PNNL-35837

UNrealized Critical Lanthanide Extraction from Sea Algae Mining (UNCLE SAM)

Domestic production of critical minerals from seawater

December 2023

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Prepared for the U.S. Department of Energy
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Final Scientific/Technical Report

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Principal Investigator:	Dr. Michael Huesemann
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Public Executive Summary

The UNCLE-SAM project, under the Biotechnologies to Ensure a Robust Supply of Critical Materials for Clean Energy program, examined the biomining applications of seaweeds for sustainable, domestic production of critical mineral feedstocks. The ocean is a vast reserve of mineralogical wealth including rare earth elements (REEs) and platinum group metal (PGMs). These elements, categorized as “critical minerals”, are used in telecommunication devices, lasers, LED lighting, turbine generators, electric car motors, jet engine alloys, and many other applications. These critical elements are increasingly vital to a thriving, efficient and sustainable society. However, only a few countries in the global market currently produce and export REEs, leading to potential geopolitical supply disruptions. Marine macroalgae, often referred to as seaweeds, bioconcentrate critical minerals from seawater, including REEs and PGMs. Marine algae cultivation can generate a significant amount of biomass with minimal freshwater, fertilizer, and land requirements. In summary, the UNCLE-SAM project successfully evaluated the technological feasibility for marine macroalgal cultivation as a feedstock for critical minerals, explored the biological capacity of different seaweeds to provide economically relevant domestic mineral production, assessed processing techniques for thermal co-conversion of seaweeds into renewable fuel and mineral feedstocks, and executed techno-economic and lifecycle assessments for identifying the most critical gaps in our current understanding to move the technology into commercially relevant deployment. Further development of this technology could transform the bioproduct and REE mining industries and catalyze the development of a more sustainable future.

Acknowledgments

We thank ARPA-E for financially supporting the project and for guiding our progress throughout its execution. In particular, we thank the program director, Dr. Doug Wicks and the Science and Engineering Technical Assistants that helped with the project including Dr. David Lee, Dr. Leonela Carriedo, and Dr. Truong Nguyen as well as advice from Dr. Kirk Liu. Additionally, we thank Dr. Wilson Freshwater for assistance in identifying, where possible, species of the morphologically cryptic genus *Ulva*.

Accomplishments and Objectives

The Pacific Northwest National Laboratory (PNNL), Colorado State University (CSU), and the University of Washington (UW), as part of project funded by the Biotechnologies to Ensure a Robust Supply of Critical Materials for Clean Energy ARPA-E exploratory topics program, established an innovative process for biomining critical minerals from seawater using macroalgae that has the potential to address domestic supply constraints on current mineral demands.

Sea algae mining (SAM) was demonstrated to be a new approach to sourcing critical minerals with minimal negative environmental impacts and potential for substantial positive environmental benefits, such as improved water quality, carbon sequestration, and the production of drop-in replacement liquid transportation fuels. This effort made progress in de-risking this technology by: 1) evaluating the technological feasibility for marine macroalgal cultivation as a feedstock for critical minerals, 2) exploring the biological capacity of different seaweeds to provide economically relevant domestic mineral production, 3) testing processing techniques for thermal co-conversion of seaweeds into renewable fuel and mineral feedstocks, 4) Designing and building techno-economic and lifecycle models for assessing the most critical gaps in our current understanding to move the technology into commercially relevant deployment. Through our investigations in this project effort, we have 1) isolated and maintained a resilient cultivar of the fast-growing green marine algal *Ulva expansa,* which is of interest in its ability to generate significant quantities of biomass on seawater with minimal inputs. 2) Demonstrated the variability of critical mineral content in a variety of seaweeds, which emphasizes the need to understand the processes governing this observed variability. 3) Established a baseline for the thermal processing for *Ulva* biomass into biocrude and biomineral resources. Demonstrated that in-pond production of marine seaweeds is a feasible pathway for biomass and mineral production, where the economics are driven largely by the electrical cost of pumping seawater. Pairing the facility with an existing use case for moving seawater, e.g., desalination facility and/or marine ocean alkalinity enhancement would significantly reduce the parasitic energy loss and related economic burden in our modeled system.

The UNCLE-SAM process, illustrated below in Figure 1, establishes the first steps in developing a robust supply of seawater-derived REEs. The biological capacity of seaweeds drives the first stage of concentration from the sub-part-per-billion levels common in the ocean to the part per million level in the tissue biomass. Biomass processing further concentrates the mineral fraction while removing the carbon-rich organic fraction for generating a renewable fuel feedstock via hydrothermal liquefaction. The resultant mineral solids can then serve as an “ore” feedstock for further REE processing and refining using current SOA metallurgical methods or adapting emerging technologies for efficient extraction.

