Novel Energy Storage for Martian Settlements
ThermoMars III

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1 Overview

- Four “novel energy storage” systems were analysed for Starship-scale Mars operations: a liquid-storage hydrogen fuel cell, a liquid carbon dioxide expander turbine, a methalox turbine and a methalox fuel cell. These were compared to current technology of lithium-ion batteries and hydrogen fuel cells with compressed gas storage.
- As with most surface ISRU systems, the total system mass is dominated by the mass of electrical generation and heat rejection systems. This emphasises the need to improve system efficiency and reduce the weight of both of these subsystems.
- In general, novel systems have a higher fixed mass than traditional, but a substantially lower weight per energy stored. This makes them higher performing at larger scales.
  - Assuming equal charge and discharge times, batteries are highest performing below around 50MWh, gas-storage hydrogen fuel cells below 200MWh, carbon dioxide expander turbines below 800MWh and methalox turbines above this point.
- Liquid hydrogen fuel cells and methalox fuel cells are likely never competitive, unless the underlying technology were to improve, as they are outperformed by similar alternatives.
- All novel systems have much heavier charging than discharging systems, so may be well suited for slow charge and relatively rapid discharge, ie not for diurnal energy storage.
- Both liquid carbon dioxide and methalox experience substantial boiloff from uninsulated tanks, on the order of 0.3-3% per day. Liquid carbon dioxide levels are best replenished by recapturing new carbon dioxide, while methalox is best kept with a cryocooler to achieve zero boiloff.

2 Working assumptions

Data on the performance of traditional systems, as well as the mass equivalency factors for power and thermal systems, were obtained from Baseline Values and Assumptions Document [1]. Additional data on fuel cells was obtained from relevant NASA publications [2] [3]. The general assumptions are given in Table 2.1.

3 Results

The results of the study are laid out in Table 3.1, with the mass efficiency of each system broken down by column. The charging specific power is the mass of the subsystem required to charge up the energy storage system, per unit **input** power. The discharge specific power is the mass of the subsystem required to discharge the energy storage system, per unit **output** power. The storage specific energy is the mass of the actual energy storage subsystem, per unit **output** energy, neglecting any boiloff mitigation. The estimated round-trip efficiency of each system is also given. No single figure of merit is calculated as this depends on the required charging and discharging power and the quantity of energy stored. Instead, the subsystems of each energy

Parameter	Value	Unit	Source
Mass equivalency of solar cells	100	kg/kWe	BVAD
Mass equivalency of Martian radiators	121	kg/kWth	BVAD
Methane-oxygen reaction energy	10	MJ/kg reactant	Cambridge databook
Hydrogen-oxygen reaction energy	13.3	MJ/kg reactant	Cambridge databook
Cryocooler mass	50	kg/kWth	Prior work
Methalox production energy from water and compressed CO2	50	MJ/kg	Prior work
Maximum turbine efficiency	85	%	Prior work

Table 2.1: Table of numerical assumptions

storage system are separated as described, allowing for a calculation of total mass for a given design requirement.

To calculate the total mass of an energy storage system, the specific input, output and stored power of the system should each be multiplied by the relevant design value. For instance, a liquid carbon dioxide system storing 100kWh with a charging power of 50kW and discharging power of 200kW would weigh $(100\,\mathrm{kW\,h} \times 0.29\,\mathrm{kg/kWh}) + (50\,\mathrm{kW_{in}} \times 241\,\mathrm{kg/kW_{in}}) + (200\,\mathrm{kW_{out}} \times 14\,\mathrm{kg/kW_{out}}) = 14879\,\mathrm{kg}$. This is true for all systems apart from batteries, where each mass value for charge, discharge and storage is calculated separately and the largest taken.

