PrOMMiS Flowsheet: University of Kentucky REE Extraction Pilot Plant

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PrOMMiS: Process Optimization and Modeling for Minerals Sustainability

PROMMIS
Process Optimization and Modeling for Minerals Sustainability

Objective: Accelerate scale-up and **deployment** of innovative CM & REE processes and establish the toolkit to compress future RD3 timelines by **leveraging IDAES**, **CCSI** and a **decade** of **DOE CM & REE investment**.

Leveraging Existing DOE Investment and Capabilities

- CMI – Critical Materials Institute – An Energy Innovation Hub
- REECM – Rare Earth Elements and Critical Minerals from Coal and Coal-Based Resources
- IDAES – Institute for the Design of Advanced Energy Systems

Core activities:

- Model Development and Cost Estimation of Novel Processes
- Process Configuration, Design and Operational Optimization
- Technical Risk Reduction

Outcomes:

- Accelerate development, analysis, and scale-up of CM & REE technologies from raw sources, waste, and end-of-life products
- Digital Twin for process improvement and operational excellence
- Reducing technical risk during scale-up development and maximizing learning from pilot scale testing

External Partnerships & Technology Development Support

National Energy Technology Laboratory | Berkeley Lab | Sandia National Laboratories | Carnegie Mellon University | West Virginia University | University of Notre Dame | Georgia Tech | U.S. Department of Energy

PrOMMiS: Guiding Principles & Approach

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- **Urgency: Rapidly Establish Capability to Get Early Wins**
  - Learn by Doing – Apply to Existing Projects (recently completed or underway)
  - Don't Reinvent the Wheel – Leverage Existing Models & Partnerships
  - Partner with Active Developers
- **Create A Long-Term Capability!**
- **Maximize Support & Integration with CM and other DOE R&D Portfolios**

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Potential Case Studies

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- **FECM Bench- and Pilot-Scale Projects (External Performers)**
  - Bituminous Coal Ash (PSI/WWS)
  - Lignite Coal (UND)
  - Acid Mine Drainage (WVU/VT)
  - Coal Refuse (University of Kentucky)
  - Several others exist
- **IIJA/BIL REE Demonstration Facility Awardee (TBD)**
- **NETL Pilot or Pre-Pilot Projects**
  - Calcium-rich Fly Ash
  - Lithium Recovery from Produced Water

Potential Case Studies (continued)

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- **NETL Pilot or Pre-Pilot Projects (continued)**
  - CM recovery from AMD Solids
- **CMI Pilot Projects**
  - Magnet Recycling
  - Hard Drive Recycling
- **Membrane for Lithium Recovery from Produced Water**
- **Others, TBD**
  - REE Recovery from bauxite residues
  - Battery recycling (ReCell)

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Case Study:
University of Kentucky Coal Waste Pilot Process

UKy Coal Waste Pilot Process

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- What did we achieve?
  - Integrated flowsheet for extraction and separation of REEs from West Kentucky No. 13 coal waste.
  - Integrates unit and costing models into single model of leaching and separation train.

- What are the benefits?
  - Proof-of-concept example of integrating model libraries to simulate real world process.
  - Capable of optimizing process for cost and/or chemical consumption.

University of Kentucky Flowsheet

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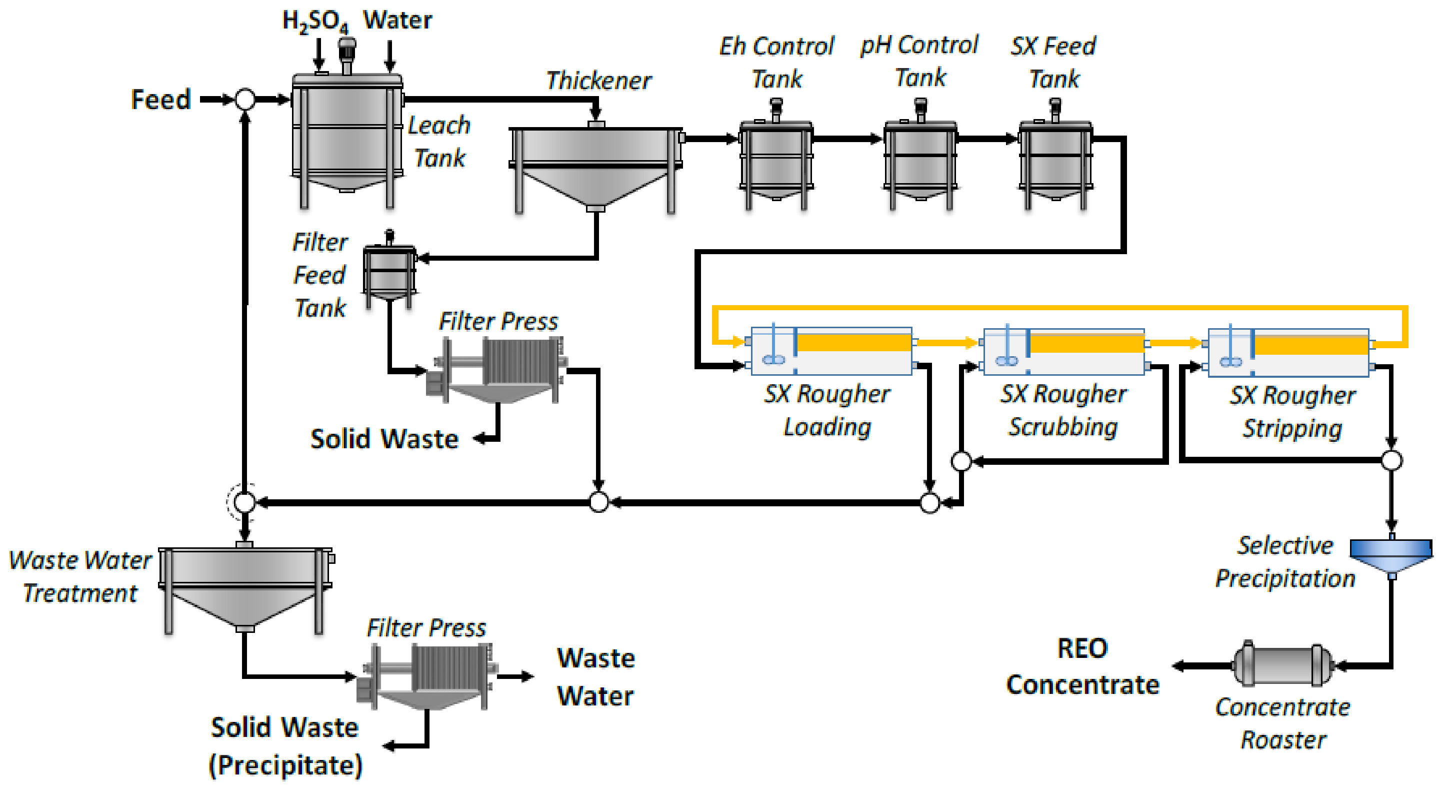
Flowsheet of the pilot-scale leaching and solvent extraction circuits



Enhancement of a Process Flowsheet for Recovering and Concentrating Critical Materials from Bituminous Coal Sources, R. Q. Honaker, W. Zhang, J. Werner, A. Noble, G. H. Luttrell & R. H. Yoon (2019)