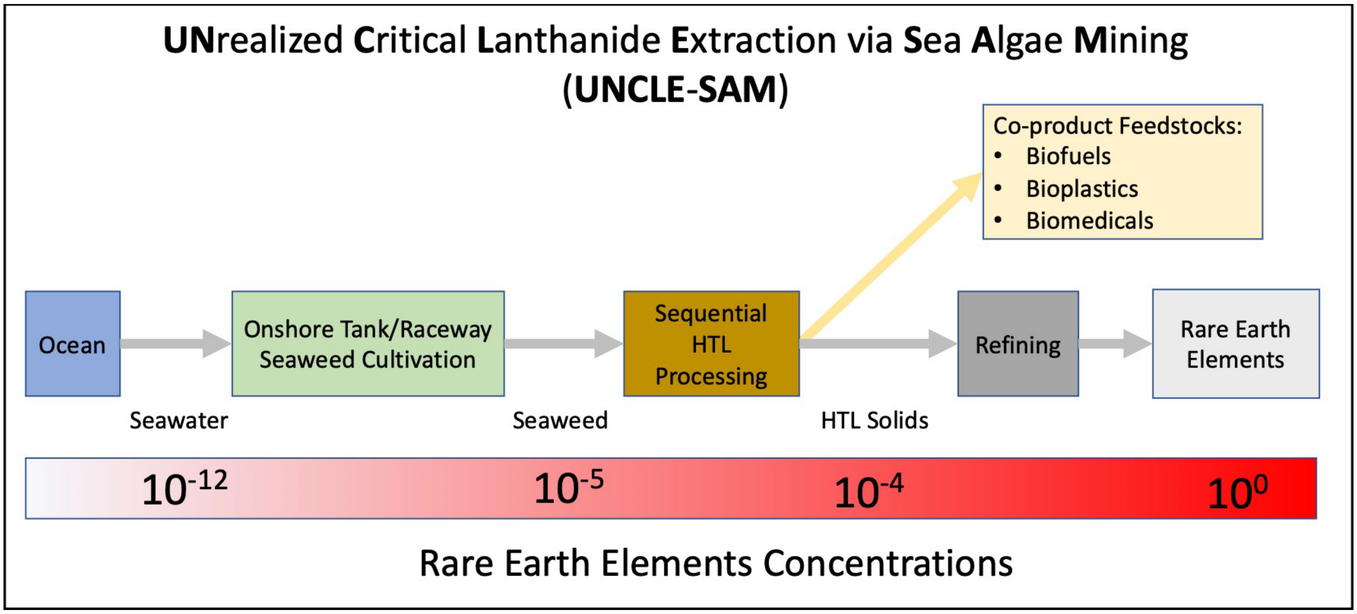

Figure 1: Overview Schematic of the UNCLE-SAM Process

Table 1. Key Milestones and Deliverables

Tasks	Milestones and Deliverables
Task 1: Refine tasks and milestones	**M1.1:** Go/No-Go: Refine Tasks and Milestones **Actual Performance:** (Q1) Project tasks and milestones were refined with the feedback from the ARPA-E program director and project technical manager.
Task 2.1: Define Baseline REE Concentration Factor	**M2.1:** Define Baseline REE concentration factor **Actual Performance**: (Q2) Trace elements were measured in collected seawater from Sequim Bay and Friday Harbor, total and 0.45 μm filtered seawater samples were tested for both field collection sites. Elemental concentrations were obtained using elemental standards from Inorganic Ventures, Inc. and an iCAP-Q inductively coupled plasma- mass spectrometer (ICP-MS, Thermo Scientific, Waltham, MA combined with SeaFast ICP-MS system (Elemental Scientific, Omaha, NE) which was used to preconcentrate ultrarare elements. There appear to be only minor differences between total and dissolved samples in our testing. The concentrations observed in Sequim Bay seawater and Friday Harbor seawater are very similar, showing similar patterns of concentration distributions (**Figure 2**). As expected, some rare earth elements were found below 1 part per trillion in seawater, including europium, terbium, holmium, thulium, and lutetium. The alternating abundance pattern of medium and heavy rare earths has been previously observed (USGS 2002[1]). Gold was detected at the expected concentrations of ca. 10 parts per trillion in seawater (Faulkner and Edmond 1990)[2]. Concentrations of several elements were outside of the method quantification limits and are given as indication values for information only. Baseline bioconcentration factors (BCFs) were determined by averaging three replicate runs with *Ulva* biomass samples from Sequim Bay and dividing the elemental content found in the dry biomass by the average of elemental concentration found in the tested seawater samples (**Table 2**). A maximum baseline bioconcentration factor of 3.9×10^4 was observed within the *Ulva* biomass for cerium and the total REE BCF was 1.0×10^4.

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[1] U.S. Geological Survey. Rare-earth elements: http://pubs.usgs.gov/fs/2002/fs087-02/

[2] Falkner, K.K. and J.M. Edmond, Gold in seawater, Earth Planet. Sci. Lett. 98 (1990) 208–221. https://doi.org/https://doi.org/10.1016/0012-821X(90)90060-B.

Task 2.2: Establish Optimal Cultivation Conditions and Seed Stock	**M2.2:** Identify Light and Temperature Optima for growth rates of at least two different macroalgae. **Actual Performance:** (Q3) We determined light and temperature optima for *Ulva californica.* TFM2080 and *Ulva cf. prolifera* TFM2105 in laboratory cultures. *U. californica* TFM2080 is a cool-water strain with a temperature range from 5 to 18 °C and an optimum at 18 °C. The optimum short duration light intensity for *U. californica* TFM2080 at 18 °C is 750 umol photons/m2/sec, with little indication of photoinhibition at higher light intensities (**Figure 3**). This culture disintegrates (autolysis) at temperatures of 25 °C and above (**Figure 4**). In contrast, *Ulva* sp. TFM2105 is a warm-water strain with a temperature tolerance range from 12 to 35 °C and an optimum at 25-30 °C (**Figure 5**). The optimum short duration light intensity for *Ulva sp.* TFM2105 at 30 °C is 500 umol photons/m^2/sec, with increasing photoinhibition noted at higher light intensities (**Figure 6**). This culture forms distinctive tubular colonies, which appear to give this culture a greater surface area per unit mass, and which may have implications for REE bioaccumulation as indicated by the abundance of REEs detected in the biomass.
Task 2.3: Determine Influence of Seawater Flowrate	**M2.3:** Identify pH and flowrate targets for optimal REE bioaccumulation for at least two different macroalgae. **Actual Performance:** (Q4) We identified the seawater inflow rate as one of the largest cost drivers for the economics of the system (see Task 5.2). We compared biomass productivity and critical mineral content under different flow regimes. The inflow of seawater also provides carbon to the growing biomass and therefore controlling the seawater flow, by default, controls the pH of the system. By altering the flow rate to align with different parts of the day we observed dramatic increases the maximum pH reached within the algae pond (ca. >10). Conditions of low flow and high pH appear to increase the total content of many critical minerals, including REEs, but do not seem to impact the biomining effectiveness for PGEs. Further, 90% reduced seawater flow rates do not appear to decrease the biomass productivity, a key metric in the economic model and energy and mass balance model. In our experiments, flowrate and pH were intimately linked and the optimal conditions observed in this study were a flowrate of 0.23% v/v/min on an intermittent flow period (12:12 h, on: off). Medium pH should be maintained between 8 and 10 for maximum growth and therefore maximum available biomass surface area for critical mineral accumulation.

Go/No-Go Milestone: **Critical Concentration Threshold**	**Go/No-Go Milestone:** Determine if the minimum expected critical bioconcentration factor of 10^5 can be met for at least one of the critical rare earth elements from seawater (*i.e.,* Scandium, Yttrium, Neodymium, Europium, Terbium, and/or Dysprosium) under optimal conditions. **Actual Performance:** (Q4) We identified several *Ulva* isolates with the capacity to accumulate REEs at greater than 1×10^5 (**Table 3**). Based on this information, we seeded our flow-through seawater climate simulation ponds with a vigorous *Ulva* sp. collected from Sequim Bay, later identified as *Ulva expansa*. This led to the establishment of *Ulva expansa* as the pond-based production strain used in generating sufficient biomass for downstream processing efforts.
Task 3: Generate Biomass for downstream testing	**M3.1:** Generate sufficient biomass (at least 8 kg dry weight) for at least one macroalga that meets the critical concentration factor threshold. **Actual Performance:** (Q5) In total we generated in excess of 100 kg of *Ulva* spp. biomass, at a solids content of ca. 12%, yielding approximately 12 kgs. Dry weight. This ambitious production target was the first attempt at scaling up pond-based macroalgal cultivation at our facility and we exceeded the target production needs in our climate simulation raceway pond system (**Figure 7**).
Task 4.1: HTL Processing Stage 1	**M4.1**: Determine mass and elemental balance stage 1. **Actual Performance** (Q6)**:** *Ulva* biomass cultivated solely on natural seawater was shipped to the PNNL bioprocess team at the Bioproducts, Sciences & Engineering Laboratory (BSEL) in Richland, WA where the biomass was evaluated to determine the best hydrothermal processing pathway. Due to the relatively low solids content (ca. 11-12%), a 2-stage processing approach was taken (**Figure 8**). The *Ulva* biomass was formatted and processed through a Stage-1 treatment at ca. 160-170 °C to densify the residual solids (denoted as "cake") for further Stage-2 processing (350 °C and 3000 PSI) to generate biocrude and the concentrated mineral algae ore. A mass balance was calculated, and elemental concentrations of the different streams analyzed to determine the fate of minerals of interest. Unexpectedly, thermal pretreatment (Stage 1) did not increase the solids concentration in the residual biomass cake. Notably, ca. 90% of the total neodymium was concentrated in the cake whereas only ca. 65% of the scandium and ca. 10% of the cerium were found in the cake, with the remaining going into the liquid "decant" fraction. Although we did not get a clean densification as planned, this experimental run nevertheless informed subsequent testing conditions. Modifications in preprocessing, e.g., increasing the alkalinity were undertaken to facilitate a more complete recovery of critical minerals (**Figure 9**).

