Powering the Moon: System Design and Analysis for Flexible Nuclear Fission Surface Power under Demand Uncertainty

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*Index Terms–* Embedded Flexibility, Uncertainty Modeling, Sequential-Decision Making, Fission Surface Power System.

***Abstract–* Energy is a critical resource for lunar operations, powering life support and operations. Current missions rely on Earth for energy supply through throwaway technologies designed to function for a short period of time and be left unfunctional, a process fraught with costs and environmental consequences. Having a reliable source of energy supply is important in the future of space operations as we establish a lunar presence, an interest expressed by NASA’s Artemis programme. One of the big challenges faced when establishing a lunar presence is responding to the energy requirement. The energy requirement is highly uncertain, especially on the Moon. This paper proposes sequential decision-making approach that provides flexibility to respond to this demand uncertainty.**

**NASA, in collaboration with the Department of Energy (DoE) plans to utilise Nuclear Fission Surface Power System (FSPS) to power their operations due to benefits such as robustness and reliability. Advancements in research of NFSP open opportunities and metrics for establishing sustainable lunar energy source over the projected 20 years timeline. The system design proposed in this paper follows a widely established narrative by NASA’s previous operations and planned Artemis programme.**

**This paper proposes a framework for the system design and simulation modeling of an energy system for lunar habitation, taking inputs such as nuclear fission mass, efficiency, and cost associated parameters (detailed in the Nomenclature). The model will take these parameters as inputs and analyse the Levelised Cost of Electiricty (LCOE)–a method of evaluating the cost of electricity–based on varying uncertainties and probabilities, analysing the effectiveness between inflexible and flexible strategies. A primary study based on assumed parameters shows that a flexible approach decreases the expected cost to 10 USD, 23% less compared to inflexible deployment with an average expected cost of 12.3 USD.**

**Ultimately, this model will equip stakeholders with the necessary tools to adapt as technologies and parameters evolve, offering strategic insights to minimize costs and effectively manage the uncertainties associated with deploying an energy system on the Moon. Moreover, researchers and engineers can freely focus on their work and leverage this system to gather insight on how to implement such system before investing large capital.**

# Introduction

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unar exploration plans, spearheaded by NASA's Artemis program, marks the Moon as a pivotal step for the next era of space endeavors. The Artemis program, with its goals to establish and sustain human presence on the Moon for an extended period of over 10 years [\_], necessitates the development of a robust and reliable lunar power system. As we transition from exploratory missions to permanent lunar settlements, the demand for continuous and efficient power generation becomes critical to support scientific research, industrial activities, and the infrastructure necessary for a sustainable lunar economy.

*Figure 1: Fission Surface Power System (FSPS) Design*

The energy source utilized for this mission is nuclear fission-based reactors. NASA, in collaboration with the Department of Energy (DoE), has invested \_\_\_\_ to research and develop Nuclear Fission-based Surface Power System (FSPS) technology to power their operations [\_]. FSPS was chosen due to its characteristics such as its robustness and reliability. It also has the capacity to continuously generate power throughout the 14.4 day night cycles unlike other methods like solar panels, making it the ideal technology choice for long-term space operations.

The main input for this system is the mass of nuclear reactors deployed at each decision stage. These capital expenditure translates to parameters that forecast energy capacity and demand as a function of time. Data related to each components is measured in past research, along with its expected parameters. This will be further expanded in the methodology section of the report to explain the formulas used and the specific parameters that impact the output value. The main output for this system is measured using the Levelised Cost of Electricity (LCOE), because of its ability to assess and compare different scenarios. LCOE is a measure of the average net present cost of electricity generation for a generator over its lifetime. The output is used for investment planning and to compare different methods of electricity generation on a consistent basis.

