cycles ([ASME Journal](https://asmedigitalcollection.asme.org/)).

**2. Thermoelectric Generators (TEGs)**

TEGs convert heat directly into electricity using the **Seebeck effect**, where a temperature difference across a thermoelectric material generates voltage.

**Process**:

* Heat from the reactor core creates a large temperature gradient across thermoelectric materials.
* The resulting current drives a generator.

**Advantages**:

* Extremely simple with no moving parts (high reliability).
* Compact and lightweight.

**Challenges**:

* Low efficiency (5–10%).
* Requires significant heat dissipation.

**Applications**:

* Used in **radioisotope thermoelectric generators (RTGs)** for space missions (e.g., Curiosity rover).

**References:**

• NASA RTG Systems for Spacecraft ([NASA RTGs](https://www.nasa.gov/)).

**3. High-Temperature Gas-Cooled Reactors (HTGRs)**

HTGRs use helium or CO₂ as a coolant, operating at very high temperatures (up to 1000°C).

**Process**:

* Heat from the nuclear reactor is transferred to a gas (helium or CO₂).
* The gas powers a Brayton cycle or directly drives a generator.

**Advantages**:

* High-temperature operation improves efficiency.
* No water required for cooling or power conversion.

**References:**

• HTGR Concepts ([International Atomic Energy Agency](https://www.iaea.org/)).

**4. Molten Salt Reactors (MSRs)**

MSRs use liquid salts as both the fuel medium and coolant.

**Process**:

* The molten salt transfers heat from the reactor core to a power conversion system (e.g., Brayton cycle).
* Operates efficiently at high temperatures without requiring water.

**Advantages**:

* High thermal efficiency.
* Can operate at lower pressures, enhancing safety.

**References:**

• MSR Development Programs ([World Nuclear Association](https://www.world-nuclear.org/)).

**5. Alternative Heat Dissipation Methods**

Instead of water-based cooling towers, reactors on Mars could use:

**Radiators**:

* Large arrays of fins or panels to radiate heat into space.
* Effective in Mars’ thin atmosphere and low ambient temperatures.

**Martian CO₂ Atmosphere**:

* CO₂ could serve as a heat transfer medium due to its abundance in the Martian atmosphere.

**References:**

• Spacecraft Thermal Management Systems ([NASA Systems](https://www.nasa.gov/)).

**Comparison of Alternatives**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technology** | **Water Requirement** | **Efficiency** | **Complexity** | **Suitability for Mars** |
| Closed Brayton Cycle | None | 40–50% | Moderate | High |
| Thermoelectric Generators | None | 5–10% | Very Low | High (for low power) |
| High-Temperature Gas Reactors | None | 40–50% | High | High |
| Molten Salt Reactors | None | 45–50% | Moderate | Medium-High |

For Mars, the **closed Brayton cycle** and **thermoelectric generators** are the most practical near-term options. They avoid water dependency and are relatively compact and reliable. In the long term, **high-temperature gas-cooled reactors** and **molten salt reactors** could provide scalable and efficient power solutions for larger settlements.

**Availability of Uranium:**

* Mars likely contains uranium, as it has been detected in Martian meteorites and the surface by rovers.
* Concentrations are unknown, and mining would require significant infrastructure.
* **Initial uranium supplies would need to be brought from Earth.**

**Advantages:**

* Nuclear reactors (like NASA’s Kilopower project) are **compact and reliable**.
* **Independent of weather and sunlight**, making them ideal for Mars’ long nights and dust storms.
* Potential to generate **heat** for habitat temperature regulation in addition to electricity.

**Challenges:**

* Transporting nuclear material and reactors to Mars is politically and technically challenging.
* Infrastructure for mining and refining uranium on Mars is not yet developed.

**Optimal Usage:**

Ideal for **continuous power supply** in medium-to-large settlements.

Could be a **primary energy source** once reactors are operational.

## 3. Wind Power

**Wind power on Mars is significantly less effective compared to Earth.**

**Martian Atmosphere:**

* The atmosphere is 100 times thinner than Earth’s, with an average pressure of ~6 millibars.
* Wind speeds can reach up to **60 m/s** (215 km/h) during dust storms, but the thin atmosphere results in **low force**.