Task 4.2: HTL Processing Stage 2	**M4.2:** Determine mass and elemental balance for Stage-2 HTL processing, generate at least 500 g of macroalgal- derived REE-ore with a mass balance recovery of the REEs of at least 90%. **Actual Performance** (Q8)**:** We tested run conditions for the 2nd stage hydrothermal liquefaction step. Solids derived from milestone 4.1 testing were further processed at higher temperature and pressure to yield three primary products: the "algae-ore" mineral solids, renewable crude oil, and an aqueous phase. The vast majority of rare earth elements was present in the alg-ore fraction as previously hypothesized. Remarkably, biocrude yields from this non-optimized run reached ca. 40% on an ash-free dry weight basis and 64% on a carbon basis, which indicates that favorable biocrude yields with *Ulva* biomass are feasible. This was the first *Ulva* biomass run on the PNNL HTL system and to the best of our knowledge the only continuous HTL run of *Ulva* biomass to date. The HTL generated an "algae-ore" mineral solid, which was enriched in REEs and other critical minerals (**Figure 10**). Simultaneously, the HTL run generated renewable biocrude oil. The execution of this first of its kind experimental run and associated mass balance of critical minerals provided key input parameters for the engineering process model.
Task 5.1: Develop the Basic Engineering Process Model	**M5.1**: Assemble the unit process model, refine mass and energy balance. **Actual Performance** (Q2)**:** The process model was assembled to encompass on-shore cultivation facilities for macroalgae (e.g., *Ulva*), seawater pumping requirements, grinding and dewatering operations, hydrothermal liquefaction processing and biocrude upgrading to drop-in fuels. Rare earth metal extractions and product transport are outside the bounds of the engineering model (**Figure 11**).
Task 5.2: Life-Cycle Energy Assessment	M5.2: Life cycle energy assessment compared to state of art mining processes. **Actual Performance** (Q3)**:** We modeled assumed process energy requirements and energy production in a hypothetical macroalgal farm. Due to the relatively low concentrations of REEs within the seaweed biomass (ppm level), a significant amount of biomass input is required per unit REE output. In order to reach the kg scale for REE production, biomass processing needs to be on the order of thousands of dry tons. Our LCEA indicates that the required cost for seawater handling (specifically pumping) is a major parasitic energy loss that, depending on required seawater inflow rate, dominates the process energy required (**Figure 12**).

Task 5.3: Economic Viability & Optimization	**M5.3**: Determine the economic viability and optimal system configuration of Sea Algae Mining compared to SOA mining processes. **Actual Performance** (Q8): Benchmark modeled minimum selling price for the “Alg-Ore” generated exceeds the value of the minerals contained in the ore, however this does not include the cost of extraction and purification. A pathway to significantly reduce the minimum selling price and allow for additional extraction/purifications steps without impacting economic viability was identified to guide iterative research efforts. Modeled results are highly dependent on system energy consumption, macroalgae biomass yield, and metals accumulation. Performance targets for future configurations of the system were successfully identified. System sustainability is dependent on minimizing seawater pumping energy and optimizing large-scale cultivation systems to maximize metals accumulation and reduce capital costs. (**Figure 13**). Cradle-to Grave Global Warming Potentials (GWP) as kg $CO_{2\text{-eq}}$/kg Alga-Ore were calculated for baseline and process improvement scenarios (**Figure 14**). Energy required for seawater pumping is the single largest contributor to GWP. Minimizing seawaer pumping through a hypothetical optimized scenario illustrates a pathway to net carbon negative critical minerals. Mined ore displacements and fuel distribution are not included in the calculations present here.

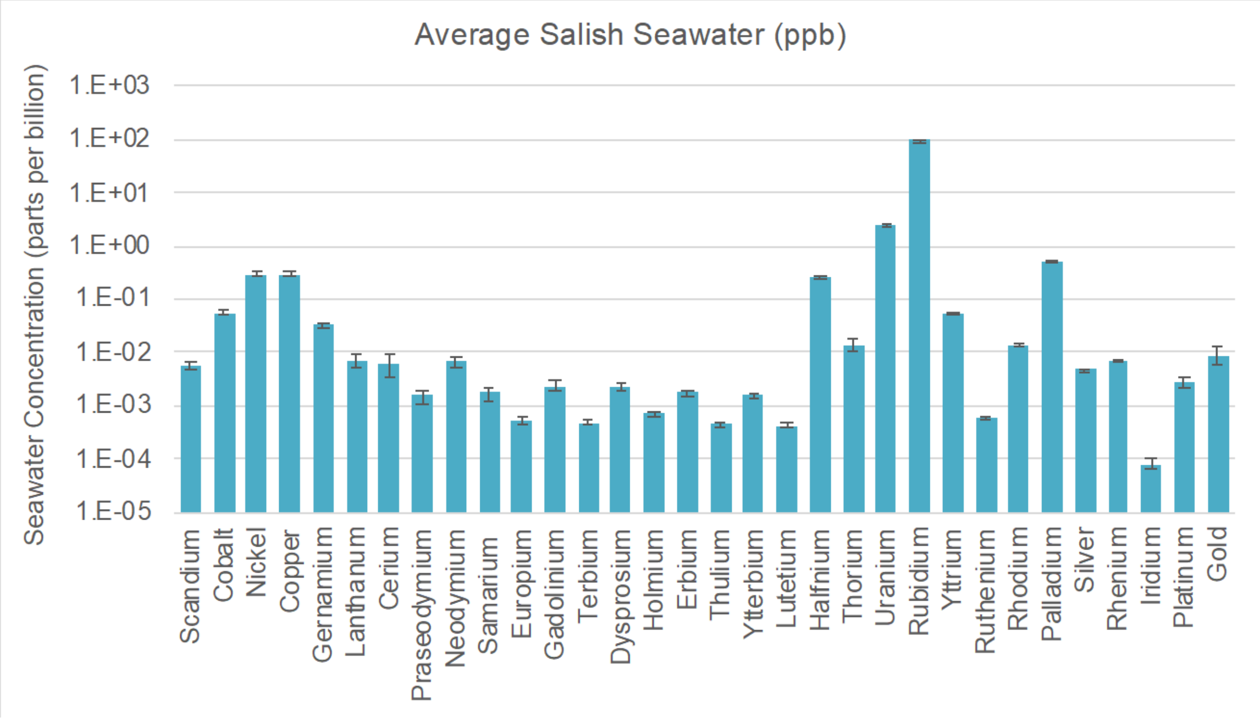

Figure 2: Average concentrations in parts per billion of critical elements in seawater from the Salish Sea. Given values represent the average measured concentration of four seawater samples, error bars represent the standard error of the mean. Due to the extremely low level of some of the elements assessed, the data given here are for information only. Note that the y-axis is logarithmic.

Table 2. Baseline elemental concentrations in seawater and marine macroalgae from the Salish Sea.