Approach	Charge specific power (kg/kW input)	Discharge specific power (kg/kW output)	Storage specific energy (kg/kWh output)	Round-trip efficiency
Li-Ion batteries	2*	2*	5*	~99%
H2 regenerative fuel cell, pressurised gases stored	0.5	0.5	1	~50%
H2 regenerative fuel cell, cryogenic liquids stored	1 (electrolyser) 20 (liquifier) 48 (radiator, 0.4kWth/kW input) **69**	1	0.12	14%
CO2 expander turbine	1.4 (compressor) 240 (radiator, 1.98kWth/kW input) **241**	14	0.29	90%
Methalox turbine	0.2 (CO2 compressor) 13 (methalox production) 28 (radiator, 1.30kWth/kW input) **41.2**	0.2	1×10^{-5}	18%
Methalox fuel cell	1?	1?	1×10^{-5}	10%?

Table 3.1: Representative performances of different energy storage systems

4 Hydrogen fuel cell, liquid reactant storage

Hydrogen fuel cells with liquefaction of reactants to increase storage density perform very poorly. While the efficiency of the electrolyser and fuel cell remain high, over 70% of the energy output of the fuel cell is required to liquify the reactants. This reduces efficiency from a respectable 50% to around 14%. This low efficiency hugely increases the mass of power generation and heat rejection to support the large liquefaction plant. A substantial improvement in liquefaction efficiency may improve the performance of this system, but the deep cryogenic temperature of liquid hydrogen make this unlikely.

5 Liquid carbon dioxide expander turbine

A liquid carbon dioxide expander turbine operates similarly to a reheated steam cycle for terrestrial power generation, using carbon dioxide rather than water as a working fluid. Cold liquid carbon dioxide is pressurised with a pump to high pressure (tens of bar), boiled in a heat exchanger and expanded through a turbine to generate mechanical power. After each turbine, the cold gaseous carbon dioxide is reheated in another heat exchanger to increase the specific work of each turbine and prevent the carbon dioxide condensing to liquid or solid inside the system. The carbon dioxide is eventually either exhausted to atmosphere or returned to a carbon dioxide acquisition compressor. Carbon dioxide is a relatively benign working fluid with substantial chemical and nuclear industry heritage, so the design of this system is not expected to be particularly novel.

This approach can theoretically produce substantial amounts of net power (ie, a round-trip efficiency greater than 100%) with sufficient reheat temperature. This would be a strong candidate for a nuclear energy power generation cycle on Mars. However, for this study the temperature of reheat was limited to 400K (127°C) as might be achieved from waste process heat utilisation. Under these conditions, an optimal cycle might achieve a round-trip efficiency of 90-100% with a boiler pressure of 50 bar and 12 turbines. The dominant system weight is the radiator needed to reject heat from liquid carbon dioxide compression.

A plot of accessible system performance is given in Figure 5.3, showing the range of available round-trip efficiencies and power outputs at a given mass flow, for different boiler pressures and reheat temperatures. Some regions of the design space are not accessible due to limitations of the carbon dioxide vapour pressure line. High efficiencies and high power outputs for a given mass flow (or high specific works) occur for high boiler pressures and high reheat temperatures as expected.

6 Methalox turbines

Methalox turbine generation presents the opportunity to directly utilise methane and oxygen rocket propellants as fuel and oxidiser in a more conventional gas turbine arrangement. Due to the need to limit turbine blade temperature to substantially below the flame temperature, carbon dioxide is also injected into the combustor. This is analagous to the air-rich operation of all industrial and aviation gas turbines. To limit the combustor temperature to reasonable values, 77% of mass flow in the turbine is composed of additional carbon dioxide. Similar to the carbon dioxide turbine, the turbine string is also limited by the formation of liquid water and liquid and solid carbon dioxide. It is assumed that water is removed by a condensing heat exchanger just above the point where it would be problematic, and the turbine string terminates when carbon dioxide condensation would be problematic.

