Selecting the Most Promising Oxygen Extraction from Lunar Regolith Technology

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Abstract. Oxygen extraction, and In-Situ Resource Utilization as a whole, is paramount to humankind's sustained lunar presence, and future Space exploration. Frazer-Nash Consultancy, a KBR company, has conducted a trade study into eight oxygen extraction technologies to determine, based on current information, which has the best chance of success. Frazer-Nash has developed a tailorable comparison matrix, compiled from a comprehensive data-gathering exercise on commercial, academic and agency developments, for the eight leading oxygen extraction processes. Key criteria for comparing these technologies have been identified (i.e. power requirements, yield, scalability), analysed and scored. A confidence factor has been applied outlining the data sources for each technology – quantifying development to date. This considers whether data is theoretical or originates from modelling, physical testing, or existing terrestrial processes. Future users can utilize this data and flexible comparison matrix to select the optimal process for any production requirements and their specific use case needs.
Keywords: ISRU, Oxygen, Regolith, Trade-Study.

Nomenclature.

Acronyms/Abbreviations.

ESA – European Space Agency
ESRIC – European Space Resources Innovation Centre
IL – Ionic Liquid
ISRU – In-situ resource utilisation
FFC – Fray, Farthing, Chen
KSC – Kennedy Space Centre
LOX – Liquid oxygen
LEO – Low Earth orbit
LH2 – Liquid hydrogen
MRE – Molten Regolith Electrolysis
MSE – Molten Salt Electrolysis
MSFC – Marshall Space Flight Centre
SME – Subject Matter Expert
TRL – Technology Readiness Level

1 Introduction

In-situ resource utilisation (ISRU) is crucial in enabling humankind to sustain a presence in space and facilitating further exploration. The oxygen-rich lunar regolith could be a source of precious oxygen, necessary for sustaining human life and a major constituent of the fuel mix necessary to launch from the lunar surface. In this paper, we share a tool developed to compare the processes used to extract this oxygen, and the associated technologies, to identify the most suitable process. These criteria can be appropriately weighted for applications from initial demonstrators to viability at industrial scale.

1.1 Scope

A successful ISRU economy depends on a wealth of stakeholders providing key infrastructure up and downstream of the oxygen extraction system. From excavation to beneficiation to the end customer. This trade-study is solely focused on the processes to extract oxygen from regolith.

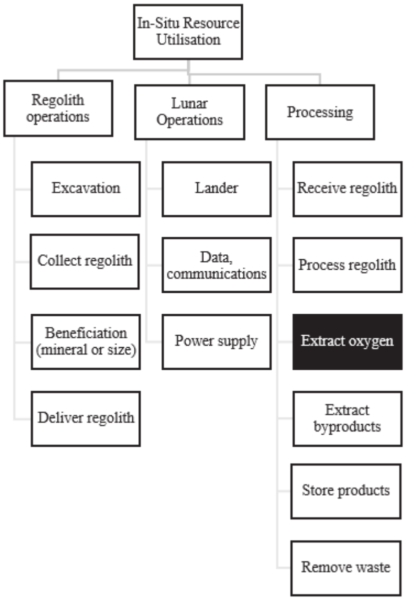

Figure 1: ISRU operations; System of interest shown in black.

Whilst there are many techniques to extract oxygen from lunar regolith, eight processes which show potential and have received funding to develop in recent years have been selected to review. The considered processes are hydrogen reduction, plasma-enhanced hydrogen reduction, molten salt electrolysis, ionic liquid electrolysis, molten regolith electrolysis, carbothermal reduction, fluorination and vapor phase pyrolysis.

This study differentiates the aforementioned oxygen extraction processes and identifies those technologies capable of demonstrating oxygen extraction from regolith on the lunar surface this decade. This was conducted with a thorough literature and market review culminating in a flexible matrix with an associated confidence score.

1.2 Viability

Lunar regolith varies in composition - dependent on grain size, location, and maturity. Approximately 45wt% of the lunar regolith is oxygen, primarily contained in silicate minerals with the remaining regolith composed of oxide minerals. Lunar regolith is distinct between the Mare and Highland regions, with the former rich in iron and titanium, and the latter richer in calcium and aluminium [1]. For oxygen mining, assuming a 2m excavation depth and a yield of 10wt% oxygen from bulk regolith, this equates to nearly 5 million megatons of oxygen [2].