*How is it deployed?*

Traditionally, energy systems for space missions have been designed with a unidirectional approach: optimized to meet expected demands based on pre-mission forecasts [\_]. Such systems are capital intensive and inflexible, given the high costs of launching materials from Earth to the Moon. This traditional method poses significant risks in the unpredictable and harsh lunar environment where actual energy demands can deviate greatly from forecasts. High demand can lead to shortages and missed operational opportunities, whereas low demand results in wasted resources and financial overheads due to maintenance and management inefficiencies [\_].

To mitigate these risks, embedding flexibility within lunar energy systems is paramount. Flexibility through the sequential deployment of technology allows the energy system to adapt to changing conditions and demands. This adaptability is achieved by designing the energy system to accommodate modifications and expansions in a modular and scalable manner. Sequential decision-making methods from literature are explored to design an approach suitable for the context and target audience. The use of decision trees and Real Options Analysis (ROA) provides a methodological framework to evaluate and implement such flexible strategies, ensuring that each decision maximizes potential benefits while minimizing costs.

The primary audience for this thesis includes project managers and engineers involved in lunar missions, who require a comprehensive and adaptable energy framework to support prolonged lunar operations. Additionally, stakeholders in space energy systems and policy makers in space agencies will find the insights particularly valuable for future mission planning and resource allocation. The outcomes of this research aim to present a nuanced vision of uncertainty, providing a blueprint for energy system deployment that is economically viable and technologically feasible.

# II. Literature Review

This paper explores a novel method for sequential decision-making, used to quantify the value of flexibility. Stochastic optimization methods aim to solve problems that involve random probability distributions, crucial for depicting the randomness and uncertainties associated with energy demand in lunar environments [20]. This approach is pivotal in designing the methodology that will be utilized throughout this study. Amongst sequential decision-making methods, multiple approaches in literature were assessed to determine the best methodology for this thesis.

The first method is a decision tree. Decision trees provide a classical method to represent sequential decision problems within a discrete framework, with or without uncertainties [20.5]. They graphically depict decisions and chance events using square nodes (for decisions) and circle nodes (for chance occurrences), respectively. The analysis typically proceeds through backward induction, where optimal decisions are made by recursively considering the outcomes of preceding chance nodes. This enables the model to conduct a breadth first search, assigning values to different states as information becomes available for its discounted downstream value [21].

A decision tree, however, has significant scalability issues. As the complexity of decisions and uncertainties increases, the size of the decision trees can grow exponentially. This increase can become computationally expensive and less practical for extensive systems. As decision trees operate in a discrete space, there is a trade-off between computational expense and model precision that is considered when framing the problem.

To analyze the value of flexibility in the system, real options analysis (ROA) is leveraged. ROA is a financial modeling technique that quantifies the value of strategic options within engineering systems, enabling flexibility in response to uncertainty by evaluating different operational scenarios as financial options. Similar studies include exploring ROA in the context of renewable energy investments [22], and space mission design [23].Top of FormBottom of Form To accurately represent this problem, the decisions will assess a range of scenarios, inflexible and flexible. Discounted Cash Flow (DCF) is utilized to analyze the discounted downstream values of the strategies employed in the model. DCF is a method used to estimate the value of an investment based on its future cash flows. This process involves forecasting the cash flows and discounting them to present value using a discount rate. The metrics required is a cash flow, the forecast period, discount rate, and terminal value.

The final method, discrete chance-constrained optimization, is a type of stochastic optimization that is designed to optimize an objective function in the presence of randomness in its constraints. Since the implementation of nuclear fission happens in discrete loads, chance-constrained optimization can be used to determine the most optimal deployment of nuclear fission at each stage, minimizing overall costs while considering the probability of meeting a fluctuating demand.

# III. System Design Considerations

3.1 Lunar Infrastructure Requirements

The design of a lunar base rapidly evolves with research and technology. In such field, it is important to add the flexibility to account for changes in developmental plans and metrics. For the simulation modeling, the specifications were researched along with the most up to date research and from similar literature. To do so, both the energy source and energy demand were extensively researched in the methodology.