Element	Average Salish Seawater (ppb)	Std error	*Ulva* sp. (ppb)	Std. error	Bioconcentration factor
Scandium	0.00591	0.00094	81.05	36.68	13,723
Cobalt	0.05665	0.00537	499.44	150.44	8,816
Nickel	0.29894	0.03346	518.44	158.53	1,734
Copper	0.29751	0.03387	3889.97	906.62	13,075
Germanium	0.03280	0.003	120.18	56.02	5,229
Rubidium	98.77905	1.157	12178.37	295.30	123
Yttrium	0.05451	0.00289	142.08	67.15	2,606
Ruthenium	0.00060	0.00005	BQL	-	-
Rhodium	0.01420	0.00061	0.16	0.00	11
Palladium	0.52542	0.01238	5.63	0.20	11
Silver	0.00484	0.00014	38.19	4.16	7,884
Lanthanum	0.00730	0.00167	147.22	67.24	20,167
Cerium	0.00645	0.00313	252.34	136.82	39,131
Praseodymium	0.00155	0.00042	36.92	18.37	23,890
Neodymium	0.00693	0.00179	158.67	78.50	22,894
Samarium	0.00173	0.00044	38.78	19.83	22,433
Europium	0.00056	0.00009	9.55	4.59	17,190
Gadolinium	0.00241	0.00048	41.48	20.57	17,192
Terbium	0.00050	0.00006	5.35	2.57	10,730
Dysprosium	0.00232	0.00038	29.75	14.14	12,843
Holmium	0.00070	0.00007	5.28	2.44	7,525
Erbium	0.00174	0.00019	13.21	6.07	7,600
Thulium	0.00045	0.00005	1.73	0.77	3,825
Ytterbium	0.00163	0.00019	10.48	4.72	6,428
Lutetium	0.00045	0.00004	1.48	0.66	3,326
Halfnium	0.27380	0.01423	165.15	39.78	603
Rhenium	0.00710	0.00033	BQL	-	-
Iridium	0.00008	0.00002	BQL	-	-
Platinum	0.00277	0.00052	BQL	-	-
Gold	0.00908	0.00336	0.10	-	11
Thorium	0.01438	0.00398	23.14	13.94	1,609
Uranium	2.58611	0.06547	35.56	3.49	14
Total REE+Sc+Y	**0.09513**		**975.381**		**10,254**

*BQL= below quantification limit
Highlighted orange elements are REES with concentration factors greater than $2x10^4$
Highlighted blue elements are REES with concentration factors greater than $1x10^4$
Values given for information only.

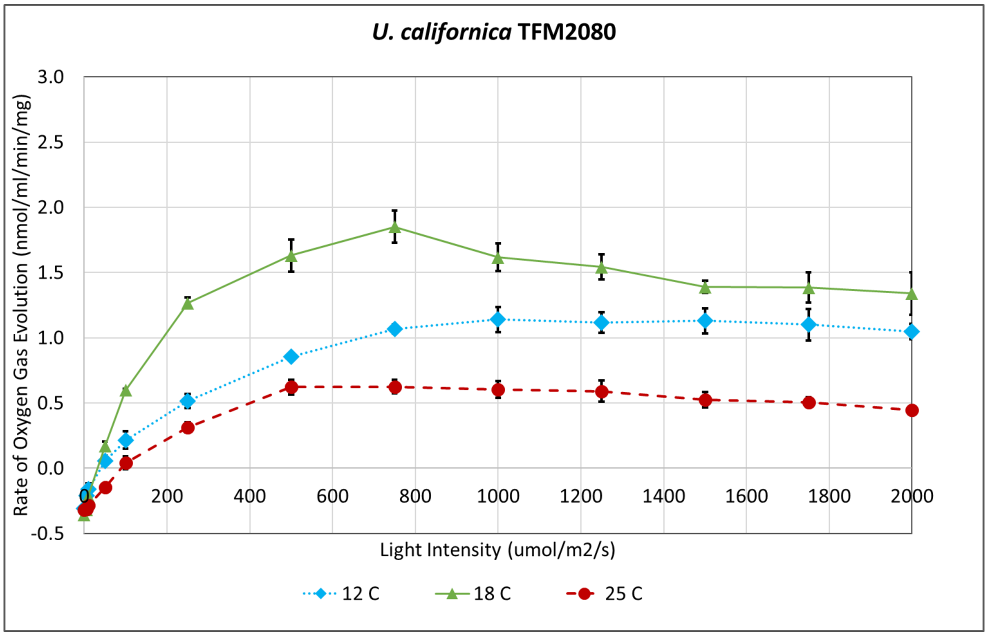

Figure. 3. *Ulva californica* TFM2080 PI curves. Error bars represent the standard error of the mean where N=3.

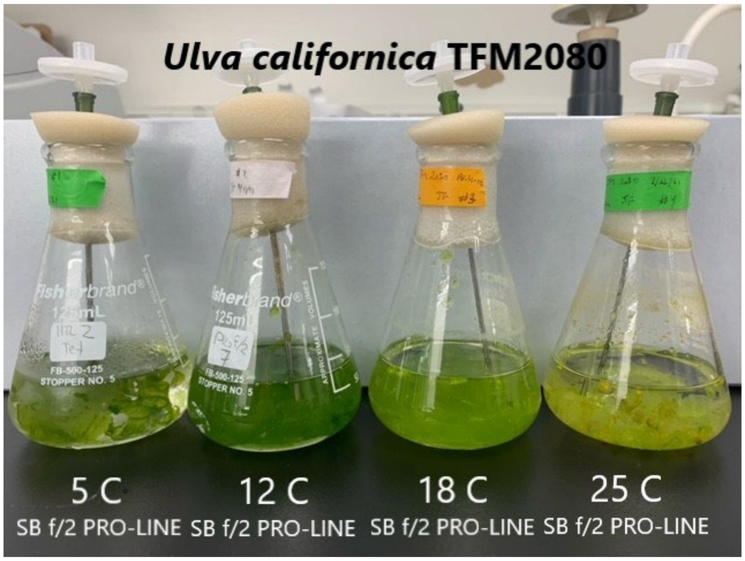

Figure 4. *Ulva californica* TFM2080 flask cultures. Temperature range is 5˚C – 25˚C.

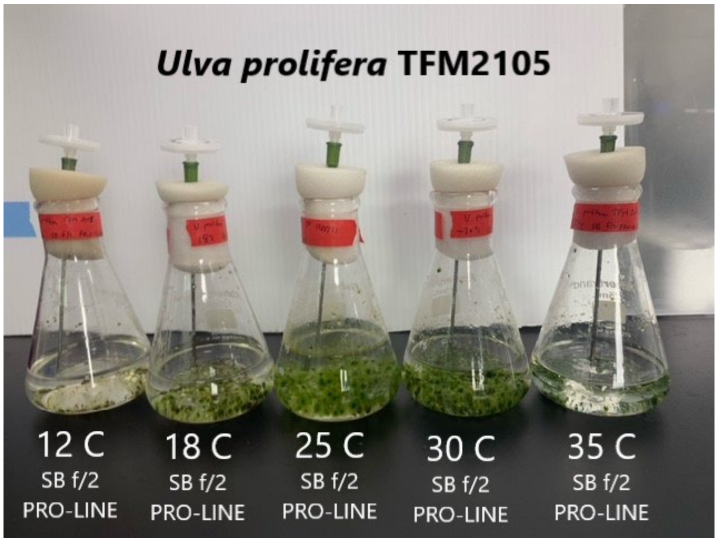

Figure 5. *Ulva cf. prolifera* TFM2105 flask cultures. Temperature range is 12˚C – 35˚C.