PrOMMiS UKy Flowsheet

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Inputs

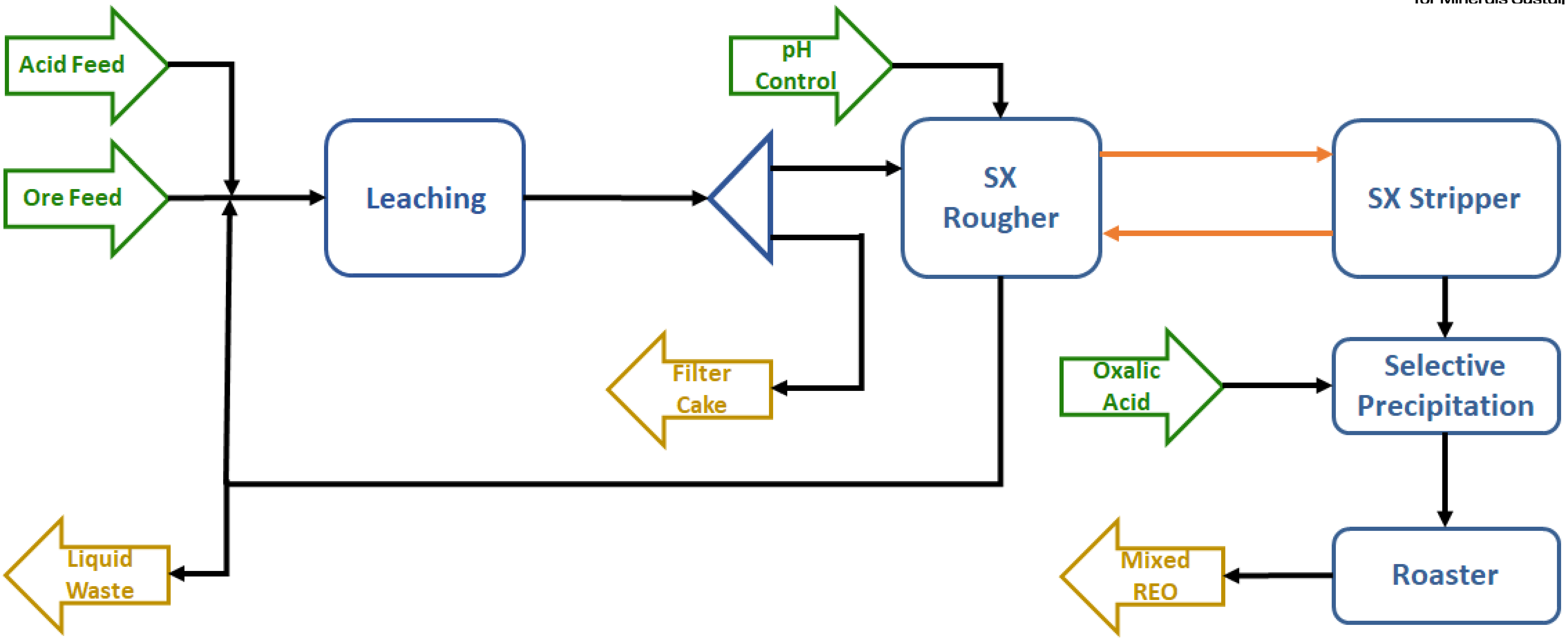
- Coal waste feedrate
- Leaching acid addition
- SX feed pH
- SX organic flowrate
- Aqueous purge rate
- Oxalic acid feed rate
- Roaster temperature

- Leach tank number and volume
- Solvent extraction circuit design
- Roaster residence time

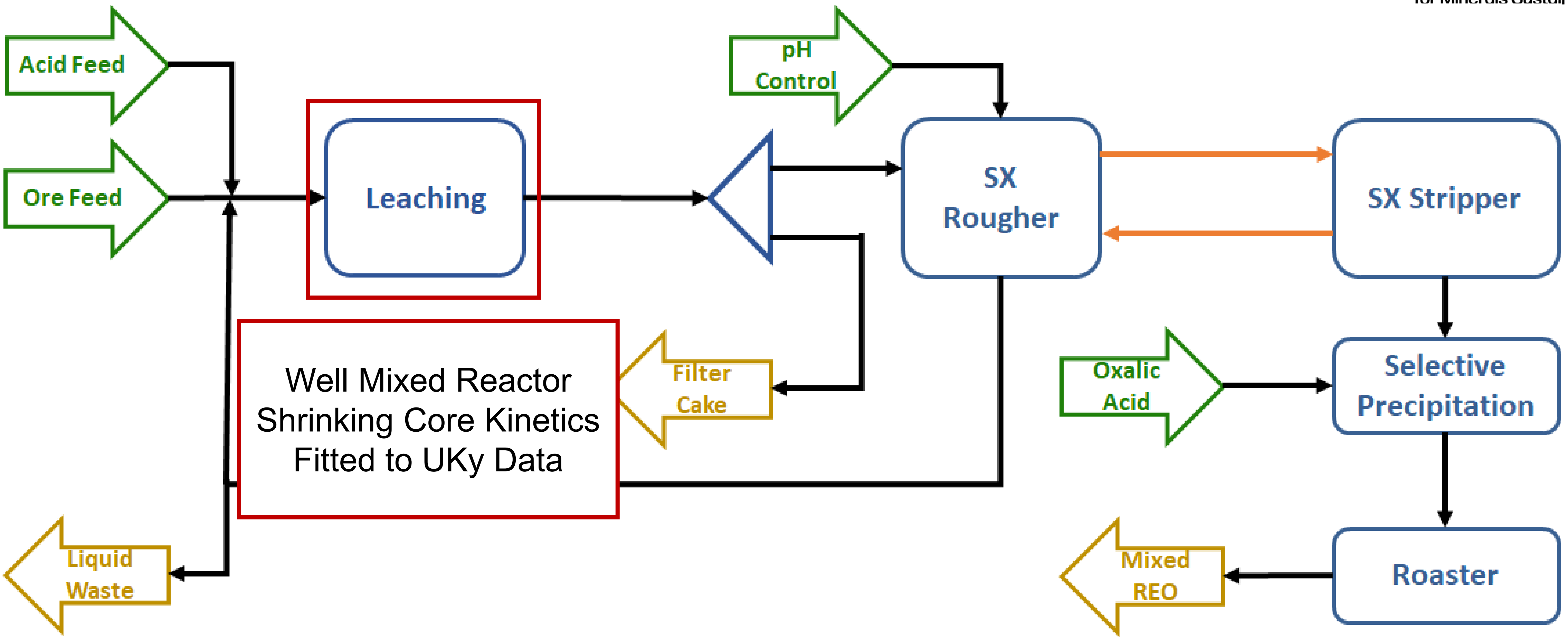
Outputs

- Mixed REE flowrate
- Mixed REE composition & purity
- REE recovery
- Roaster energy demand
- Liquid and solid waste flowrates
- Capital and operating costs

PrOMMiS UKy Flowsheet



PrOMMiS UKy Flowsheet



PrOMMiS UKy Flowsheet

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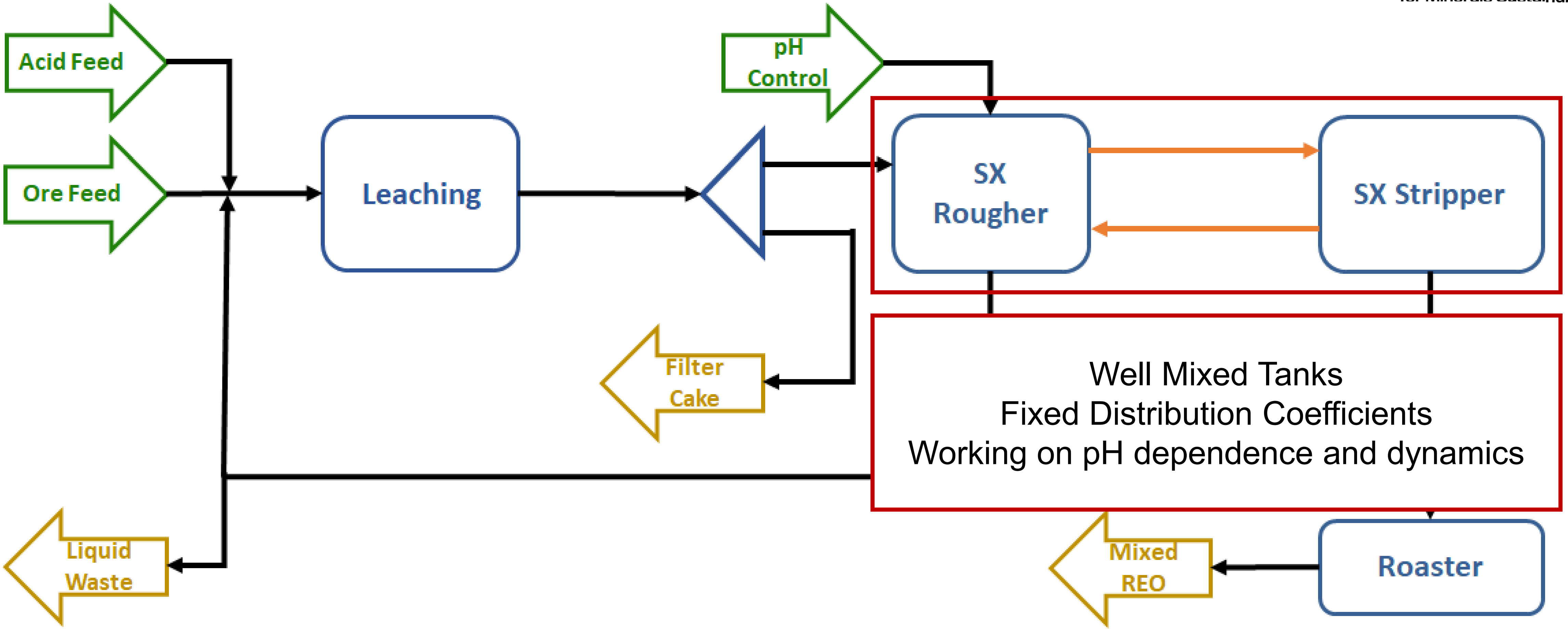