3.1.1 Power System Sizing

*3.1.1.1 Nuclear Fission Reactors*

Collaborative efforts by NASA and the U.S. Department of Energy (DOE) have been established to explore the application of nuclear fission reactors on the Moon, highlighting their potential in future lunar colonization [34]. Nuclear-based reactors, such as radioisotope thermoelectric generators, are prevalent energy sources in space applications due to their high reliability, operational availability, and redundancy. Nuclear reactors are able to continuously supply power to a lunar base without a need for a massive, high capacity energy storage system (ESS). These qualities make them ideal for providing the base-load energy required for lunar operations. The initial deployment strategies rely on these nuclear-based reactors to establish a base-load energy framework, facilitating subsequent expansion and sustained operations.

*Power Capacity*

The expected operational lifespan of these reactors is at least 10 years, setting a conservative default of ***t = 10*** years for planning and evaluation cycles. At the end of this period, expansion decisions can be reevaluated based on operational performance and technological advancements.

***Ptotal* = *Pnf* ×(1 – *rdecay*)t**

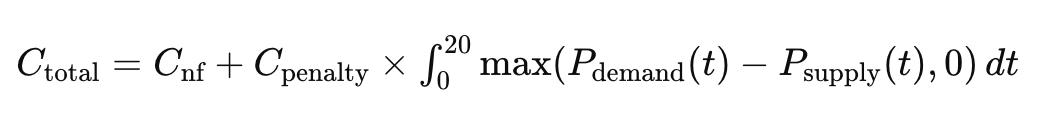
***Pnf* = *Mnf*** ×***EOPM***

The power output capacity of nuclear fission reactors (***Ptaol)*** is defined. ***Mnf*** represents the total mass (kg) of the reactor, serving as a consistent metric to estimate the capital cost and its electric output. ***EOPM***is the Electric Output per Mass, measured in kW/kg. These two metrics provide the power output of the reactors ***Pnf***with a decay factor ***rdecay****.*

*Cost Modeling*

There are three ways that the FSPS can incur costs:

1. Initial Deployment Cost: *Cdeployment*
2. Additional Capacity Cost: *Cexpansion*
3. Penalty Cost: *Cpenality*

******

***C­nf =* (*Mnf* + *Mcomponents*)× (*Claunch​*) *​***

**+ (*Mnf* × *Cproduce***

**+ (*Mnf​* + *Mcomponents​*)× *Cpayload​*) × (1 – *r*))**

The financial model (***Ctotal***) encompasses the penalty cost for not meeting demand (***Cpenalty***) and expenditures necessary to establish Nuclear Fission on the Moon (***Cnf***). These costs are treated as upfront capital investments. Operational cost is negligible as the design is highly robust with minimal interventions. The cost is relative to ***Mnf*** and ***Mcomponents***​, aligning the financial outlay with the reactor’s output capabilities. This formula assumes ***Cpayload*​** and ***Cproduce*​** decrease linearly with an increase in production volume, represented by 𝑟, suggesting a rate for economies of scale.

PV(C) = C/(1+r)^t

The expenditure within this model must also account for its discounted value. Whenever a cost 𝐶 is incurred, its present value 𝑃𝑉 is calculated based on the discount rate 𝑟 at the time 𝑡 (years) the cost is incurred, as suggested in equation 1.

3.1.2 Energy Demand Requirement

To estimate the power requirements for the lunar base and its operations, we calculate total power requirement (***P­demand***) based on the energy consumption estimates from various components that constitute the basecamp and its activities, as shown in Equation 1. The heat power requirement is estimated at approximately 4.096 kW, which is considered negligible since the heat produced internally by habitat systems is expected to suffice for maintaining habitable temperatures. Similarly, for the case of this simulation, minor energy demands such as those for communications are considered negligible in the context of ***Pdemand***.