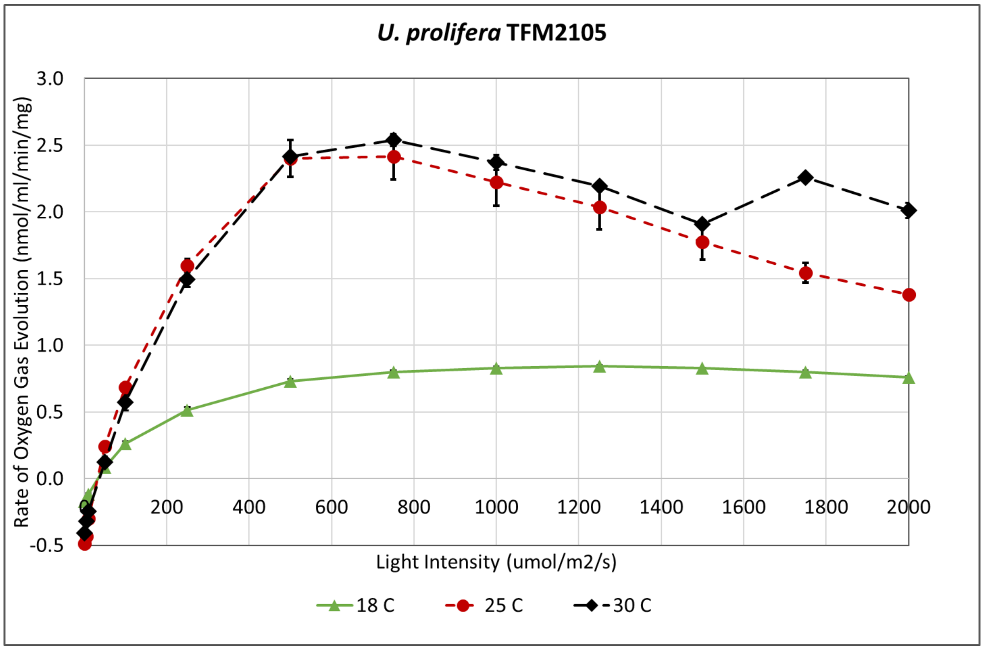

Figure 6. *Ulva cf. prolifera* TFM2105 Photosynthesis-Irradiance curves. Error bars represent the standard error of the mean, where N=3.

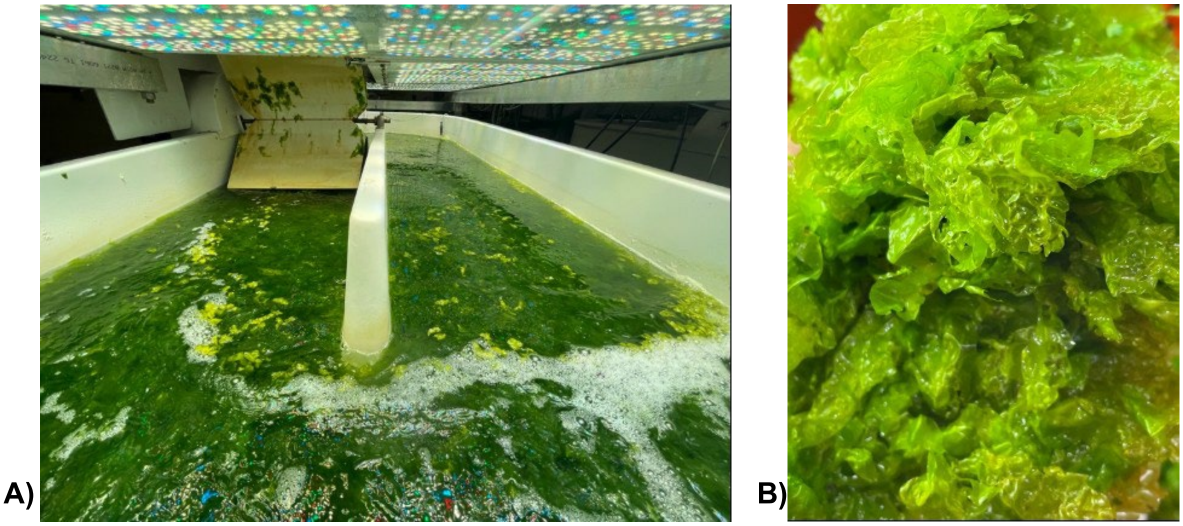

Figure 7: PNNL-Climate simulation raceway pond cultivation of *Ulva expansa* PC-3 (A) Close-up of harvested *Ulva expansa* biomass (B).

Table 3. Bioconcentration factor of Seaweeds from the Salish Sea (ash basis).

Sample Description	Scandium	Praseodymium	Neodymium	REE SUM	Copper	Nickel	Cobalt
Ulva cf. linza 2068	**3.52E+05**	**4.81E+05**	**4.79E+05**	**4.85E+05**	**1.08E+05**	**3.82E+04**	**7.54E+04**
Ulva sp. 2067	2.25E+05	3.43E+05	3.22E+05	3.39E+05	**1.35E+05**	**4.16E+04**	**5.68E+04**
Ulva sp. 2074	1.58E+05	1.80E+05	1.76E+05	1.97E+05	**7.52E+04**	**3.91E+04**	**4.31E+04**
Agarophyton sp. 2059	3.22E+04	8.46E+04	8.45E+04	7.91E+04	**5.33E+04**	**1.04E+04**	**1.43E+04**
Mazzaella sp. 2062	3.98E+04	4.98E+04	4.72E+04	5.27E+04	**6.36E+04**	**1.82E+04**	**1.17E+04**
Gracilaria sp. 2060	4.23E+04	1.38E+05	1.29E+05	1.31E+05	**5.75E+04**	**1.65E+04**	**1.32E+04**
Sargassum muticum 2075	1.37E+04	2.37E+04	2.40E+04	2.70E+04	**2.18E+04**	**1.31E+04**	**2.00E+04**
Fucus sp. 2076	1.81E+04	2.82E+04	2.96E+04	3.66E+04	**3.95E+04**	**4.89E+04**	**5.30E+04**
Unidentified diatom 21629	6.37E+04	6.58E+04	6.29E+04	8.81E+04	**3.95E+04**	**2.77E+04**	**1.66E+04**

