MEMO

To: Mike Paluszek, Charles Swanson
From: Stephanie Thomas
Date: March 26, 2020
Re: LCOE Model Breakdown

LCOE Definitions

The LCOE, levelized cost of energy, model is derived from the model by NREL, the National Renewable Energy Laboratory, available at:

https://www.nrel.gov/analysis/tech-lcoe-documentation.html
https://www.nrel.gov/analysis/tech-lcoe.html

The basic formula cited by NREL for "simple" LCOE is:

LCOE = {(overnight capital cost * capital recovery factor + fixed O&M cost)/(8760 * capacity factor)} + (fuel cost * heat rate) + variable O&M cost

where the overnight capital cost is measured in dollars per installed kilowatt ($/kW) and the capital recovery factor is:

CRF = {i(1 + i)^n} / {[(1 + i)^n]-1}

where *n* is the number of annuities received and *i* is the interest rate. As *n* goes to infinity, the CRF goes to *i*. Also:

In the denominator 8760 is the number of hours in a year and capacity factor is a fraction between 0 and 1 representing the portion of a year that the power plant is generating power. Fuel cost is expressed in dollars per million british thermal units ($/MMBtu) and heat rate is measured in british thermal units per kilowatt-hour (Btu/kWh).

A key issue is the decision about the value of the discount rate i. The value that is chosen for i can often 'weight' the decision towards one option or another, so the basis for choosing the discount must clearly be carefully evaluated. The discount rate depends on the cost of capital, including the balance between debt-financing and equity-financing, and an assessment of the financial risk.

Fuel Cost

We have computed the LCOE for three sources for the Helium-3 consumed by the PFRC:

1. PFRC using Helium-3 available at the current market's spot prices
2. Helium-3 mined from Uranus assuming a fusion-propelled rocket transports the fuel
3. Helium-3 produced from D-D breeders

We assume a spot price of $2000 per liter, which is $15M per kg. The deuterium spot price is $1897 for 850 L of D_2 gas (Cambridge Isotopes, March 2020), or $13,362/kg. The D-D breeder reactors plus the main D-3He reactor will consume 5 deuterium for every Helium-3, assuming a 1:1 fuel ratio, which reduces the cost by a factor of over 300 compared to the terrestrial Helium-3. (The 5:1 atomic ratio converts to a 3.3 mass ratio.)

There is abundant Helium-3 on Uranus, and a fusion-propelled one-way trip would be about 3 years. Assumptions for an infrastructure to mine Helium-3 from Uranus are:

- $300B for the mining infrastructure (Uranus airship)
- $1B for each Helium-3 transport tanker
- 7500 kg total Helium-3 mined per year
- 6 tankers operate, each with a lifetime of 40 years and a roundtrip transit time of 6 years
- Tanker operating cost of $50M/year, similar to Voyager, assuming they are unmanned

Using these assumptions, we can estimate that the cost of the mined Helium-3 is $1.01M/kg, which would be equivalently $131 per liter. If we assume that the lifetime of the tankers is only 30 years, the price rises to $1.4M/kg, or $180/liter.

A summary of the Helium-3 cost model output is:

Table I. Helium-3 Fuel Cost Model Results

Model	$/kg	$/L
Terrestrial D Spot Price	$13,362	
Terrestrial 3He Spot Price	$15,400,000	$2000
Uranus Mined 3He	$1,010,000	$131
D-D Bred 3He	$44,539	$6

We compute the fuel cost in $/BTU using the 18.3 MeV released per D-3He reaction and the reactions per kg.

O&M Costs

The fixed and variable O&M costs are computed using the numbers for Combustion Turbine from a 2016 from by the US Energy Information Administration. The cost for advanced nuclear are shown for comparison.

Table II. Reference Overnight Capital Costs and O&M, EIA, 2016

	Overnight Capital Cost	Heat Rate	Fixed O&M	Variable O&M
ANGCC	1104 $/kW	6300 Btu/kWh	10 $/kW-yr	2.0 $/MWh
Combustion Turbine	1101 $/kW	10000 Btu/kWh	17.50 $/kW-yr	3.5 $/MWh
Advanced Nuclear	5945 $/kW	0	100.28	2.30

Overnight Capital Cost

The overnight capital cost is computed using a scaling developed from our models of PFRC reactor cost, both a ground-up estimate and considering the recent BETHE cost model for a pilot plant. We estimate a base cost of $4M, a cost for a 1MW reactor of $10M and a cost for a 20 MW reactor of $18M. The scaling factors are:

Table III. Overnight Capital Cost scaling model

Cost ($M)	4	10	18
Power (MW)	0	1	20

For the D-D breeder reactor, we must estimate the additional overnight cost of the D-D reactor. For instance, we might assume that it takes two comparably sized D-D reactor to produce the Helium-3 consumed by one D-3He reactor, so the OCC for one reactor would be multiplied by a factor of 3.