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PrOMMiS UKy Flowsheet

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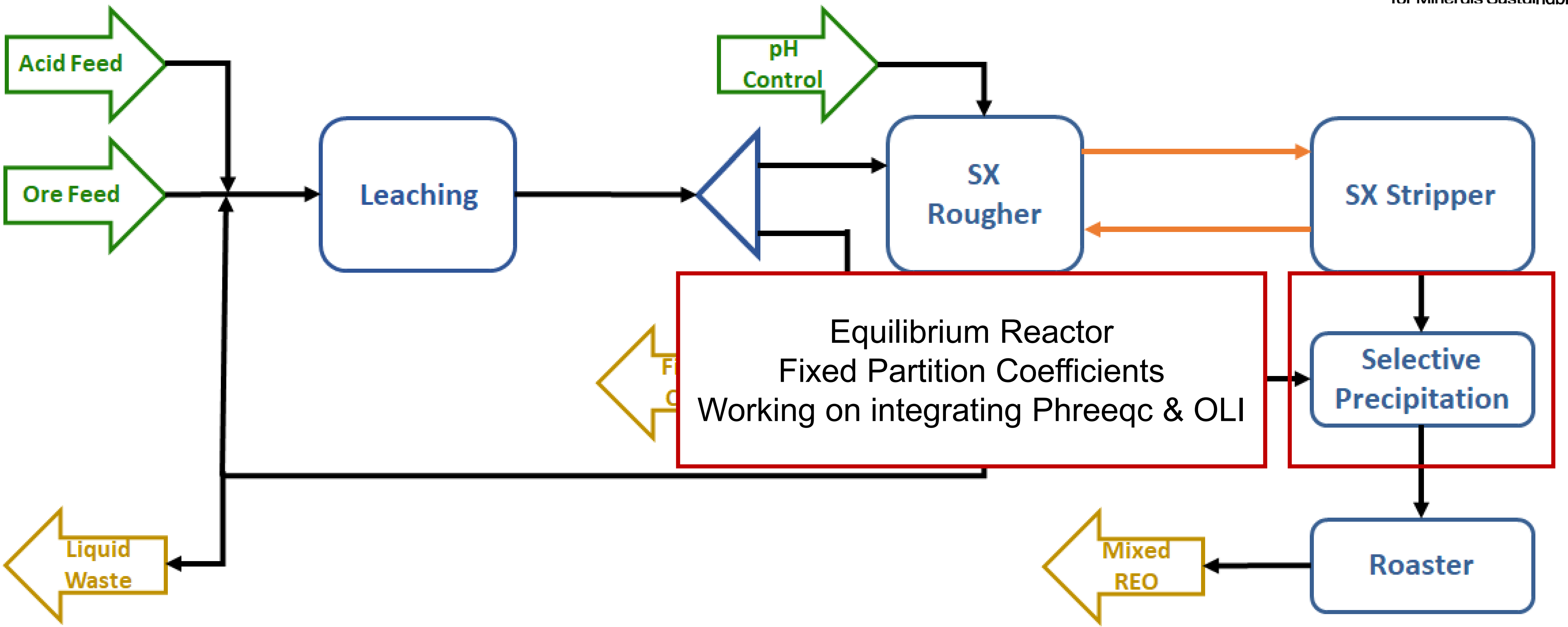
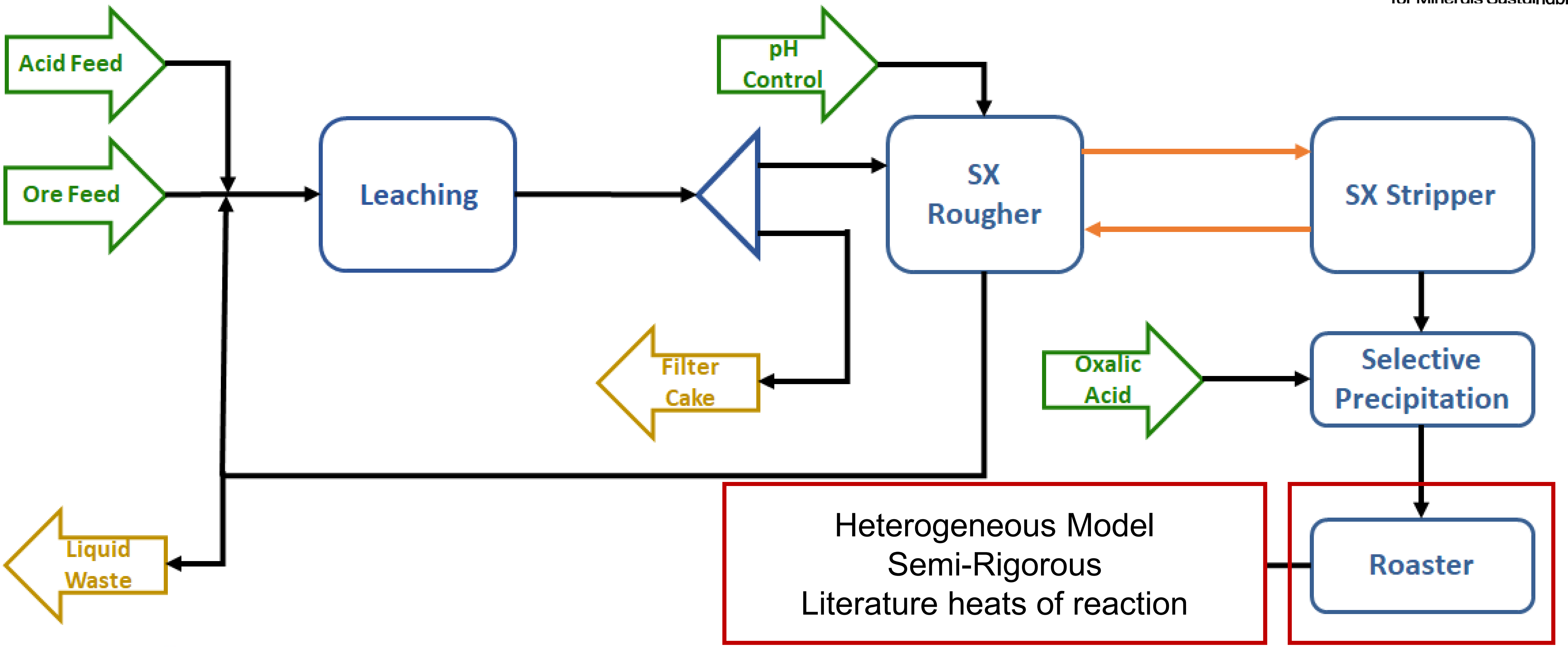


PrOMMiS UKy Flowsheet



PrOMMiS UKy Flowsheet

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- What can we do?
  - Replicate steady-state operation of pilot plant.
  - Confirm optimal design and operation parameters.
  - Study trade-offs between SX and precipitation costs.
  - Examine costs of reducing water consumption.
  - Compare alternative technologies for separations.