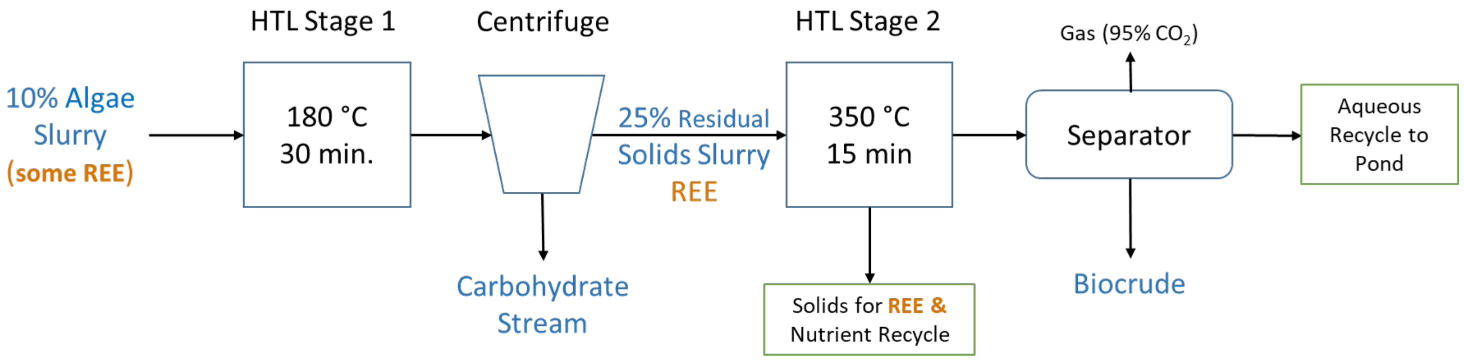

Figure 8. Sequential, 2-stage continuous flow hydrothermal liquefaction for the production of biocrude, carbohydrates, and algae-ore, with the hypothetical fate of the rare earth elements (REE) highlighted.

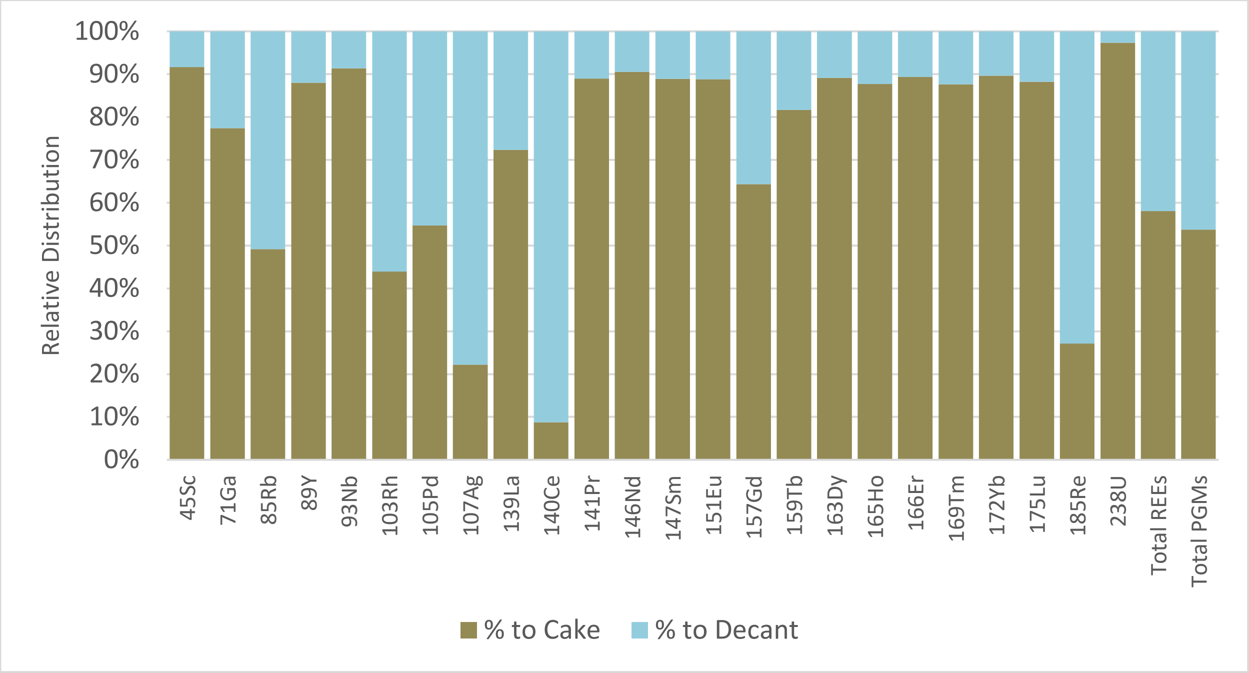

Figure 9. Relative mass balance distribution of individual critical minerals in Stage-1 hydrothermal processing showing allocation to the solids fraction (cake) or the liquid fraction (decant). .

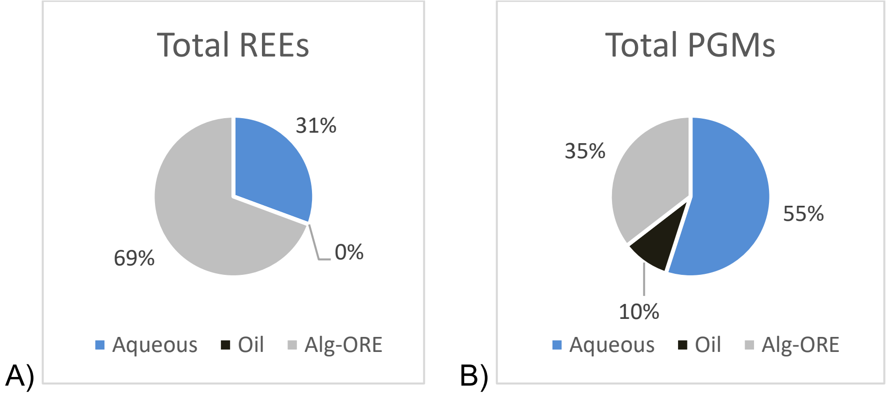

Figure 10. Relative mass balance distribution after continuous hydrothermal processing of macroalgal biomass **A)** total REEs and **B)** individual critical minerals. Aqueous fraction represents the liquid water-based phase, oil phase represents the biocrude fraction, and the "Alg-Ore" represents the precipitated solids captured during the HTL processing.