Summary of LCOE Factors

The capacity factor is taken from EIA website, "Electric Power Monthly," using the final data from 2018. The value for “nuclear” for 2018 is 92.5%.

The heating rate assumes a 30% thermal conversion efficiency. This is the total efficiency from fusion power to net electrical power out.

A discount rate of 3% is assumed with an annuity period of 20 years. With these assumptions, the capital recovery factor is 0.067.

The final component values are shown below.

Table IV. LCOE Model Inputs

Component	Value
Heating Rate	11374 BTU/kWh
Capital Recovery Factor	0.067
Fixed O&M	17.5 $/kW-yr
Variable O&M	2.0 $/MWh
Overnight Capital Cost, 1 MW reactor	10,000 $/kW
Capacity Factor	92.5

Model Results

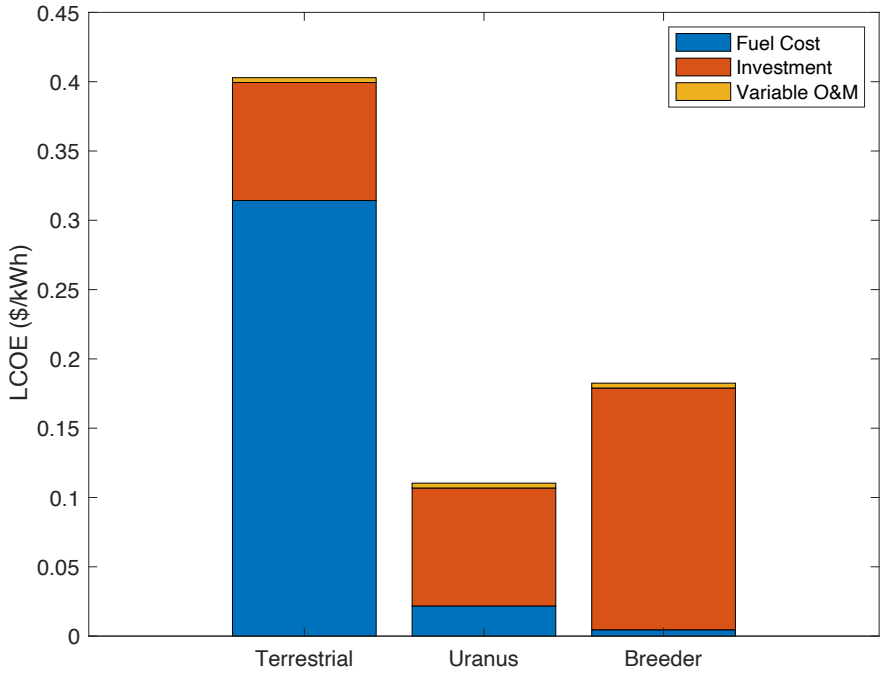
With these terms, we define three components to the LCOE:

- **Fuel cost**: (fuel cost * heat rate)
- **Investment cost**: {(overnight capital cost * capital recovery factor + fixed O&M cost)/(8760 * capacity factor)}
- **Variable O&M cost**

Figure 1 shows the results. The fuel costs for the Uranus mined Helium-3 are about 1/15 of the terrestrial spot costs, and with the D-D breeder reactor, fuel costs are smaller still. Recall that the entire infrastructure for the Uranus mining operation is absorbed in the fuel cost, so the

investment costs for the terrestrial and lunar options are the same. The Breeder option has higher investment costs reflecting the cost of additional reactor(s). The Variable O&M is a very small contributor.

Figure 1. Components of the LCOE for the three Helium-3 Sources



The results for terrestrial Helium-3 are very sensitive to the heat rate, or the assumed total efficiency of the plants. If the total thermal efficiency to net power can be increased from 30% to 40%, the terrestrial LCOE drops to 32 cents per kWh from 40 cents.

References

National Renewable Energy Laboratory website:

https://www.nrel.gov/analysis/tech-lcoe.html
https://www.nrel.gov/analysis/tech-lcoe-documentation.html

US Energy Information Administration documents:

EIA, "Capital Cost Estimates for Utility Scale Electricity Generating Plants," November 2016.
https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf

EIA, "Electric Power Monthly," final data from 2018.
https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b