Next Steps

- Bring on student to gather project PID data and bridge gap between modeling and experimental
- Reproduce University of Kentucky's optimization results
- Develop superstructure for plant to explore:
  - Product-slate optimization
  - Waste minimization
  - Separations & Enrichment train optimization (IX vs. SX vs. MSX)
- Implement 2nd generation or more rigorous unit operation models
  - Solvent Extraction (SX)
  - Precipitation

Capabilities Needed for Design of Novel CM Systems

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Capability needed	Tools
Existing process unit model library for rapid assembly and modeling of flowsheets	Steady-state and dynamic equation-oriented modeling framework
Flexible capabilities to model novel technologies and optimize new materials	Custom models for critical minerals separation and processing
Efficient optimization tools to explore large space of potential process flowsheets	Rigorous framework for superstructure optimization for rapid flowsheet screening
Construction of optimization-ready surrogates and physical property relations	ALAMO, HELMET, OMLT, PYSMO: Surrogate capabilities for data-driven modeling and thermo-physical properties
Scalable identification and handling of uncertainty inherent in novel design	Robust optimization and Design of Experiments for reducing technical risk

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$CCSI^2$
Carbon Capture Simulation for Industry Impact

Water TAP

IDAES
Institute for the Design of Advanced Energy Systems

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Solvent Extraction Summary

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Process Optimization and Modeling for Minerals Sustainability

Feed Composition Data Used

- Aqueous feed: REESim excel file, buffer tank of cleaner circuit, concentration of components
- Organic feed: REESim excel file, stripping operation of cleaner circuit, concentration of components
- Components considered: Al, Ca, Fe, Sc, Y, La, Ce, Pr, Nd, Sm, Gd, Dy
- Extractant considered: DEHPA

Model Equations and Data for Unit Process

- Komulanein et. al., Hydrometallurgy, 81, 52-61, 2006, Lyon et. al., Industrial and Engineering Chemistry Research, 56, 1048-1056, 2017, and several other papers
- REESim excel file, Phase-1 report, Final phase report,
- Extraction percentage, extractant dosage and pH variation data, feed and product concentration, etc.

Validation Data Used

- Aqueous and organic streams concentration values from REESim excel file, Phase-1 report, and final phase report

Additional Data Required

- Following data are lacking in general in the literature in this area including UKy literature- studies on emulsification, if any, density gradients in the mixer/settler, axial and radial mixing, mass transfer rate, studies on interfaces and continuous and dispersed phase distributions, and ion concentration variation, also dynamic data are mostly lacking.

Solvent Extraction Summary

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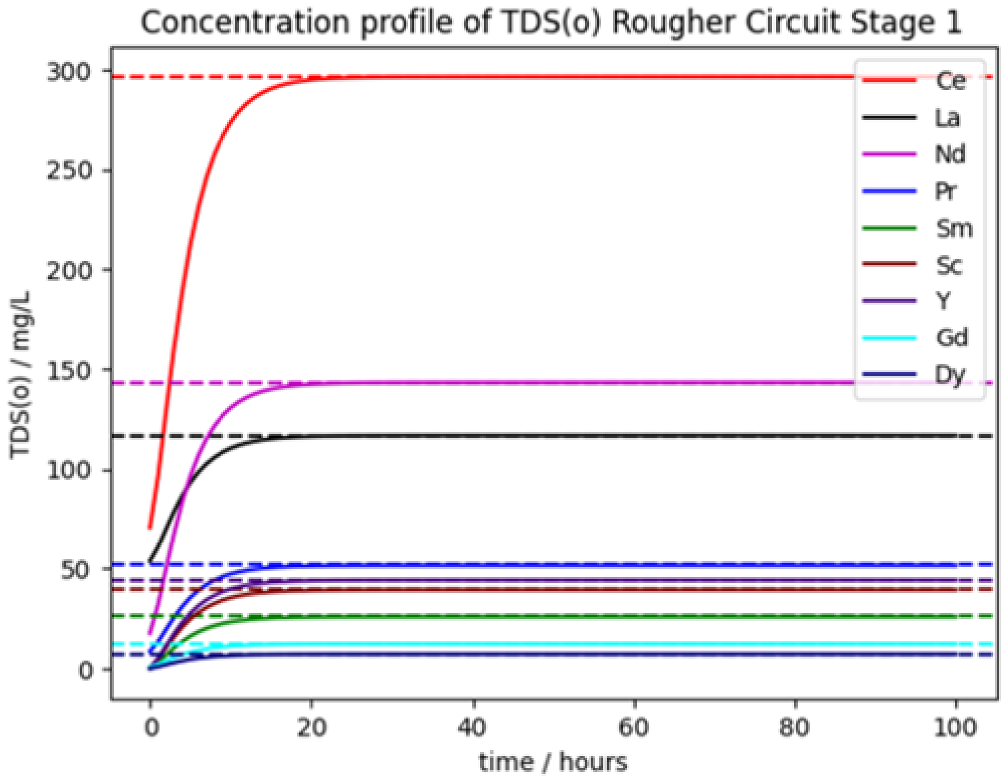

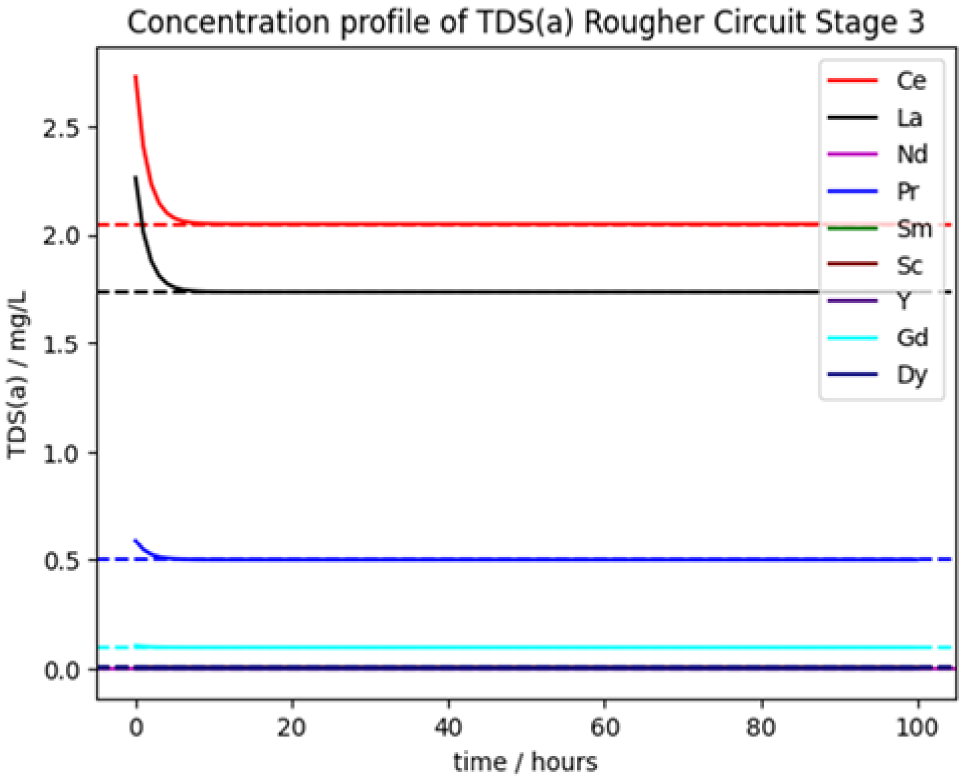

- First-principles, dynamic model of the counter-current multi-stage, multi-component solvent extraction system followed by stripping
- Model results compare well with the data from the UKy pilot plant data.