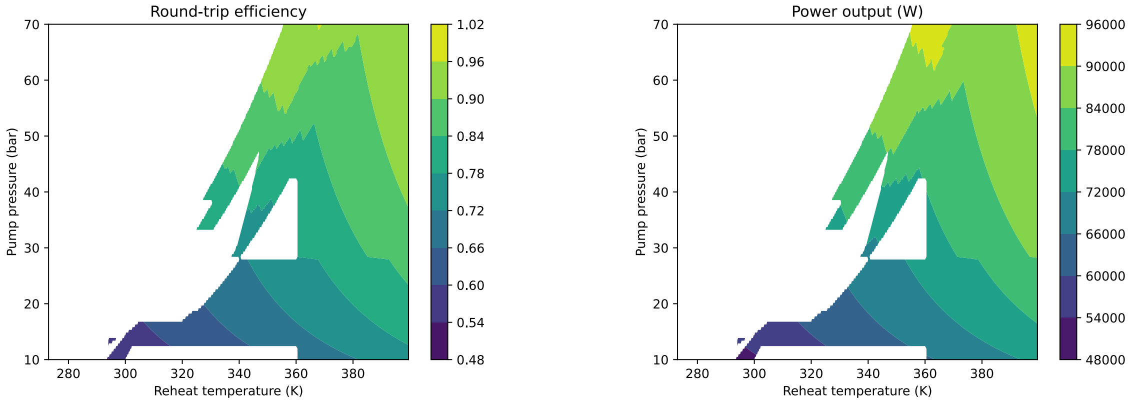

Figure 5.1: Liquid carbon dioxide expander turbine round-trip efficiency

Figure 5.2: Liquid carbon dioxide expander turbine power output (W)

Figure 5.3: Performance plots for the liquid carbon dioxide expander turbine with constant mass flow (215g/s). Some regions are inaccessible due to the approach of the carbon dioxide in the turbine to the vapour dome or sublimation line.

As expected, this approach is extremely lightweight due to the small size of the turbines required and lack of need for multiple reheating heat exchangers. However, it suffers from poor efficiency of the methalox production process. Based on prior work (ThermoMars II, At-Scale Process Engineering) it was found that current technology assumes a 20% production efficiency with an electrochemical process. Even with the roughly 85% energy conversion efficiency of the turbine stack, the round trip efficiency is still low. This makes the methalox turbine well-suited for extremely large-scale energy storage systems, and means it benefits the most from improvements to the methalox production process.

7 Methalox fuel cells

Methalox fuel cells suffer from the same issues with methalox production efficiency as turbines, but with lower round-trip efficiency and thus a higher overall system mass. Even with an optimistic fuel cell efficiency of 50%, higher than the well-studied hydrogen fuel cell, efficiency is substantially worse than the turbine equivalent. This is unlikely to change in the near future, making methalox fuel cells an unattractive option.

8 Starship tanks for energy storage

The potential of Starship propellant tanks for energy storage are given below. Data for propellant tank volumes are taken from Twitter use @fael097, and are presumed correct for SN15 as of February 2021. Since then, some values may have changed slightly.

When fully loaded, the largest energy storage is provided by the methalox turbine when carbon dioxide is acquired as-needed rather than stored. This would provide over 2700MWh of energy, or over 100MW-days. Second to this is the carbon dioxide expander turbine, which can store around 164MW-h or one MW-week of energy. Methalox turbine with liquid carbon dioxide stored reduces the energy capacity substantially, and there is predictably very little energy stored in gases at the pressures of the Starship main tanks

	CH4 main	O2 main	CH4 header	O2 header	Total
Volume (m3)	603	796	16.2	18.6	1433.8
Fluid capacities (kg)					
Liquid CO2 (6 bar)	703,000	928,000	18,900	21,700	1,671,600
Liquid oxygen (1 bar)		908,000		21,000	929,000
Liquid methane (1 bar)	254,000		6,800		260,800
Oxygen gas (6 bar, 0C)	5,100	6,800	174	158	12232
Hydrogen gas (6 bar, 0C)	320	423	8.6	9.9	761.5
Energy storage capacities (MWh)					
Liquid CO2 expander	69.2	91.4	1.86	2.14	164.6
Methalox turbine CO2 stored	(CO2, 12%)		(CH4, 77%)	(O2, 100%)	67.4
Methalox turbine no CO2 stored	(CH4, 89%)	(O2, 100%)	(CH4, 100%)	(O2, 100%)	2740
Hydrogen gas fuel cell	(O2, 15%)	(H2, 100%)	(H2, 100%)	(H2, 100%)	2.2