A key use case of liquid oxygen (LOX) from the lunar surface is as propellant. The reduced delta-v required to launch from the lunar surface compared to Earth's, means even to reach low earth orbit (LEO), launching from the lunar surface could be more cost efficient [3]. Noting however, this is technology dependent and must compete with decreasing terrestrial launch costs. Whilst Metzger [3] has focussed on Lunar Water to produce LOX and liquid hydrogen (LH2) as required by United Launch Alliance and Blue Origin, LOX is typically a minimum of 75% [4] of the mass ratio in rocket engines and is required for both hydrogen and hydrocarbon engines, such as SpaceX's methane/LOX mixture. As of 2022, water ice was still classified as a speculative resource whilst regolith oxygen is a measured resource [2].

Similarly, the cost of LOX shipped from Earth to the lunar surface is approximately $35,000/kg (assuming a $1/kg cost on Earth) [5]. The oxygen required per person per day is 0.84kg. Taking estimated values of 1000 lunar inhabitants by 2040 [6], this would equate to a daily cost of $29.4 million if supplied from Earth.

To provide oxygen for life support to a colony of 100 people living on the lunar surface for 10 years, oxygen mining has been estimated to be about the same cost as that of life support wastewater recycling. Wastewater recycling must also be supplemented with mined resources to offset recycling losses [7], hence in-situ resource utilisation is a pre-requisite for a sustained human lunar presence.

The above considerations suggest oxygen extraction from lunar regolith is at the very least a desirable, if not necessary, factor in enabling future space exploration.

2 Method

To facilitate the trade study, it was necessary to identify the criteria of interest. These criteria were selected with the initial aim of selecting a suitable technology to extract oxygen from the lunar surface within this decade (the 2020s). These criteria were selected to be clear, specific and measurable with consideration also granted to the future capabilities, outlining that a demonstration should represent viability for industrial scale oxygen production. The mass criteria (yield, launch and resupply efficiency) are all ratios of kg/kg. For consistency, where varying efficiencies at different scales were found, the values selected were at the scale of a pilot plant (10,000kg of oxygen production per year).

The key steps followed to conduct this trade study were:

1. Defining the requirements
2. Identifying candidate solutions to the requirements
3. Establishing the option judging criteria
4. Gathering information to allow option assessment against criteria
5. Producing a flexible comparison matrix for technical information and scoring this information numerically.
6. Producing a secondary "confidence" matrix to quantify the sources used, and scoring based on the type of experimentation or analysis conducted
7. Calculating a normalized confidence factor from this secondary matrix.
8. Multiplying the technical matrix's score by the confidence factor to produce a resultant score for each candidate solution.

As detailed in section 1.1 the candidate solutions were processes with the capability to extract oxygen from regolith, and with sufficient maturity for analysis. This paper does not aim to provide a definitive answer as to the recommended solution to the challenge of extracting oxygen from lunar regolith, but rather provide the tools to enable others to do so based on their specific needs.

3 Criteria

To facilitate the trade study, it was necessary to identify the criteria of interest. These criteria were selected with the initial aim of selecting a suitable technology to extract oxygen from the lunar surface within this decade (the 2020s). These criteria were selected to be clear, specific and measurable with consideration also granted to the future capabilities, outlining that a demonstration should represent viability for industrial scale oxygen production. The mass criteria (yield, launch and resupply efficiency) are all ratios of kg/kg. For consistency, where varying efficiencies at different scales were found, the values selected were at the scale of a pilot plant (10,000kg of oxygen production per year).
The selected criteria are as follows:

Criteria	Assessment
Scalability	The capacity to scale the process from demonstrator to pilot plant, to industrial scale is desirable.
Process Complexity	Process complexity and the number of steps required to produce oxygen should be minimised.
Safety	The likelihood to harm an operator or endanger a lunar settlement should be minimised. Secondary considerations are damage to itself or a vehicle platform to which it's integrated.
Robustness	The system should survive the required design life with margin. Tolerance and resilience to varying conditions is key as maintenance requirements should be minimal.
Energy Efficiency	The system should minimise the energy required to produce oxygen. This was quantified in MJ of energy per kg of oxygen produced.
Temperature Requirements	The temperatures required for the reaction to occur will impact on the system's thermal management. Hence, lower process temperatures are desirable.
Mass Efficiency (Yield)	Tonnes of oxygen produced per tonnes of Regolith should be maximised. The yield will drive throughput requirements.