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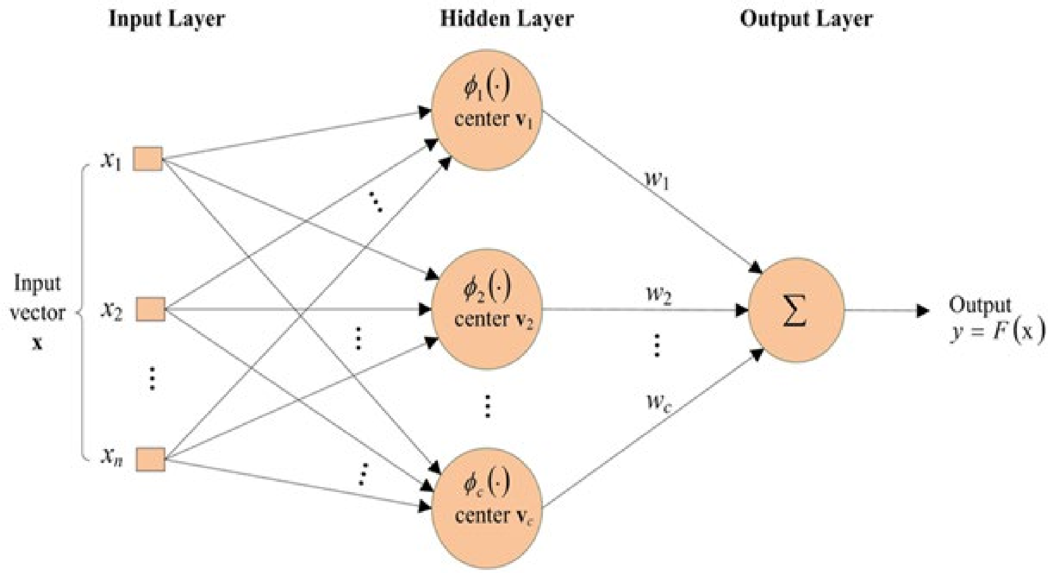
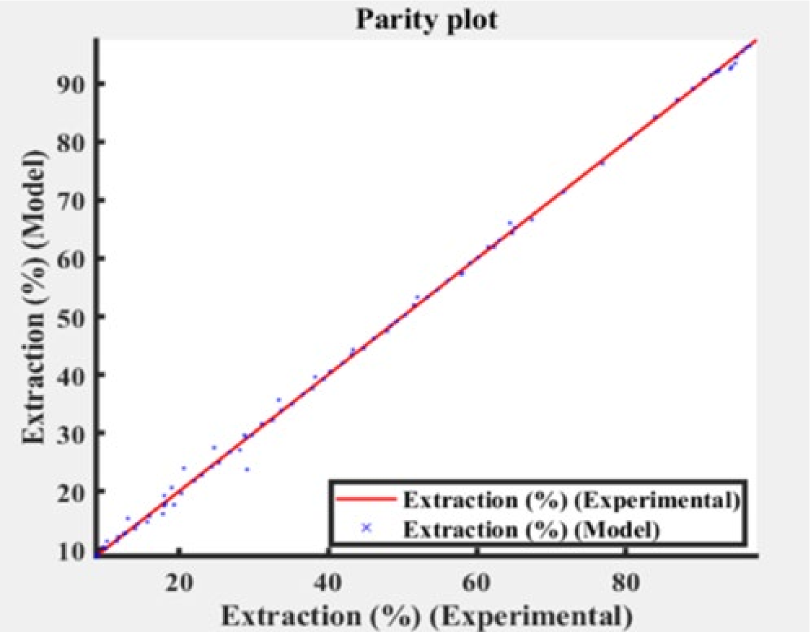
Solvent Extraction Summary

- Using the UKy pilot plant data, a data-driven model for the distribution coefficient as a function of pH and extractant concentration.
- Future work will include development of higher fidelity models of the solvent extraction system, inclusion of more solvent materials in the database, validation of the dynamic model of the solvent extraction system, control system development for feed and other disturbance rejection, and development of a model for the membrane solvent extraction system with validation using the NETL in-house data.





Solvent Extraction – Primary Separation Process

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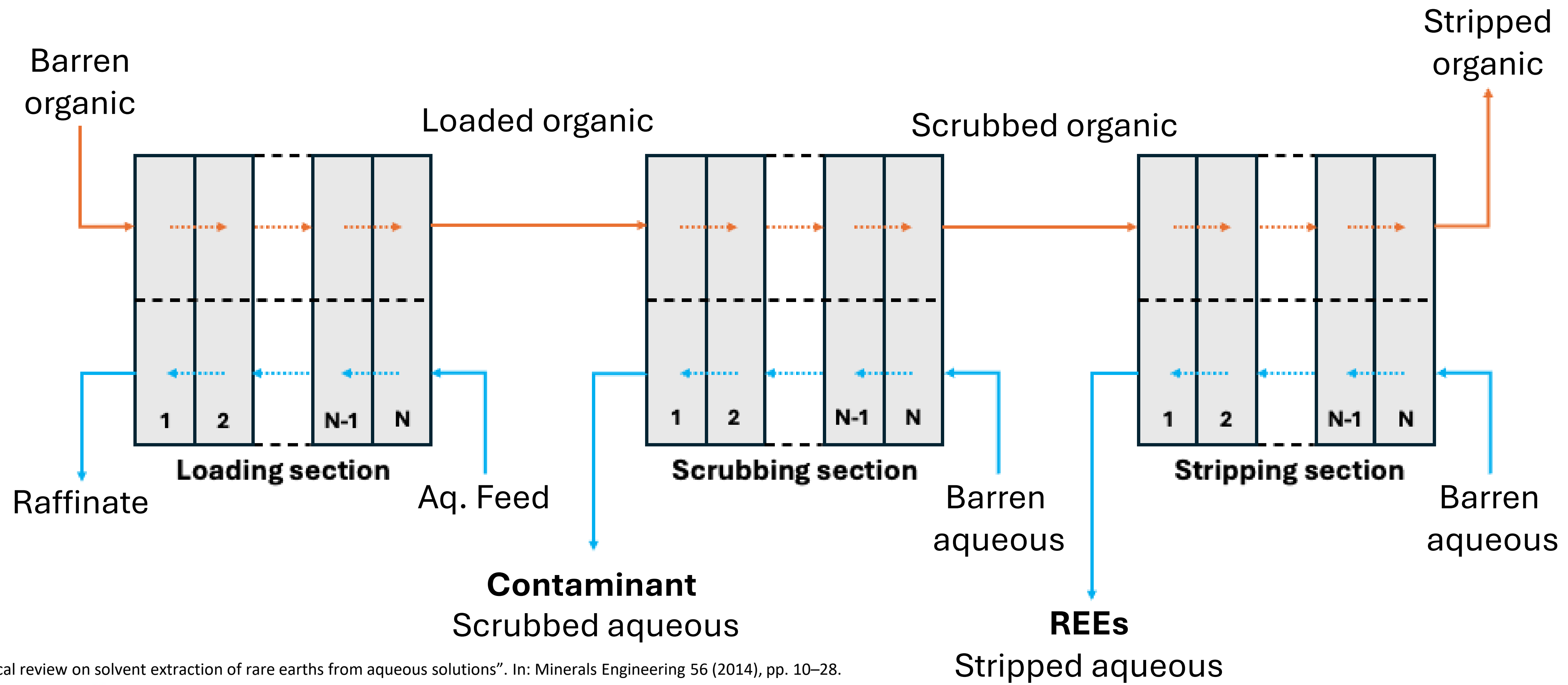
- Primary separation: separate **metal contaminants** from **CMs/REEs**.



Feng Xie et al. "A critical review on solvent extraction of rare earths from aqueous solutions". In: Minerals Engineering 56 (2014), pp. 10–28.

