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Author: Mr. Kosuke Ikeya
Imperial College London, United Kingdom

Dr. Michel-Alexandre Cardin
Imperial College London, United Kingdom
Prof. Jan Cilliers
Imperial College London, United Kingdom
Mr. Stanley Starr
Imperial College London, United Kingdom
Dr. Kathryn Hadler
European Space Resources Innovation Centre (ESRIC), Luxembourg

MULTI-OBJECTIVE DECISION ANALYSES ON DEPLOYING LUNAR IN-SITU RESOURCE UTILIZATION PLANTS UNDER RESOURCE AND OPERATIONAL UNCERTAINTY

Abstract

To establish a self-sustained human presence in space and to explore deeper into the solar system, extensive research has been conducted on In-Situ Resource Utilization (ISRU) systems. Previous studies typically focus on optimizing the design and deployment plans for lunar ISRU plants and evaluating various technologies for extracting oxygen and for various space applications. However, these studies often overlook uncertainties related to the lunar environment and operations of ISRU plants, such as resource content and operational availability, potentially leading to lower production or higher system requirements, such as higher energy consumption. To address uncertainty stemming from limited information availability, this research adopts an Expected Value of Information (EVoI) methodology, which is commonly used in the terrestrial mining industry. Utilizing multi-objective decision analysis for lunar ISRU plant deployment, EVoI highlights the importance of gathering more data to better understand the potential benefits and risks associated with ISRU system design and planning. Monte Carlo simulations are used to build a decision tree estimating the impact of uncertain parameters on ISRU plant performance using metrics capturing cost, efficiency, and power consumption. Furthermore, the detailed concepts of operations outline the mass and power consumption depending on the decisions made considering ISRU technology selection and plant production capacity. A case study deploying pilot and full-scale ISRU oxygen production plants in the lunar southern polar region demonstrates the practicality of the proposed approach. This case study examines three plant architectures: carbothermal reduction of dry regolith, water extraction from icy regolith, and a hybrid combination of both technologies. Building a pilot plant relying only on one oxygen extraction technology or the other potentially limits the performance of the full-scale plant since actual performance is difficult to predict until deployed on the Moon. The proposed hybrid plant helps gather more information on system performance and supports decision-makers to make more informed choices regarding the deployment of a full-scale plant in a subsequent phase. Preliminary multi-objective decision analysis shows the viability of the hybrid pilot plant to improve product yield by about 10% and mass payback by about 5% compared to a carbothermal reduction plant. Further analysis reveals water content significantly affects the system mass and power consumption of both water extraction and hybrid plant architectures, highlighting the importance of gaining more information about lunar water ice. A more extensive analysis incorporates power consumption as an additional objective, providing a more comprehensive view of ISRU plant deployment decisions.