Site Specificity	Processes which can reduce both Highland and Mare Regolith are desirable.
Technology Readiness Level	Higher TRL processes are desirable, as this considers process maturity and development to date.
Re-Supply Efficiency	Minimal reagents and replacement equipment should be required. This is quantified as kg of re-supply needed per kg of oxygen produced in a systems lifetime.
Launch Mass Efficiency	This criterion quantifies the initial equipment and chemical agents required for a process. This has been normalised to kg of launch mass required per kg of oxygen produced.
Byproducts	Whilst oxygen is the priority at the demonstration stage, identification of useful byproducts will increase economic viability of the system.

4 Data collection

To populate information on each process it was necessary to conduct a State-of-the-Art review for oxygen extraction from lunar regolith technologies. This was conducted primarily in early 2024.

This involved a literature review, market review and interviews with subject matter experts (SMEs), academics and private companies developing the technologies. To quantify this data, a record of sources was maintained. This contained details about the origins of the data – be it theoretical, from modelling or simulations, experimental data or know-how from terrestrial processes. These were then scored accordingly to produce a confidence factor, as discussed in section 6: data utilisation.

All processes identified were researched until we were unable to obtain further information within the project timescales. It should be noted that for some lower-TRL processes, data was less readily available, and hence some fields are unpopulated, or with a decreased confidence score.

5 Overview of Processes

This section details a high-level overview of the processes, their advantages and disadvantages and an acknowledgment of the current work. Whilst the subsequent matrix considers only the most mature technology for each process, initial research was considered all technologies with publicly available information.

5.1 Hydrogen Reduction

The hydrogen-reduction method is undertaken at temperatures of approximately 800-1000°C with solid, granular regolith within a flow of hydrogen to reduce the oxides and produce water, which is then purified and electrolysed to generate oxygen and hydrogen. The oxygen can be stored, with hydrogen available for reuse in the extraction process. Fixed bed reactors, moving bed reactors, fluidised bed reactors and entrained flow reactors are all suitable for facilitating this reaction [8].

These processing technologies are well understood, and terrestrial hydrogen reduction has received a wealth of investment in the green steel sector, as the steel industry is responsible for 7% of annual greenhouse gas emissions [9]. However, the sole regolith constituent able to be effectively reduced by hydrogen reduction is iron oxide [10]. *Hence, in the lunar poles with minimal ilmenite ($FeTiO_3$), oxygen yield from hydrogen reduction can be estimated at approximately 1wt% of oxygen from reg*olith [11].

A fluidized hydrogen reduction reactor has been built and field tested in the volcanic ash on Mauna Kea volcano, which has a similar chemical composition to lunar regolith, demonstrating the feasibility of producing oxygen at rates of 660 kg/year [12] *with a TRL of 5* [13].The European Space Agency (ESA), have also explored this technology, developing ALCHEMIST-ED *(*A Lunar CHEmical In-Situ Resource Utilisation Test Plant - Earth-based Demonstrator), which will demonstrate the ability to produce oxygen from lunar simulant [14].

5.2 Plasma Enhanced Hydrogen Reduction

Plasma enhanced hydrogen reduction follows the same chemical principles as hydrogen reduction, but with an increased yield. The simplest form of this is a bed of regolith, with the hydrogen plasma passing over it. Hydrogen gas is ionised to form a plasma of excited hydrogen ions and electrons. These excited particles have thermodynamic and kinetic advantages to molecular hydrogen, hence lowering the Gibb's free energy and making the reaction more favourable [15].

This enables a wider range of oxides to be reduced, such as silicates. The Kennedy Space Centre (KSC) have reduced lunar highland simulant, raising the TRL to 3 [16]. Ongoing work at the European Space Resources Innovation Centre (ESRIC) uses a hydrogen/argon gas mixture for the plasma process, demonstrating the reduction of titanium oxides at 600degC [17]. Thermal plasma processing at elevated temperatures (3000degC+) has also been investigated [18] with the advantage of regolith spheroidization, in which the high temperatures melt the regolith particles, reshaping them into spheres – useful for lunar infrastructure as spherical powders have improved properties for additive manufacturing [19].

5.3 Carbothermal Reduction

Typically, carbothermal reduction uses methane to reduce regolith. This process produces carbon monoxide and carbon dioxide, which can be converted with hydrogen into methane and water in a Sabatier reactor, with the water subsequently electrolysed to hydrogen and oxygen. At temperatures above 1200°C, silicates and titanium oxides can be partially reduced, increasing oxygen production to 20wt% of oxygen from bulk regolith [8].