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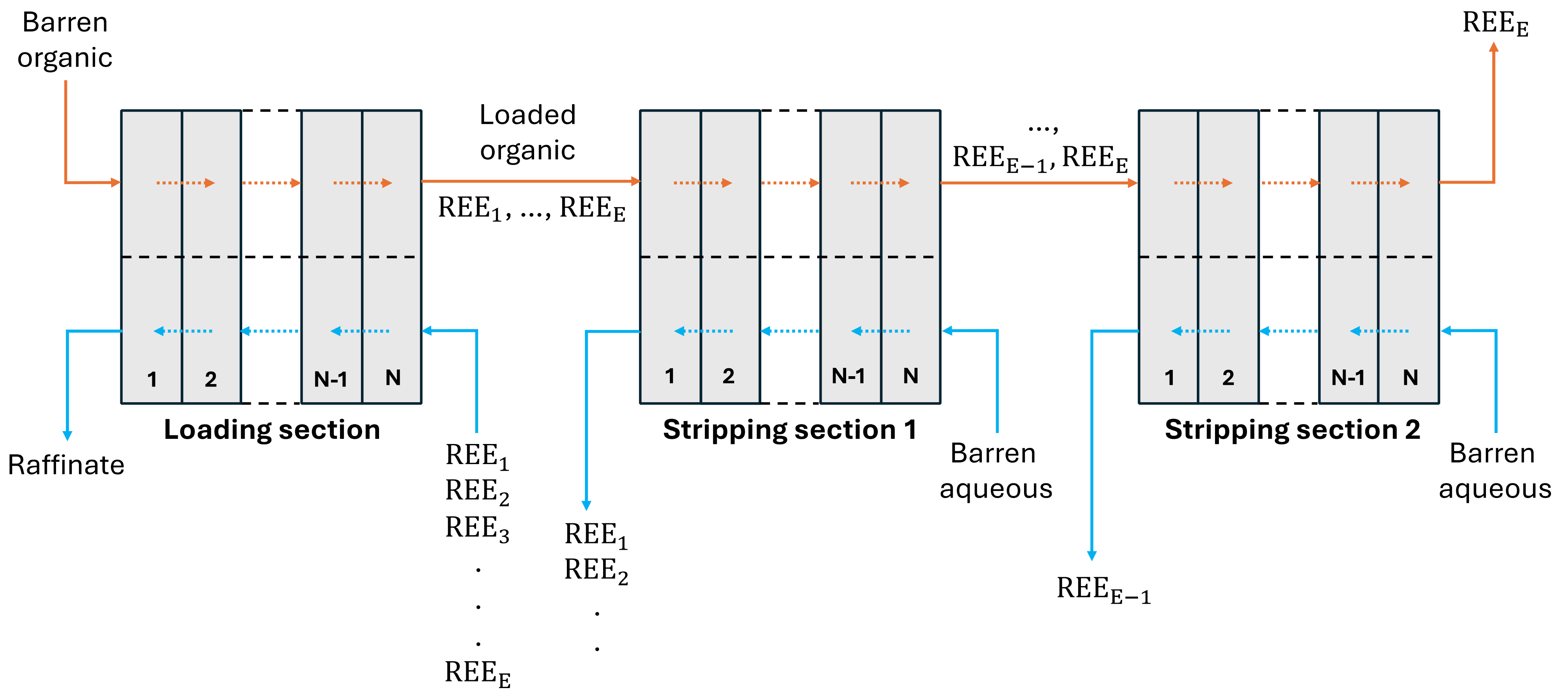
Solvent Extraction – Secondary Separation Process

- Secondary separation: separate **CMs/REEs** into **single or mixed-product**.



Feng Xie et al. "A critical review on solvent extraction of rare earths from aqueous solutions". In: Minerals Engineering 56 (2014), pp. 10–28.

Solvent Extraction Superstructure Formulation

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$$\min \sum_{q\in Q}\sum_{s\in S_q} y_{q,s} - \sum_{q\in Q}\sum_{s\in S_q}\sum_{j\in J_{qs}} \left(\alpha(\mathrm{PH}_v)(z_{q,v,j})\right)$$ — Minimize the total number of stages include a cost term for acid usage (pH)

$$\bar{x}^{out}_{q,s,e} = \bar{x}^{in}_{q,s+1,e}$$
$$x^{in}_{q,s-1,e} = x^{out}_{q,s,e}$$
— Connect the stages

$$\bar{F}_q \bar{x}^{in}_{q,s,e} + F_q x^{in}_{q,s,e} = \bar{F}_q \bar{x}^{in}_{q,s,e} + F_q x^{in}_{q,s,e}$$ — Stagewise material balances

$$\bar{F}_L \bar{x}^{out}_{L,N,e} = \bar{F}_S \bar{x}^{in}_{S,1,e}$$
$$F_L x^{in}_{L,N,e} = F_S x^{out}_{S,1,e} + F_{Feed} x_{Feed,e}$$
— Connect the sections

$$\sum_{v\in V_q}\sum_{j\in J_q} z_{q,v,j} = 1, \forall\, q \in Q$$ — Select only one pH per section

$$\tilde{x}_{q,s,e} = \sum_{v\in V_q} (D_{q,v,e,j}\, z_{q,v,j}) x^{out}_{q,s,e}$$
$$\bar{x}^{out}_{q,s,e} = \tilde{x}_{q,s,e} y_{q,s,j} + (1 - y_{q,s,j})\, \bar{x}^{in}_{q,s,e}$$
— Stage existence and equilibrium

$$y_{q,s-1} \geq y_{q,s}$$ — Stage existence ordering

$$\sum_{v\in V_q} z_{L,v,j} = \sum_{v\in V_q} z_{S,v,j}\ \forall\, j \in J$$ — Select the same extractant for both sections

$$\bar{F}_S \bar{x}^{out}_{S,N,O_{key}} \geq R_{min} F_{Feed} x_{Feed,O_{key}}$$
$$F_L x^{out}_{L,1,A_{key}} \geq R_{min} F_{Feed} x_{Feed,A_{key}}$$
— Minimum recovery on the outlet concentration of key components

$Q = \{\text{Load, Strip}\}$, $S = \{1,\ldots, N_{max}\}$, $J=\{J_1, \ldots, J_4\}$, $E=\{\text{REE}\}$

$z_{q,v,j}, y_{q,s} = \{0,1\}$, $\tilde{x}_{q,s,e}, \bar{x}_{q,s,e}, x_{q,s,e} \in \mathbb{R}$

- Formulated in Pyomo as a mixed integer quadratically constrained programming (MIQCP).
- Solved using Gurobi
- ~3500 variables, 3000 constraints, 100 binaries