Table 8.1: Volumetric and fluid storage capacities of Starship tanks

8.1 Heat gain into Starship tanks

In each case where liquid reactants are stored in the Starship main tanks, the temperature must be maintained to prevent substantial boiloff. The significance of this boiloff must be considered when evaluating the effectiveness of any system of energy storage that uses liquids as energy stores. To calculate this heat loading, the Syrtis one-dimensional heat transfer modelling code was used. This Python code solves heat transfer from radiation, convection, solar insolation and conduction on the Martian surface to assess heat transfer to habitats and other pressure vessels [4].

The Starship tanks were modelled as bare stainless steel with thickness 3.2mm and diameter 9m, placed at a latitude of 30 degrees north (the approximate target Starship landing sites). Heat gains per metre of tank length are given in Table 8.2, along with calculated boiloff quantities in kilograms per metre of tank length and percent total load.

The maximum heat load into liquid carbon dioxide is 2.8kW per metre, or 70kW for both main tanks. Rejecting this heat in a cryocooler would require around 700kW of electrical input with a 3.5t system. Instead replenishing boiloff gas by producing additional carbon dioxide from the atmosphere would require 18,000kg of production per day or 180kW of constant energy input. The boiling off carbon dioxide could be used to drive an expander turbine with 53kW of output power, so a net power input of just 127kW would be needed. Replacing rather than re-condensing carbon dioxide is thus an optimal choice for this power system. As the vehicle tanks store 164.6MWh, the boiloff figure of merit (energy stored over energy required for zero boiloff) is 1300.

	Summer condition	Winter condition
Daily heat gain Liquid CO2	2.5×10^8 J/m 2.8kW/m	0.7×10^8 J/m 0.8kW/m
Daily boiloff Liquid CO2	720kg 1.0%	200kg 0.3%
Daily heat gain Cryogen	4.5×10^8 J/m 5.1kW/m	2.8×10^8 J/m 3.2kW/m
Daily boiloff Cryogenic O2	2110kg 2.9%	1310 1.8%
Daily boiloff Cryogenic CH4	880kg 3.3%	550kg 2.1%
Daily heat gain Gas	0.7×10^8 J/m 0.8kW/m	-1.0×10^8 J/m -1.0kW/m

Table 8.2: Heat load into, and boiloff from, Starship tanks on the Martian surface

The maximum heat load into cryogenic tanks is around twice as large, requiring 128kW of cooling power or 1275kW of electrical input for a cryocooler. Replacing the roughly 40,000kg of reactant boiloff per day would require a much larger 22,500kW of input power to a methalox production stack, so cryocooling is the appropriate choice. This would be a substantially heavier overall boiloff reduction system due to increased cooler mass, power system and heat rejection. The boiloff figure of merit is 2150.

References

[1] M. Anderson et al. *Life Support Baseline Values and Assumptions Document*. 2015.

[2] K. A. Burke. *Fuel Cells for Space Science Applications*. Technical Memorandum NASA-TM-212730. Glenn Research Center, Cleveland, OH: National Aeronautics and Space Administration, 2003.

[3] C. P Garcia et al. *Round Trip Energy Efficiency of NASA Glenn Regenerative Fuel Cell System*. Technical Memorandum NASA-TM-214054. Glenn Research Center, Cleveland, OH: National Aeronautics and Space Administration, 2006.

[4] S. Ross. *Syrtis: A Python package for Martian heat transfer analysis*. `https://github.com/smross106/Syrtis`. 2023.