This can be further increased at temperatures above 1600°C, in which the regolith is molten, and silicates can be fully reduced, with yield up to 28wt% Oxygen from Regolith [8]. With molten regolith, this process is effective regardless of location, whilst with solid state/partially molten regolith, high ilmenite content will increase efficiencies.

Carbothermal reduction has been developed to TRL 5 [13], after successful tests were conducted in a moon-like environment on lunar soil simulant by NASA scientists using Sierra Space Corp.'s carbothermal reactor [20]. Plant capacity of up to 19,000kg/year has also been investigated [21] Carbon losses occur due to carbide formation, or carbon deposition onto solid or molten regolith [8], and hence re-supply of carbon from Earth is required, assuming the small amounts of carbon implanted in regolith from solar wind [1] are insufficient.

5.4 Fluorination

Fluorine is the most reactive element, and a stronger oxidising agent than oxygen [22]. Fluorination can substitute oxygen, releasing gaseous oxygen and producing fluoride salts or gaseous fluorides [8]. To create a sustainable cycle, fluorine must be recycled. A multitude of concepts for this exist such as sodium reduction, addition of atomic hydrogen followed by electrolysis, re-use of fluoride salts in molten salt electrolysis, or gaseous distillation to separate oxygen and fluorine from metal fluorides which are reduced in a furnace with potassium and subsequently electrolysed to form potassium metals and fluorine gas [8].

Fluorination (and the steps to recycle fluorine) requires at least 6 distinct reactors [8] – all resistant to fluorine corrosion. Fluorination has the capacity to release all oxygen from the regolith, allowing for some reoxidation to produce fluorine, the oxygen yield is up to 44.8wt% of regolith [22]. This is currently highly conceptual work; however fluorine has been used to extract oxygen from terrestrial rock [22] and studies to extract breathable oxygen from regolith using fluorinated plasma are ongoing with promising results [23].

5.5 Molten Salt Electrolysis

Molten Salt Electrolysis (MSE) has been used terrestrially to reduce aluminium in molten cryolite and to reduce titanium oxide in molten calcium chloride [8]. The general MSE principle consists of submerging metal oxides in a bath of molten salt, in which metal oxides will dissociate into metal cations and oxygen anions and be able to be collected from the cathode and anode respectively [24].

The Metalysis-FFC (Fray, Farthing, Chen) Cambridge MSE process has received focus in recent years and has been selected for ESA’s demonstration mission [25]. This technology is terrestrially mature at a commercial scale [26], and has successfully reduced JSC-2A lunar regolith simulant, extracting 96% of Oxygen at 950°C and producing a metal alloy product [27]. It is believed with refinement, close to 100% oxygen yield could be obtained [27]. Utilising molten salt enables electrolysis to take place with solid state regolith, and hence process temperatures of 680°C can produce over 40wt% oxygen from regolith [28]. These experiments were undertaken with a salt:regolith ratio of 1:33 [28], and previous experiments have noted limited lifetimes due to progressive anode erosion, declining conductivity [29] and oxygen being lost to corrosion of the reactor vessel [27].

There are competing processes in development, such as Airbus’ Mini-ROXY which utilises a solid oxide membrane in the anode assembly to allow only the passage of oxygen ions, alleviating some of the concerns around anode erosion and reaction chamber corrosion [30]. Due to limited published testing of the Mini-ROXY system to date, the results in the subsequent matrix focus primarily on the Metalysis-FFC process.

5.6 Ionic Liquid Electrolysis

Ionic Liquids (IL) are salts which are liquid below 100°C and composed entirely of ions, which can act as charge carriers, leading to good conductivity [31]. IL electrolysis is envisioned as a 3-step process. Firstly, regolith is dissolved in IL to convert metal oxides into water and metallic ions. This water is then electrolysed to produce hydrogen and oxygen, and IL is regenerated by oxidation of hydrogen at the anode and reduction of the metallic ions at the cathode. Alternatively, the water generated when the constituent oxides of regolith are solubised can be distilled out, condensed and electrolysed to produce hydrogen and oxygen [32].