Optimal Design for Sharp Separation with 5% DEPHA 10% TBP

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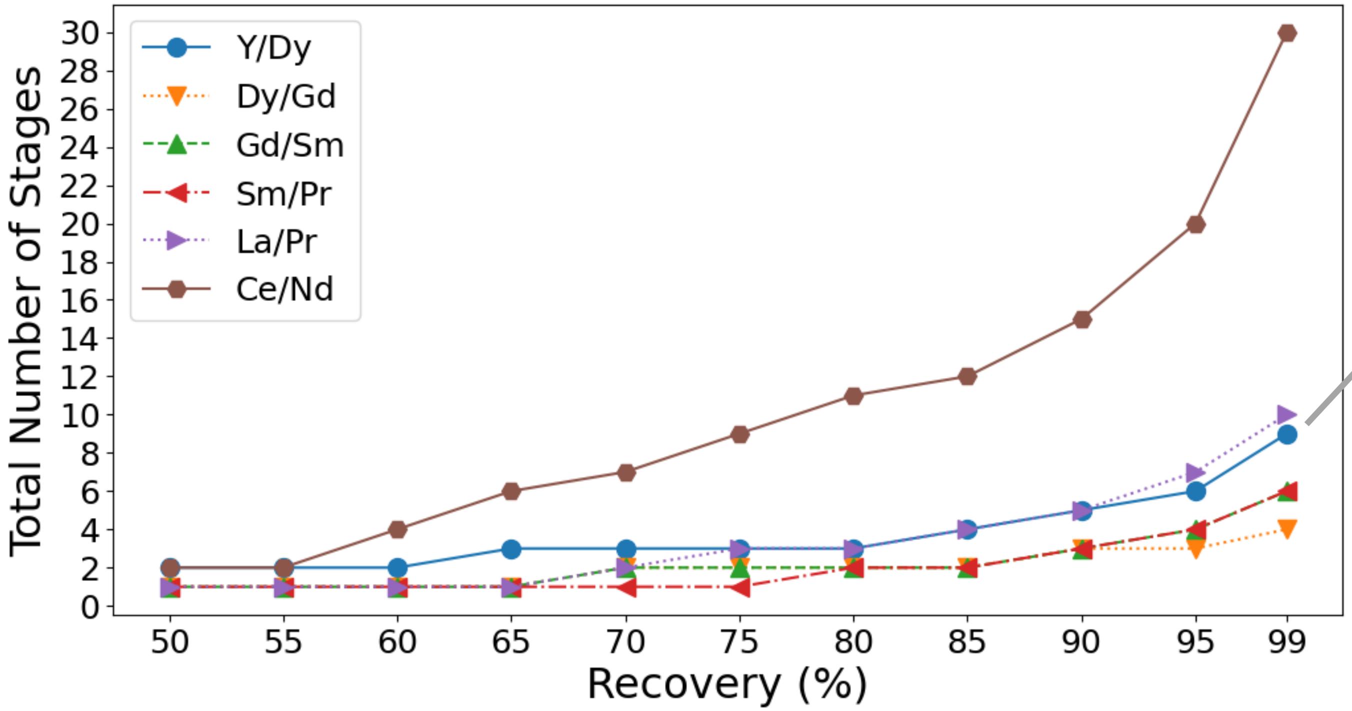
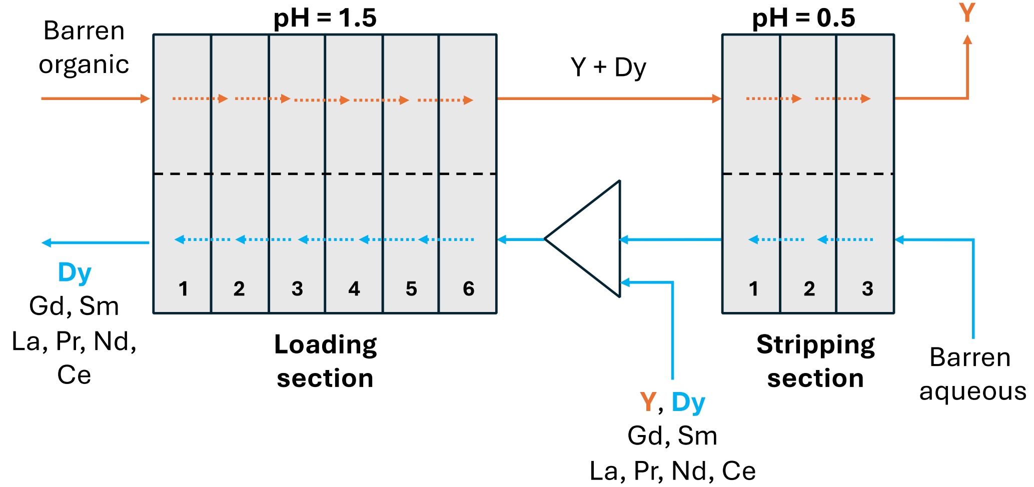
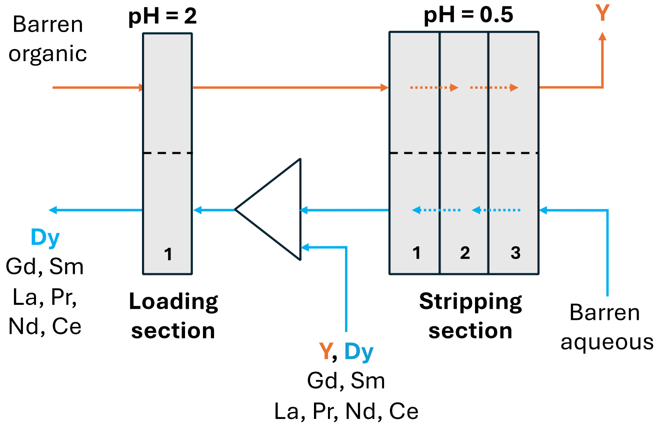




140 Binary variables
1790 Continuous variables
1856 Constraints

With different extractant



Solved to global optimality with average runtime of 20s

Project Overview - Collaborations

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The team has established close **collaborations** with several universities & other entities:

	Wayne State University	University of Kentucky	Virginia Tech	National Energy Technology Laboratory	CMI Critical Materials Innovation Hub
Research PI	Tim Dittrich	Rick Honaker, Joshua Werner	Aaron Noble	Nicholas Siefert, Alison Fritz, Ward Burgess, Jon Yang, Bret Howard	Ikenna Nlebedim, Parans Paranthaman, Jason Pries
Research Focus	Sorbent/IX modeling & validation	REE recovery and pilot plant support	Mining and Economics Analysis	Experimental data and modeling support (precipitation, leaching, solvent extraction, etc.)	Acid Free Recycling of Magnets; Membrane solvent extraction

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Acknowledgements:

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For questions and comments, please contact our Technical Director, Thomas Tarka (Thomas.Tarka@netl.doe.gov).

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National Energy Technology Laboratory: Thomas Tarka, Tony Burgard, Steve Zitney, Andrew Lee, Miguel Zamarripa, Alison Fritz, Alejandro Garciadiego, Brandon Paul, Anca Ostace, Radhakrishna Gooty, Jinliang Ma, Lingyan Deng, Marcus Holly, Elmira Shamlou, Javal Vyas.

Sandia National Laboratories: John Siirola, Bethany Nicholson, Michael Bynum, Edna Soraya Rawlings.

Lawrence Berkeley National Laboratory: Dan Gunter, Keith Beattie, John Shinn, Oluwamayowa Amusat, Sarah Poon, Ludovico Bianchi.

Carnegie Mellon University: Larry Biegler, Ignacio Grossmann, Carl Laird, Chrysanthos Gounaris, Ana Torres, Jason Yao, Christopher Laliwala, Daniel Ovalle.

West Virginia University: Debangsu Bhattacharyya, Quang-Minh Le, Akintomiwa Ojo, Arkoprabho Dasgupta.

University of Notre Dame: Alex Dowling, Molly Dougher, Hailey Lynch.

Georgia Tech: Nick Sahinidis, Dimitros Fardis.

2023 Joint PROMMIS/CCSI$_2$/IDAES Technical Team Meeting
Lawrence Berkeley National Lab

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Backup Slides

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Leaching Summary

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Feed Composition Data Used

- Coal Composition: UKy Final Report Appendix E, Tables 2 & 6

Model Equations and Data for Unit Process

- Shrinking Core kinetic model
- Operating Conditions: UKy Final Report Tables 3.7.1 & 3.7.2
- Elemental Recovery: UKy Final Report Figures 3.7.4, 3.7.5, & 3.7.6a

Validation Data Used

- None available

Additional Data Required

- Additional experimental data for fitting and validation

Table 6. Mineralogy analysis results from X-ray Diffraction performed on samples obtained from each vertical segment associated with the West Kentucky No. 13 coal seam.