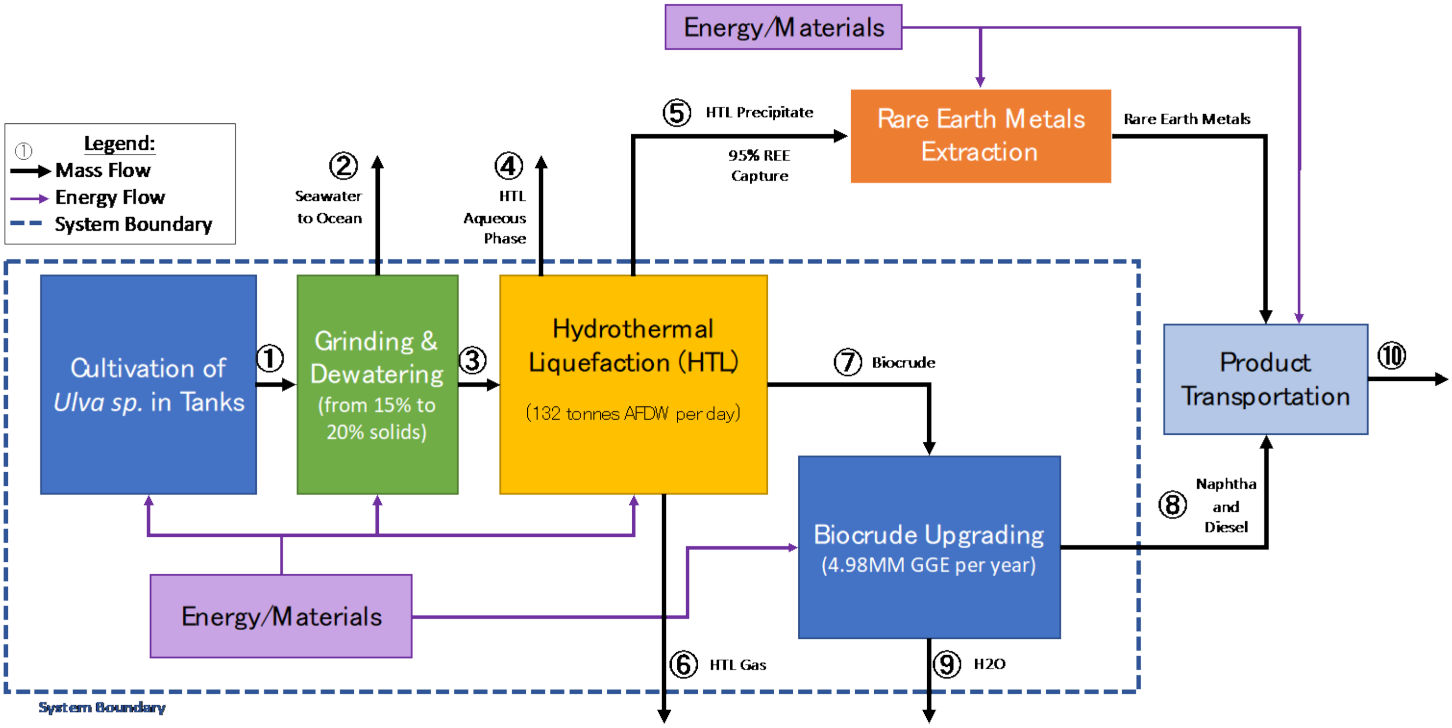

Figure 11: Engineering process model for the co-production of fuels and minerals from macroalgae showing the mass and energy flows and unit sup-processes and system boundaries.

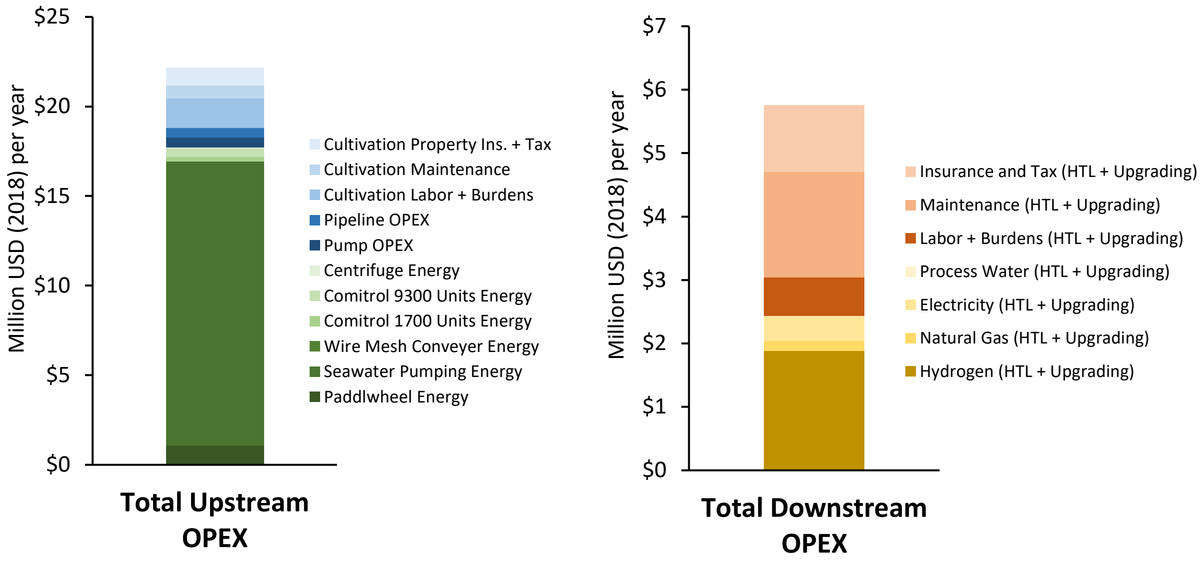

Figure 12: Total annual operational expenses for cultivation, seawater delivery, and grinding/dewatering operations (left) and total annual operational expenses for HTL and fuel upgrading (right). All values shown are representative of a 1000 wetted-acre facility.

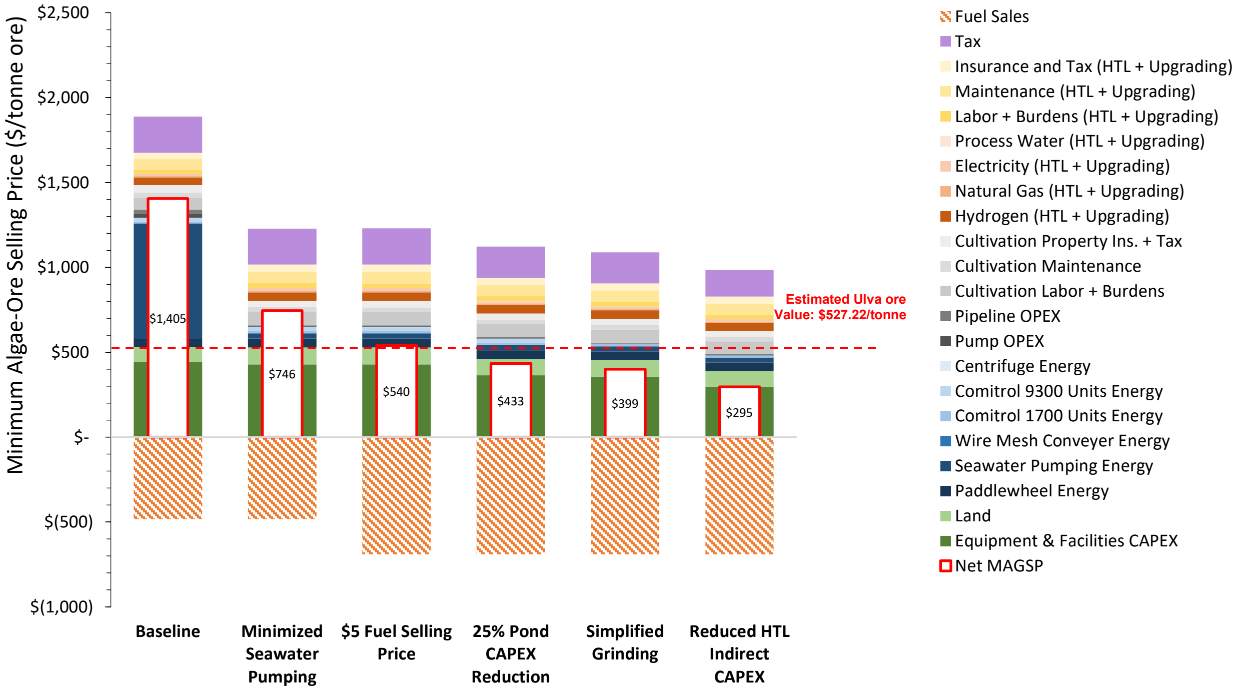

Figure 13: Potential process improvements to lower the minmum algae-ore selling price (MAOSP). Process improvements compound from left to right and the scenarios with a total MAOSP below the dotted red line represnet scenarios where the cost of production is less than the total value of the ore.