This process is expected to take place, entirely, at temperatures below 300°C [32]. NASA's Marshall Space Flight Centre (MSFC) conducted experiments with 6 ILs, extracting 75% of the available oxygen from lunar simulant at only 150°C using an IL/phosphoric acid solution [32]. Whilst IL's acidity is required to dissolve the metal oxides, they are less volatile and corrosive than conventional mineral acids [32]. Should a suitable IL be found, this process could extract all the oxygen from lunar regolith [32], however the regeneration of IL is challenging and removal of metal ions from the solution has been unsuccessful to date [31].

5.7 Molten Regolith Electrolysis

Molten Regolith Electrolysis (MRE) is a direct electrolysis process in which regolith is melted and molten metallic ions are reduced at the cathode and oxygen gas is formed at the anode [33]. This is an attractive technique due to process simplicity, with no import of consumable agents or secondary processes required to obtain elemental oxygen [34].

This process has been demonstrated by NASA's MSFC at temperatures approaching 1600°C, with subsequent work by the Kennedy Space Centre (KSC) suggesting that almost 16wt% oxygen could be extracted from regolith [33]. Blue Origin's Blue Alchemist operates at temperatures in excess of 1600°C with byproducts of aluminium, iron and silicon [35]. Experiments focussed on electrolysis of silicate mixtures have shown concern about cell performance over extended lifetimes, as the molten mixture becomes more electrically resistive and additional fluxing agents are required to maintain efficiency [36].

5.8 Vapour Phase Pyrolysis

Vapour-phase pyrolysis is distinct as the separation of metals and oxides occurs in the gas phase. This process utilises the ultra-high vacuum on the lunar surface, which results in sublimation of oxides being favourable at moderate temperatures [37]. Regolith is heated in a vacuum to a fully gaseous form, and the metal is condensed immediately following evaporation to prevent recombination with the oxygen. The oxygen must be continuously extracted from the process to maintain the vacuum [8]. Carbon monoxide, carbon dioxide, water and other solar wind implanted elements can be released in this process [1].

Various techniques for heating the regolith and collecting the oxygen can be investigated. Laboratory studies have been conducted using concentrated sunlight to heat regolith simulants, however the glass window through which sunlight was concentrated cracked due to thermal shock and internal condensation [8]. Development of an appropriate sunlight concentration method and oxygen extraction system would make this viable for scaling with minimal transport required from Earth as no reactants other than regolith are required. A prototype has been developed and scaling has been investigated – with 15kW power, extraction at 1500°C and a 60kg reactor, 4,000 kg/year oxygen could be produced [38], noting that 13 kW of power is also required for the cooling and condensing module. Yields of up to 23wt% oxygen from regolith could be achieved, dependant on oxide dissociation and condenser efficiency [39]. Realistic yields have been estimated at 1 to 8.5wt% oxygen from regolith [40].

6 Data utilisation

Information regarding each process in section 5 was populated against the criteria detailed in section 3. For clarity, we have researched each processes' associated technology and conducted the scoring process regarding only the most mature technology (or that with the most readily available information) for each process.

The information for each process and criteria was then rated from a scale of 1-6, with 6 being the best. These ratings were defined relative to the other processes' capabilities; however, the processes were not ranked – numerical positions can be skipped and where processes' performance was similar the same rating was assigned.

The confidence factor was determined by assigning a value to each piece of information denoting its source. A value of 1 was assigned to theoretical studies or scientific papers based on simulated systems/models, a value of 2 assigned to scientific papers on existing relating systems (i.e. terrestrially mature technologies which are similar), and a value of 3 assigned to experimental results and existing demonstrations with proven capabilities. From here, a total score for each process was calculated, and this was normalised relative to the average score across all processes to determine a confidence factor, which the initial matrix score can be multiplied.

$$\text{Confidence Factor} = \frac{\text{Process Confidence Score}}{\text{Average Confidence Score}}$$

It is at the user's discretion to adjust weightings for their application – be it a high TRL demonstrator that can produce oxygen within 3 years, or a scalable concept that would produce a high yield at an industrial level over a longer time frame. Likewise, the resultant matrix will output a score which reflects only the technical information, and a secondary score which incorporates the confidence factor, enabling users to prioritise either theoretical technical performance or risk reduction through previous work.

7 Results

The matrix containing the confidence scores, and resultant confidence factor for each source are in Appendix A. The technical matrix is in Appendix B, with the final row relating the sum of the technical scores multiplied by the confidence factor.