***Pdemand* = *PECLSS* + *Poperations …* (1)**

The primary power requirement (***PECLSS***) accounts for the environmental control and life support system (ECLSS), which includes various power-consuming elements such as air handing, biomass, food storage and processing, thermal cooling, waste processing, water processing, and extra vehicular activities (EVA) [4]. The power breakdown for a six-person habitat is as follows:

***PECLSS* = *Pahc + Pbm + Pfd­ + Pwst + Pwp + Peva …* (2)**

[37] suggests that the initial phase’s ECLSS cost is near 25 kW. ***PECLSS*** is proportional to the number of inhabitants, assuming a linear correlation between this power demand and the population size. Within 5 years, the expected

For ***Poperations***, an examination of the Lunar Base Construction Overview [1] provided insights into the infrastructure requirements for lunar inhabitance and operations. The use of automated systems reduces the reliance on EVA. Therefore, ***Poperations*** is independent from the number of occupants. While existing studies by NASA do not provide explicit power metrics, they offer a broad perspective of the operational capabilities, technological needs, and scenario, based on precedents like Desert Research and Technology Studies (D-RATS) and other historical data [2]. The operations listed include O2-Regolith ISRU, H2/O2 Ice Mining, and Human Mobility Platforms (e.g., such as Lunar terrain vehicle (LTV)). Additional operations can be added to the formula modularly [5].

A graph showing the number of the day and night

Description automatically generated with medium confidence

Data collected from the D-RATS project was used to estimate the operational power for operational components. This data shows an average power consumption range of 2.5 to 7.0 kW over the total period of operation [3]. Consequently, a conservative power consumption estimate of 7.0 kW is used initially. For the subsequent phase of the decision-making process, a projection of 14.0 kW is adopted, anticipating a doubling in operational scope. It is important to note that these figures are preliminary and subject to refinement as further empirical data becomes available.

*Insert figure of energy demand*

Based on the power system sizing, an expected power demand of 34.2 kW with standard deviation of approximately 4.9 kW.

# IV. Methodology: Valuation Framework

Strategies

Design Variables

Four stages: system definition, base case analysis, uncertainty analysis, and flexibility analysis.

Decision tree

The strategies for the implementation of an energy system on the Moon are as follows:

**ΠN:** an inflexible strategy with initial deployment of large nuclear-based reactors with subsequent addition of similar units upon the end of their lifecycle.

**ΠL:** a flexible strategy with an initial deployment of large nuclear-based reactor followed by gradual integration of PV panels.

**ΠS:** a flexible strategy with an initial deployment of a small nuclear-based reactor base followed by gradual integration of PV panels.

This 2-stage decision process ensure methodical preliminary analysis and facilitate comparative assessments of various strategies. Upon establishing its values, advanced models like discrete chance-constrained optimization is used tow further refine the quantity of deployment strategies.

**ΠC:** discrete chance-constrained optimization to minimize each steps while meeting expected demand with a probability of 90% default (1-α).

# V. Case Application and Results

* 1. Flexible layer: implement PV panels utilizing ISRU for additional energy needs. Adaptable based on operational requirements.
  2. ADD FIGURE OF WHAT IT LOOKS LIKE

1. Uncertainty and Scenario Modeling
   1. Model the energy demand as a sthocashtic process, using geometric brownian motion, which reflects varying operational scales and unpredicted needs
   2. ADD FIGURE OF DECISION TREE W EQUAL PROBABILTIEIS
2. Decisions:
   1. Scale of intial nuclear fission implementation
   2. Scale of PV panel rollout (10 year intervals)
3. Design of an energy system (Calculating Energy Supply): Detail the design choices for nuclear fission and solar panels, including capacity considerations.
   1. Capacity equation

A solar array with black text

Description automatically generated

1. Figure 30.—Research photovoltaic (PV) cell efficiencies over time from National Renewable Energy Laboratory (NREL) part of the Department of Energy (DOE) (Ref. 17). – assume the best case
2. Economic Analysis Tools
   1. How we calculate each step.