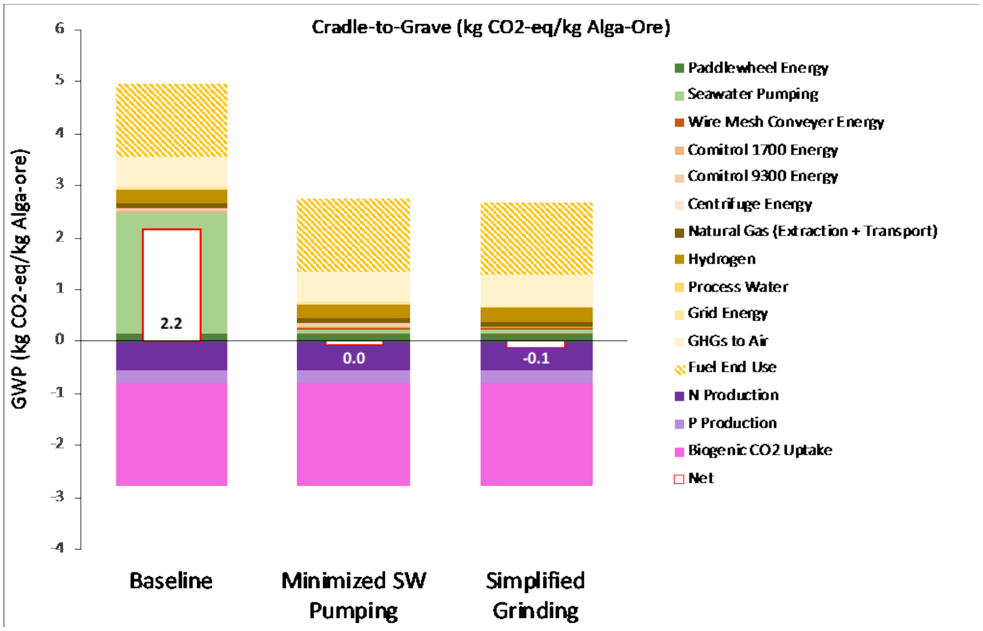

Figure 14: Cradle-to Grave Global Warming Potentials (GWP) as kg $CO_{2\text{-eq}}$/kg Alga-Ore. Baseline and process improvement scenarios to lower the are given. Energy required for seawater pumping is the single largest contributor to GWP. Minimizing seawaer pumping through a hypothetical optimized scenario illustrates a pathway to net carbon negative critical minerals. Mined ore displacements and fuel distribution are not included in the calculations present here.

Project Activities

The UNCLE-SAM project examined the biomining applications of seaweeds for sustainable, domestic production of critical mineral feedstocks. The ocean is a vast reserve of mineralogical wealth including rare earth elements (REEs) and platinum group metal (PGMs). These elements, categorized as "critical minerals", are used in telecommunication devices, lasers, LED lighting, turbine generators, electric car motors, jet engine alloys, and many other applications. These critical elements are increasingly vital to a thriving, efficient and sustainable society. However, only a few countries in the global market currently produce and export REEs, leading to potential geopolitical supply disruptions. Marine macroalgae, often referred to as seaweeds, bioconcentrate critical minerals, including REEs and PGMs. Marine algae cultivation can generate a significant amount of biomass with minimal freshwater, fertilizer, and land requirements. The aim of the project was to 1) evaluate the technological feasibility for marine macroalgal cultivation as a feedstock for critical minerals, 2) explore the biological capacity of different seaweeds to provide economically relevant domestic mineral production, 3) assess processing techniques for thermal co-conversion of seaweeds into renewable fuel and mineral feedstocks, 4) execute techno-economic and lifecycle assessments for identifying the most critical gaps in our current understanding to move the technology into commercially relevant deployment. Further development of this technology could transform the bioproduct and REE mining industries and catalyze the development of a robust supply of critical minerals for clean energy and a more sustainable future.

Project Outputs

A. Journal Articles

1. Edmundson et al., "Critical minerals from marine macroalgae" *in preparation.* (Dec 2023).
2. Greene et al., "Land-based production of macroalgae for coproduction of fuels and minerals" in preparation (Dec 2023).

B. Conference Papers

1. Jonah M. Greene, Scott J. Edmundson, Charles F. Hibbeln, Andrew J. Schmidt, Michael Huesemann, Jason C. Quinn "Techno-economic analysis and life cycle assessment of an on- shore macroalgae biorefinery to produce renewable transportation fuels and recover critical minerals, nutrients, and carbon from seawater" International Conference on Algal Biomass Biofuels and Bioproducts 2023.

C. Status Reports

Quarterly reports and technical updates to DOE.

D. Media Reports

8/12/2022	*Peninsula Daily News*: “Secretary of Energy tours Pacific Northwest National Laboratory-Sequim https://www.peninsuladailynews.com/news/secretary-of-energy-tours-pacific-northwest-national-laboratory-sequim
7/24/2023	*Tri-City Herald* “PNNL researchers are mining minerals from the sea for vital energy independence research” https://www.tri-cityherald.com/news/local/pacific-northwest-national-lab/article277546223.html

E. Invention Disclosures

We filed an invention disclosure report (IDR# 32456-E), entitled, “Methods for concentrating valuable or strategic elements from seawater by marine algae” (iEdison No. 0685901-22-0064).

F. Patent Applications/Issued Patents

None

G. Licensed Technologies

H. Networks/Collaborations Fostered

Established collaboration with groups in academia and industry:

- Dr. Eleftheria Roumeli (University of Washington)
- Mr. Beau Perry (Blue Evolution, CA)
- Mr. Markos Scheer (Sea Grove Kelp, WA)
- Dr. Scott Lindell (Woods Hole Oceanographic Institute)
- Phoenix Tailings (https://phoenixtailings.com/)
- Dr. Yet-Ming Chiang (Professor of Materials Science and Engineering, MIT)

I. *Websites Featuring Project Work Results*

Feature article: "PNNL Researchers Are Mining Minerals from the Sea for Vital Energy Independence Research"
https://www.pnnl.gov/news-media/pnnl-researchers-are-mining-minerals-sea-vital-energy- independence-research

Feature article: Secretary of Energy tours Pacific Northwest National Laboratory-Sequim
https://www.peninsuladailynews.com/news/secretary-of-energy-tours-pacific-northwest-national- laboratory-sequim/

J. *Other Products (e.g., Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)*

K. *Awards, Prizes, and Recognition*

Follow-On Funding

Additional funding committed or received from other sources (e.g., private investors, government agencies, nonprofits) after effective date of ARPA-E award.

Table 2. Follow-On Funding Received

Source	Funds Committed or Received
Exploring Macroalgae as Critical Mineral Crops, E=(MC)2	$1,676k 2-year project
Seaweed-based Emissions Abatement with Sustainable Aviation Fuels (SEA-SAF)	$330k/yr for 3 years

PNNL-35837

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