The results from the technical matrix (numerical scores in brackets) are as follows:

1. Molten Salt Electrolysis (45)
2. Plasma Enhanced Hydrogen Reduction (44)
3. Ionic Liquid Electrolysis (42)

T4. Hydrogen Reduction (41)
T4. Carbothermal Reduction (41)
5. Molten Regolith Electrolysis (40)
T6. Vapour Phase Pyrolysis (37)
T6. Fluorination (37)

When the confidence factor is included, the resultant scores are as follows. The numbers in brackets denote the confidence factor and the resultant score:

1. Molten Salt Electrolysis (1.149, 51.72)
2. Carbothermal (1.195, 49.01)
3. Hydrogen Reduction (1.103, 45.24)
4. Molten Regolith Electrolysis (1.057, 42.30)
5. Plasma Enhanced Hydrogen Reduction (0.874, 38.44)
6. Ionic Liquid Electrolysis (0.874, 36.69)
7. Fluorination (0.966, 35.72)
8. Vapour Phase Pyrolysis (0.782, 28.92)

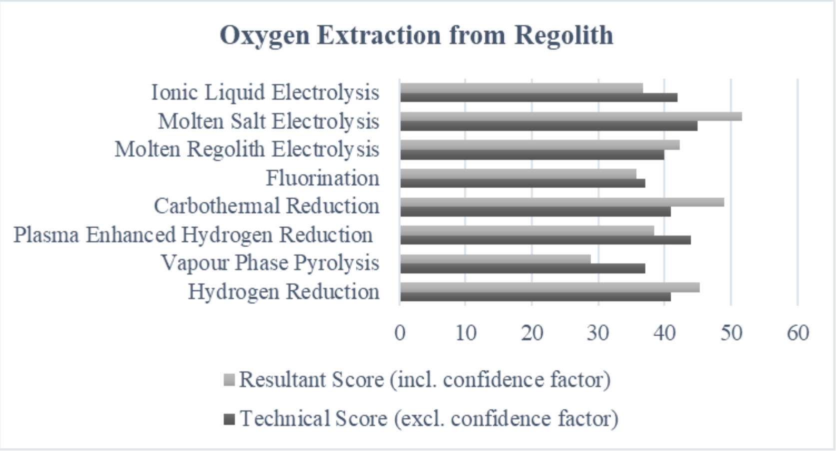

Figure 1: Graphical representation of results including/excluding the confidence factor

8 Discussion

The results firstly highlight the complexity of selecting the optimum process at this time, with all processes separated by only 8 points, with the top 6 processes separated by only 5 points out of an available 72.

When considering the confidence metric, the scores tend to align with those that have had the greatest investment to date, and those that are most public with their data. The 4 processes with positive confidence factors are those of molten salt electrolysis, carbothermal reduction, molten Regolith electrolysis and hydrogen reduction. As mentioned, MSE is ESA's demonstration mission, and the majority of published testing for carbothermal and hydrogen reduction have been undertaken by NASA. MRE is currently being developed by Blue Origin, however NASA's MSFC and KSC raised this process's TRL in the 2000s. As Space Resources becomes more commercially viable, private development is accelerating, but hopefully information surrounding these developments will be as readily available as the developments to date under public funding.

Molten salt electrolysis tops both tables. The impressive technical score is due to the high yield of oxygen and the quality of byproducts – although it should be noted that this process scored lowest in terms of mass efficiency for launch and re-supply, due to the quantities of salt required for the process and expected equipment degradation.
Carbothermal reduction was technically consistent – it received all technical scores in the range of 3-5, suggesting no major areas of concern. The yield was moderate, however as not all oxides were reduced there is an element of site specificity to be

considered. The process also requires multiple stages and partial re-supply of carbon. However, its extensive development for ISRU and its terrestrial commercial maturity have produced a positive confidence factor which has placed this process in second place when all is considered.

Ionic liquid reduction is akin to MSE, scoring well technically due to the theoretically high yield of oxygen at low process temperatures. This process could have scored higher had more information been published, with a notable lack of sources regarding scalability of this technology and robustness.

Molten Regolith electrolysis can reduce a wide range of oxides, producing high quality by-products (Blue Origin have reported silicon purity in excess of 99.999%, as required for efficient solar cells [10]). The technical drawbacks are primarily the energy efficiency and high process temperatures.
Hydrogen reduction is terrestrially mature and has been investigated thoroughly by both ESA and NASA for lunar applications. It scores well in scalability, due to this terrestrial advancement, with multiple demonstration plants in development currently [18], [19]. Hydrogen reduction’s primary drawback is the limited yield due to only being able to reduce ilmenite. This affects its score across yield and site specificity as ilmenite is more abundant in Mare regions.