**Advantages:**

* Could be useful during dust storms when solar power is limited.
* Could complement other energy sources.

**Challenges:**

* Power output would be extremely low due to the thin atmosphere.
* Large turbines would be needed to generate modest amounts of electricity.

**Optimal Usage:**

Wind power is **not a primary option** but might have niche applications in specific scenarios.

## 4. Fossil Fuels (Oil, Gas, Coal)

**Fossil fuels are not available on Mars.**

Mars lacks the biological history to form hydrocarbons like oil or coal.

Methane has been detected in small amounts in the atmosphere, but its origin is likely geological and not sufficient for energy production.

## 5. Hydrogen (Electrolysis)

**Hydrogen can be a key energy carrier on Mars, but its production requires significant water resources.**

**Availability of Water:**

* Water is available on Mars in the form of **ice**:

Polar ice caps contain vast reserves.

Subsurface ice deposits are scattered across the planet.

Liquid water is rare due to low atmospheric pressure and temperatures.

**Production of Hydrogen:**

* Electrolysis of water (using solar or nuclear power) could produce hydrogen as a **fuel for fuel cells or rockets**.
* Hydrogen can be combined with Martian CO2 (via the Sabatier process) to produce methane and oxygen.

**Advantages:**

* Hydrogen fuel cells can provide **backup power** for solar energy during nighttime or dust storms.
* Hydrogen can be used for **rocket fuel** and **chemical synthesis**.

**Challenges:**

* Requires significant energy input for electrolysis.
* Infrastructure for extracting and transporting ice is necessary.

**Optimal Usage:**

**Secondary energy carrier** or **backup source** rather than primary generation.

## 6. Geothermal Energy

**Geothermal energy is not well-explored on Mars but has potential in specific regions.**

**Thermal Gradient:**

* Mars is less geologically active than Earth, with a lower thermal gradient.
* Volcanic regions (e.g., Olympus Mons, Tharsis) may have geothermal hotspots.

**Challenges:**

* Requires detailed exploration to locate geothermal reservoirs.
* Drilling and extraction technologies would need to be developed for Martian conditions.

**Optimal Usage:**

Feasible only in **volcanic regions** and would require advanced infrastructure.