Maths

Problem structure:

1. time stages (t)
2. state variables (s): current energy capacity, energy storage levels, anticipated and actual energy demand
3. decisions (x): amount of nuclear installed in the beginning/ pv panels installed at each stage

min F = C(n)\*x(n) + f

s.t. P{E >= dtω​ ∀t,∀ω} >= 1 – alpha

f = Cpv(capex)\*x(pv)+ ∑t=1 T (Cpv(opex)\*x(pv)t)

while t < T:

if E < dtω: min(f) s.t. E >= dtω

t += 1

E = E(n)\*x(n) + E(pv)\*x(pv)

Sensitivity Analysis

1. Identifying Key Variables: variables affecting the system
2. Analysis Approach: how will we conduct a sensitivity analysis
3. Impact on System Design: how does the result impact the model

Results

Results

1. Simulation Outcomes
2. Economic Analysis Outcomes
3. Optimisation Strategies(?)

Discussion

Discussion:

1. Interpreting the results
2. Limitations and Assumptions

Conclusion and Future Work:

1. Summary of findings
2. Contribution: how does my work advance lunar exploration
3. Extra-terrestial bodies: how can we use this model for other implementations

DECISION TREE

1st decision node – 1) 1 nuclear fission 2) 2 nuclear fission 3) 3 nuclear fission

Deploying cost

1st chance node – energy demand variability

2nd decision node – 1) pv small, 2) pv med, 3) pv large, 4) nuclear fission

Costs: operational + expansion

2nd chance node – energy demand variability

end nodes – energy sufficiency (meets demand, cost efficiency)

1. Added value for energy production

**Appendix *Nomenclature***

|  |  |  |
| --- | --- | --- |
| **Notation** | **Total power requirement (kW)** | **Default parameters** |
| ***Pdemand*** | Total power requirement (kW) |  |
| ***PECLSS*** | Basecamp (life support) power requirement (kW) |  |
| ***Poperations*** | Operational power requirement (kW) |  |
| ***C(nf,cap)*** | Fixed cost for nuclear fission-based reactors (USD) |  |
| ***C(nf,ops)*** | Variable Cost for nuclear fission-based reactors (USD) |  |
| ***C(pv,cap)*** | Fixed cost for PV panels (USD) |  |
| ***C(nf,ops)*** | Variable Cost for PV panels (USD) |  |
|  |  |  |

**ECLSS**

**P(demand)** = total power requirement [kW]

**P(eclss) =** basecamp (life support) power requirement (per capita) [kW], lets assume \_\_ kW per person

**P(op) =** operational power requirement [kW]

**P(demand) =** P(bc) + P(op)

**C(nf, cap)** = Fixed Cost for Nuclear Fission

= Deployment Cost (per mass) + Development Cost (per mass)

**C(nf, ops)** = Variable Cost for Nuclear Fission (NA)

**C(pv, cap)** = Fixed Cost for PV Panels + battery

**=** Area (A) \* Development Cost (per Area)

**C(pv, ops)** = Variable Cost for PV Panels = Area (A) \* Maintenance Cost (per Area)

C(launch) = launch cost to the moon ($ per kg): <https://ntrs.nasa.gov/api/citations/20230013555/downloads/Take%20or%20Make%20in%20space.pdf> 10.8 $k/kg

**C(total)** = Total Cost = C(nf, cap) + C(pv, cap) + C(pv, ops)

**P(supply)** = Total Energy Supplied in System (kWh)

**P(pv)** = Energy Capacity of P(pv) below.

See the document (p.35)

**ρ(pv) =** fixedparameters [I η t]

**I =** Average Solar Irradiance [MWh/m²/day]

**A =** Area covered by PV Panels [m^2]

**η =** efficiency

**t =** time elapsed

**P(nf)** = Energy Capacity of Nuclear Fission System **=** M \* EOPM

**M =** Total mass (kg)

**EOPM =** Electric Output Power per Mass (kW/kg) = 10/1545 kW/kg, lets assume 50 kW to begin with

**π(N, L, S, C)** = Strategies (inflexible, large flexible, small flexible, discrete chance-constrained)