Plasma enhanced hydrogen reduction scored well on mass efficiency and site specificity, as the ionised hydrogen could reduce a range of oxides. The scoring reflected that of “non-thermal” reduction, and so temperature requirements were also favourable, resulting in a high technical score. This process however had a negative confidence factor as experimentation to date is not as advanced as other processes, with the quantity of oxygen produced from simulants not yet measured and recorded.

Fluorination has lower process temperatures (600-700K), and high yield (32%) [43], but the system complexity and concerns about safety and robustness prevent it from scoring better. As 6-8 reactors are required for the full system there is a high risk in design development and many points of failure throughout the system. Fluorine is highly corrosive, and the energy efficiency of this system was relatively poor in comparison to others.

Vapour phase pyrolysis scored the highest of all processes in launch and resupply efficiency – primarily due to the lack of chemical agents required for a continuous process. This process did score the lowest in temperature requirements, however as much of this can be supplied by concentrated sunlight the energy efficiencies are not as poor. This technology was impeded by its poor projected yield and the challenges mentioned in experimentation.

9 Conclusion

Within this paper, a comprehensive comparison matrix for selecting the appropriate technology has been developed. The results presented here outline the technologies in a concise, comparable way. The results matrix in Appendix B can be tailored to output varying results dependant on system requirements.

Whilst the confidence factor accounts for the type of research conducted, and the depth of experimentation, there will still be inconsistencies within the conditions assumed by each source. This study has not attempted to subjectively assess the merit of each source but quantify the development to date.

As the ISRU community develops further this study should be revisited – not only to document advances in technologies and processes but to identify whether the criteria of importance have evolved as our ISRU capabilities advance.

Acknowledgments

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Appendix A (Confidence Factor Matrix)

	Ionic Liquid	Molten Salt Electrolysis	Molten Regolith Electrolysis	Fluorination	Carbothermal	Hydrogen Plasma Reduction	Vapour Phase Pyrolysis	Hydrogen Reduction
Scalability	0	3	2	1	3	2	1	1
Process Complexity	2	3	3	1	3	2	1	2
Safety Risks	2	2	1	3	3	2	2	3
Robustness	0	3	1	3	2	2	2	3
Energy Efficiency (MJ/kg O2)	2	1	1	1	1	2	1	1
Temperature Requirements	2	2	3	3	2	2	2	2
Mass Efficiency (tonnes of Regolith: 10tonnes O2)	2	3	3	1	2	3	2	2
Site Specificity	2	3	3	3	3	2	1	3
Technology Readiness Level	2	2	3	2	2	2	2	2
Re-supply efficiency (annual tonnes of payload/ tonnes of O2)	2	1	2	1	2	1	3	2
Launch Mass efficiency (tonnes of payload/ tonnes of O2)	2	1	1	1	2	0	1	2
Byproducts	3	3	3	3	3	1	1	3
Total	19	25	23	21	26	19	17	24
Confidence factor	0.874	1.149	1.057	0.966	1.195	0.874	0.782	1.103

Appendix B (Technical Matrix)

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	Ionic Liquid	Molten Salt Electrolysis	Molten Regolith Electrolysis	Fluorination	Carbothermal	Hydrogen Plasma Reduction	Vapour Phase Pyrolysis	Hydrogen Reduction
Scalability	0	5	4	3	5	4	4	5
Process Complexity	4	5	5	1	3	4	3	5
Safety Risks	5	5	3	2	5	4	4	3
Robustness	0	3	3	2	4	3	2	5
Energy Efficiency (MJ/kg O2)	4	4	1	1	5	4	3	6
Temperature Requirements	6	3	2	5	3	5	1	3
Mass Efficiency (tonnes of Regolith: 10tonnes O2)	5	6	4	5	3	4	2	1
Site Specificity	6	6	6	6	3	5	3	1
Technology Readiness Level	3	4	4	4	5	3	3	5
Re-supply efficiency (annual tonnes of payload/ tonnes of O2)	5	1	4	3	3	4	6	4
Launch Mass efficiency (tonnes of payload/ tonnes of O2)	2	1	3	4	3	0	6	5
Byproducts	5	6	5	5	4	4	3	3
Total (Data only)	42	45	40	37	41	44	37	41
Total (Including confidence factor)	36.69	51.72	42.30	35.72	49.01	38.44	28.92	45.24

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