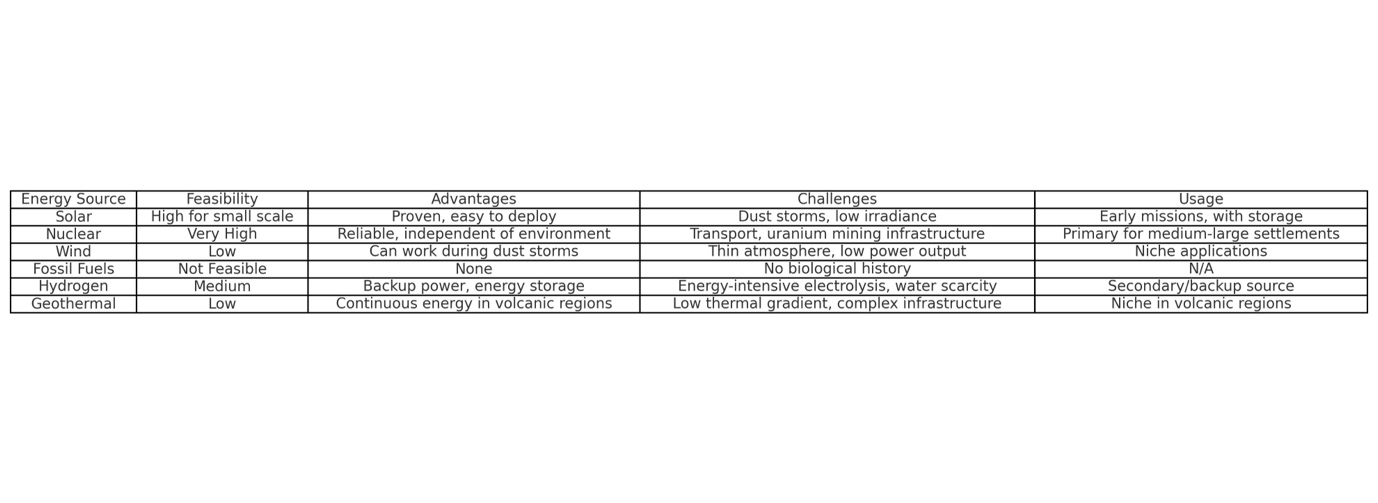
## 7. Other Exotic Options

* **Fusion Power**:

Theoretically viable in the long-term but not yet practical.

* **Compressed CO2 Power**:

The Martian atmosphere is 95% CO2, which could be used for innovative power cycles.



REF:

**1. Solar Power**

• **Martian Solar Irradiance**:

• NASA data shows Mars receives about 590 W/m² of solar irradiance on average, about 43% of Earth’s ([NASA](https://mars.nasa.gov/resources/)).

• **Challenges with Dust Storms**:

• The effects of dust storms on solar power were observed during the Mars Opportunity rover mission ([NASA Opportunity Rover Mission](https://www.jpl.nasa.gov/missions/mars-exploration-rover-opportunity-mer)).

• **In-situ Panel Production**:

• Research into regolith-based silicon extraction supports the idea of locally producing solar panels ([NASA Technical Reports Server](https://ntrs.nasa.gov/)).

**2. Nuclear Power**

• **Kilopower Reactor Design**:

• NASA’s Kilopower project is a compact nuclear reactor designed for extraterrestrial use ([NASA Kilopower](https://www.nasa.gov/directorates/spacetech/kilopower)).

• **Uranium Availability**:

• Mars’ crust is expected to have uranium based on findings in Martian meteorites and surface studies ([Mars Meteorite Study](https://doi.org/10.1111/maps.13750)).

• **Advantages of Nuclear Power**:

• Detailed NASA studies outline the reliability of nuclear power for space missions ([NASA Nuclear Power Systems](https://www.nasa.gov/directorates/spacetech/niac/2022/Kilopower.html)).

**3. Wind Power**

• **Thin Atmosphere**:

• Mars’ atmosphere is 100 times thinner than Earth’s, making wind power less effective ([Planetary Fact Sheet](https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html)).

• **Wind Speed**:

• Maximum wind speeds during Martian dust storms reach up to 60 m/s ([NASA Dust Storm Data](https://mars.nasa.gov/news/8415/)).

• **Low Power Output**:

• Studies on wind turbine performance on Mars confirm the significant reduction in power output compared to Earth ([The Role of Wind on Mars](https://doi.org/10.1016/j.pss.2018.05.009)).

**4. Fossil Fuels**

• **Lack of Biological History**:

• Mars lacks sufficient biological activity to produce oil, gas, or coal ([NASA Astrobiology](https://astrobiology.nasa.gov/)).

**5. Hydrogen (Electrolysis)**

• **Water Availability**:

• Subsurface ice has been confirmed by the Mars Reconnaissance Orbiter and other missions ([NASA Mars Reconnaissance Orbiter](https://mars.nasa.gov/mro/)).

• **Electrolysis and Hydrogen Production**:

• The Sabatier process and water electrolysis have been studied extensively for Mars missions ([NASA ISRU Studies](https://www.nasa.gov/directorates/spacetech/isru)).

• **Challenges with Liquid Water**:

• Mars’ low atmospheric pressure prevents liquid water from existing stably on the surface ([Mars Climate Data](https://mars.nasa.gov/resources/)).

**6. Geothermal Power**

• **Thermal Gradient**:

• Mars’ geothermal gradient is estimated to be lower than Earth’s but varies regionally ([Geophysical Studies on Mars](https://doi.org/10.1016/j.icarus.2011.06.036)).

• **Potential Geothermal Hotspots**:

• Volcanic regions like Tharsis and Elysium Planitia may have geothermal potential ([USGS Mars Geology Studies](https://pubs.er.usgs.gov/publication/70041187)).

