LIFETIME EMBODIED ENERGY: A NEW VALUE SYSTEM FOR THE ISRU SPACE ECONOMY

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Executive Summary: Energy is the natural metric for work, and all in-space activities require costly direct and indirect energy sources, but aerospace engineers have been using mass, e.g. Initial Mass in Low Earth Orbit (IMLEO), as a trusted proxy for space mission costs. However, in recent years, the true cost of human space exploration is progressively being decoupled from IMLEO, mainly as a result of technological advances in In Situ Resource Utilization (ISRU) and reusable rockets. To address this we propose *Lifetime Embodied Energy* (LEE) as an improved physics-based metric of cumulative past work and of the 'true' value and cost of in-space activities [1]. A case study of seven scenaria for a simple Mars outpost over 20 and 40 years, all with identical IMLEO but widely varying embodied energies, is used to demonstrate how the LEE costing system can quantify the value and cost impact of decisions to invest in ISRU capabilities in support of long campaigns to the same outpost. This work is useful for architecting long-term human space exploration campaigns which involve the accumulation of infrastructure at in-space destinations through ISRU and in-space manufacturing. The LEE metric can be incorporated in new modeling approaches for the *ex ante* optimization of extended supply chains as well as the designs of permanent habitats on other worlds. The proposed LEE metric contributes to the establishment of human outposts on other worlds which can grow sustainably in an organic manner, shortening the time between their establishment and Earth independence.

Motivation: The ongoing reductions in the cost of access to space and in the cost of development of new space systems have led to renewed expectations of a new era of extended human spaceflight beyond Earth orbit and on the surfaces of other worlds. The substantial energy surpluses required so that humans will not just survive but thrive on new worlds will require a pioneering mentality ("living off the land"), as well as an ongoing investment in the accumulation of ISRU-based infrastructure. This emerging context undermines the long-established coupling between IMLEO and total mission cost, leading us to wonder whether *all* tradespace exploration approaches for long-term human spaceflight which ultimately correlate cost with a logistical mass metric are in fact subtly missing broader architectural opportunities, specifically opportunities related to the early establishment of ISRU-supplied manufacturing capabilities on other worlds.

Recognizing this gap, an energy-based metric and costing system has been developed for use during the the early system architecting of long campaigns[1].

Current State of the Art: We have reviewed costing systems currently in use at NASA or being developed by academia which are suited for early-stage space mission tradespace exploration[1]. We find that almost all such systems, including Equivalent System Mass in use at NASA (ESM) [2]) and multi-commodity dynamic network flow models such as Global Multi Commodity Network Flow (GMCNF) developed at MIT [3] rely on space system dry mass as the key driver of, or proxy for, space mission cost.

In our search for a physics-based cost metric for in-space activities that is not denominated in units of mass or dollars we reviewed the literature for *energy theories of value*. Energy-based value and cost metrics such as embodied energy had been developed during the oil crises of the 1970's and are in use today only in the narrow sector of the energy performance of buildings. Since embodied energy is calculated by summing and allocating all the past energy flows required to develop the system of interest, and as these energy flows can be estimated analytically from first principles for any well-understood physical process, *embodied energy* is a good candidate to improve classical factor-based theories of economic production and value.

Methodology: Lifetime Embodied Energy (LEE) is defined as the thermodynamic sum of past, present and future work required to create, operate, maintain and decommission a system, including appropriate shares of indirect contributions from upstream systems. The units of LEE are embodied joules; embodied joules are not conserved – they can be created and destroyed depending on losses to entropy and the method of calculation.

The important methodological choice of primary energy source and system boundary in embodied energy modeling is linked to the nature of the figure of merit targeted for optimization. For example, by specifying the *embodied energy of space logistics* as the primary energy source and common cost denominator of all technological systems and processed resources delivered to Mars, it is possible to closely replicate the conclusions of standard IMLEO-based or ESM [2])-based analyses, but also to go beyond them.

There are three main methodological approaches for embodied energy analyses: sectoral input-output models, process-based models and hybrid models. The depth and breadth of Earth-based supply chains make the application of process based models on Earth challenging, leading to the truncation of process trees and to large error bars. These difficulties do not apply to the Mars industrial development context, thereby making the LEE methodology more attractive for broad application for space mission architecting.

Embodied energy model of an early human outpost on Mars: Two lifetime embodied energy modeling approaches for a prototype human settlement on Mars with an industrial focus are presented. The first is a dynamic, graphical approach using Howard Odum's energy language diagrams[4], featuring four key sectors: energy production, resource extraction, resource utilization and habitation. Elements in each sector are linked via flows and allocations of embodied energy to upstream and downstream elements throughout the system. The closed loops demonstrate that all physical value creation can be accounted for by summing and allocating past flows of energy into 'embodied' energy.

The second approach is an Excel-based static, single-period model tracing the flow of LEE through a toy model of a Mars outpost, using a simplified lifetime-basis input-output method. This model, with its simplifications and approximations, facilitates the quick exploration of alternative ISRU-enabled outpost architectures and plotting the results in a tradespace of cumulative useful mass at the destination vs. specific lifetime embodied energy.

Model results and discussion: Seven scenaria were studied with increasing investment in a variety of modeled ISRU & industrial capabilities, for campaign durations of 20 and 40 years [1].

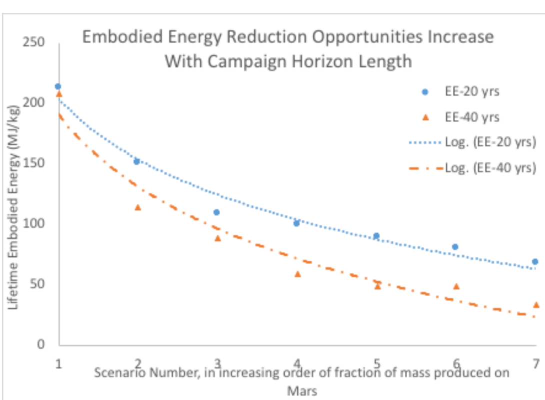

Figure 1: *Fully allocated Lifetime Embodied Energy costs fall with increased investment in ISRU infrastructure and longer campaign horizons* [1]

The quantified link between specific LEE, ISRU architectures and length of campaign horizons evident in Fig. 1 is in line with expectations and assists the architect to select among ISRU architectures.

This result also confirms our hypothesis that *LEE can quantify the impacts of ISRU-related strategic decisions that an IMLEO analysis might miss*, because all seven scenaria start with exactly the same cumulative IMLEO yet vary widely in LEE, almost by an order of magnitude from 200 MJ/kg to <40 MJ/kg.

Embodied energy – the natural and objective metric of work: The universal cost proxy, IMLEO, is being progressively decoupled from true space mission cost due to changes including the advent of reusable rockets and the inclusion of ISRU in design reference missions. At the same time, significant cost reductions arising from new forms of contracting and the activities of "New Space" companies are undermining the validity of old cost databases and CER's.

Energy is a natural, physics-based metric of work. Embodied energy is the sum of past work that was required to create something of value. Its use in a space application is novel. The key result is the ability to measure all costs on the same denominator of embodied Joules of energy from the selected primary energy source, which in our study is the energy of space logistics. This approach makes it possible to compare all types of diverse human spaceflight architectures, with or without investment in ISRU and ISM, without unfairly disadvantaging any one family of concepts. Using the LEE of space logistics as the cost metric is robust to the ongoing disruptive changes in the industry, and allows the architect to go beyond IMLEO-based optimization by simultaneously optimizing the logistical, ISRU and in situ manufacturing architectures of a contemplated long-term campaign.

References:

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