**General Resources**

• **Martian Environment and Resources**:

• NASA Mars Fact Sheet ([NASA Fact Sheet](https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html)).

• **In-situ Resource Utilization (ISRU)**:

• NASA’s studies on ISRU systems for water, oxygen, and fuel production ([NASA ISRU](https://www.nasa.gov/isru)).

## Final Choices

### 1. Solar Photovoltaics (Solar PV)

**Why Solar PV?**

* **Abundant Resource**: Solar power is readily available during Martian daytime.
* **Proven Technology**: Widely used on Mars missions (e.g., Mars rovers).
* **In-Situ Manufacturing**: Future potential for producing panels using Martian regolith (silicon extraction).

**Challenges:**

* Reduced solar irradiance (~590 W/m², ~43% of Earth’s).
* Frequent **dust storms** (can reduce generation capacity for weeks/months).
* Requires robust **energy storage** systems to compensate for night and dust storm periods.

**Assumptions:**

* **Efficiency**: Assume 20–25% efficiency for state-of-the-art PV panels.
* **Capacity Factor**: ~25% average, accounting for irradiance and downtime during dust storms.
* **Scaling**: Solar PV primarily supports daytime electricity demands and contributes to charging storage systems.

### 2. Nuclear Reactor Coupled with Supercritical CO₂ Brayton Cycle

**Why Nuclear Power?**

* **Continuous Operation**: Provides baseload power, independent of weather or sunlight.
* **Heat Generation**: Excess heat can be used for habitat temperature regulation.
* **High Efficiency**: Supercritical CO₂ Brayton cycles achieve efficiencies >50%.

**Challenges:**

* Initial reactors and uranium must be imported.
* Complex installation and shielding requirements.
* Long-term development for in-situ uranium mining and reactor maintenance.

**Assumptions:**

* **Reactor Size**: Modular reactors with a capacity of ~10 MW.
* **Efficiency**: ~50% thermal-to-electric efficiency for the Brayton cycle.
* **Scaling**: Serves as the primary energy source during night/dust storms and supports heat demand.

### 3. Geothermal Power Plants

**Why Geothermal?**

* **Continuous Power**: Offers a reliable, weather-independent energy source.
* **Heat for Habitats**: Ideal for direct heat use and co-generation systems.
* **Potential on Mars**: Volcanic regions (e.g., Tharsis, Elysium Planitia) may have geothermal activity.

**Challenges:**

* Martian geothermal gradient is lower than Earth’s (~10 K/km vs. Earth’s ~25–30 K/km).
* Requires advanced drilling technology and exploration to locate viable hotspots.

**Assumptions:**

* **Resource Availability**: Geothermal is only feasible near volcanic regions.
* **Efficiency**: Geothermal plants achieve 15–20% efficiency for electricity.
* **Scaling**: Supplementary energy and heat source for settlements in suitable regions.

### 4. Battery Energy Storage System (BESS)

**Why BESS?**

* Efficient for **short-term storage** (daily cycles).
* Crucial for storing solar energy for night-time use.

**Challenges:**

* Limited by battery capacity and degradation over time.
* Requires periodic resupply or in-situ production of battery materials.

**Assumptions:**

* **Efficiency**: Round-trip efficiency of ~90%.
* **Capacity**: Scaled to provide 8–12 hours of backup power for solar systems.

### 5. Hydrogen Storage

**Why Hydrogen?**

* **Long-Term Storage**: Ideal for seasonal or dust-storm backup.
* **Energy Carrier**: Hydrogen can be used in fuel cells or combined with CO₂ to produce methane (rocket fuel).

**Challenges:**

* Energy-intensive electrolysis process.
* Requires infrastructure for hydrogen production, storage, and fuel cell integration.

**Assumptions:**

* **Production**: Electrolysis powered by solar and nuclear systems.
* **Efficiency**: ~70% for hydrogen production and ~50% for fuel cell electricity generation.
* **Scaling**: Long-duration backup storage for dust storms or seasonal fluctuations.