Lithology	SiO2 (%)	Al2O3 (%)	Fe2O3 (%)	CaO (%)	MgO (%)	MnO (%)	Na2O (%)	K2O (%)	P2O5 (%)	TiO2 (%)	BaO (%)	SrO (%)	SO3 (%)	Total (%)
Roof Shale	58.18	21.57	6.57	0.56	1.60	0.09	0.58	3.71	0.14	1.00			3.01	97.00
Roof Shale	43.80	22.21	4.89	0.36	1.32	0.02	0.53	3.60	0.08	0.97			6.77	84.55
Coal	54.51	23.58	15.61	0.60	1.42	0.02	0.61	3.40	0.07	1.06	0.21	0.03	0.39	101.52
Coal	9.73	8.27	75.42	1.53	0.19	0.02	0.15	0.39	0.07	0.31	0.04	0.03	0.73	96.88
Coal	35.13	20.58	36.35	2.91	0.54	0.02	0.40	1.15	0.75	1.50	0.06	0.17	1.04	100.60
Parting	53.33	24.79	2.78	0.53	1.01	0.01	0.65	2.69	0.58	1.37			3.37	91.11
Coal	16.51	9.75	69.50	0.45	0.32	0.04	0.05	0.85	0.05	0.54	0.07	0.02	0.30	98.45
Coal	23.90	10.98	62.10	0.54	0.52	0.04	0.19	1.45	0.15	0.60	0.02	0.02	0.23	100.75
Parting	35.31	16.68	15.32	0.56	0.80	0.01	0.40	2.01	0.51	0.70			7.23	79.52
Parting	54.71	25.11	5.20	0.41	1.08	0.06	0.63	3.20	0.11	1.07			4.45	96.02
Parting	57.32	24.76	5.51	0.33	1.13	0.07	0.55	3.52	0.04	1.00			2.91	97.14
Parting	57.18	23.67	6.03	0.29	1.25	0.05	0.50	3.65	0.04	1.01			3.67	97.33
Parting	58.63	23.57	5.12	0.27	1.27	0.04	0.50	3.67	0.04	0.98			2.34	96.42
Parting	58.20	24.41	4.53	0.25	1.24	0.03	0.57	3.72	0.04	0.97			2.36	96.33
Parting	54.70	28.31	3.55	0.28	0.91	0.02	0.72	2.58	0.04	1.08			1.58	93.77
Parting	54.98	28.97	2.37	0.27	0.58	0.00	0.68	1.85	0.10	1.62			1.41	92.83
Coal	53.00	23.84	18.10	0.72	0.72	0.01	0.26	2.47	0.05	1.08	0.04	0.02	0.63	100.94
Coal	27.43	12.63	53.01	0.86	0.43	0.04	0.14	1.19	0.05	0.67	0.02	0.02	0.52	97.01
Coal	38.60	19.00	36.24	0.93	0.57	0.02	0.14	1.58	0.07	0.94	0.21	0.03	0.56	98.88
Coal	31.39	16.67	23.23	14.17	0.79	0.08	0.14	1.33	0.10	0.69	1.39	0.05	7.91	97.95
Coal	36.19	21.49	27.53	5.03	0.64	0.03	0.42	1.41	0.12	0.83	0.03	0.05	5.04	98.81
Coal	45.39	19.11	28.33	1.86	0.62	0.02	0.36	1.59	0.21	0.85	0.03	0.05	1.21	99.62
Coal	54.41	22.09	16.83	1.15	1.05	0.02	0.32	2.70	0.39	1.03	0.04	0.03	0.63	100.68
Coal	40.60	16.32	35.19	1.70	0.79	0.02	0.23	2.07	0.56	0.78	0.03	0.03	0.94	99.27
Parting	8.74	3.26	87.59	0.41	0.18	0.02	0.00	0.48	0.11	0.27	0.00	0.01	0.28	101.34
Coal	45.45	17.07	23.17	5.30	0.93	0.04	0.34	2.11	0.29	0.79	0.03	0.03	4.20	99.75
Coal	47.91	17.20	26.14	2.19	0.99	0.02	0.34	2.39	0.61	0.82	0.21	0.03	1.03	99.87

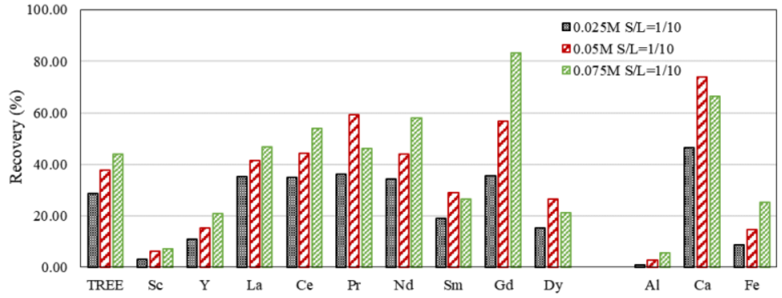

Figure 3.7.4. Effect of acid concentration on major REE and contaminants leaching recovery.

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Precipitation Summary

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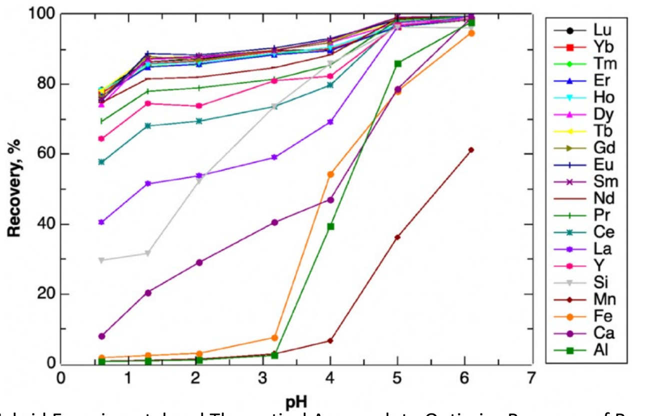
Feed Composition Data Used

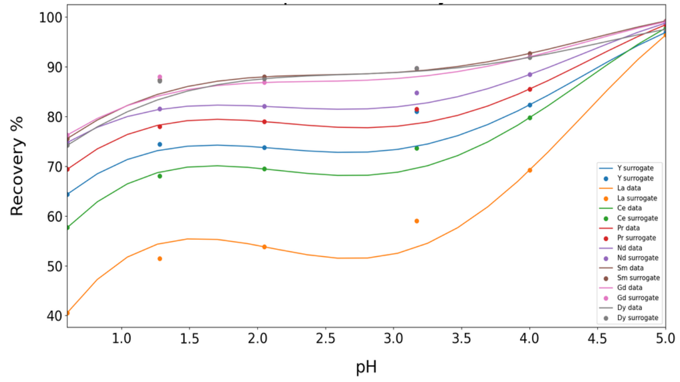
- Input is fed from the solvent extraction system
- Output would need to be validated from inputs and specific pH, acid dosage, and reaction time

Model Equations and Data for Unit Process

- Equilibrium reactor with fixed partition coefficients
- Partition coefficients calculated from data in the literature
- A Hybrid Experimental and Theoretical Approach to Optimize Recovery of Rare Earth Elements from Acid Mine Drainage Precipitates by Oxalic Acid Precipitation, Y. Wang, P. Ziemkiewicz, and A. Noble, Minerals 2022, 12, 236
- One problem is that since it is not a multivariable study, the surrogate model can only be created for one variable



A Hybrid Experimental and Theoretical Approach to Optimize Recovery of Rare Earth Elements from Acid Mine Drainage Precipitates by Oxalic Acid Precipitation, Y. Wang, P. Ziemkiewicz, and A. Noble, Minerals 2022



Surrogate model results

Precipitation Summary (Model Validation)

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Validation Data Used

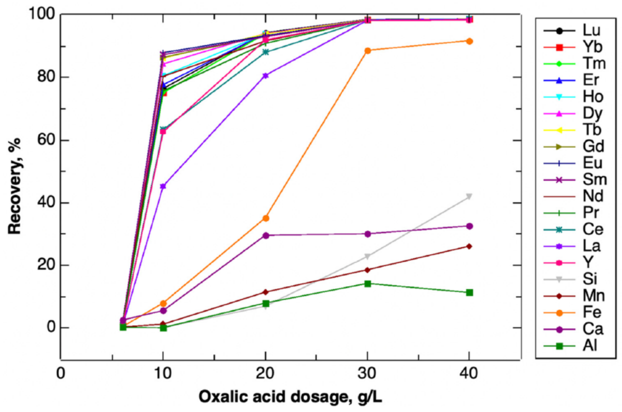
- The validation test are based on partition calculated from data
- The model is validated with this data as the surrogate model being built will be based on this data as it is a full data base
- Paper recovery %

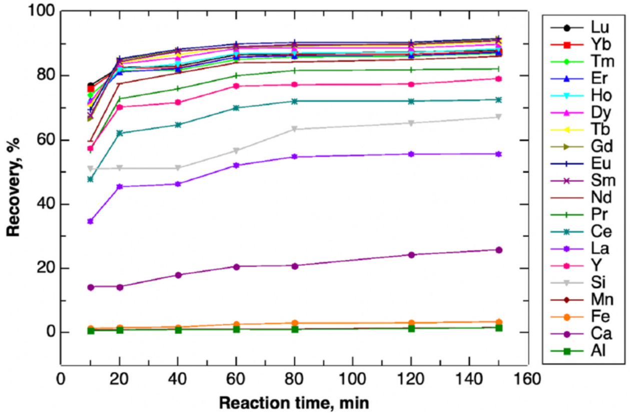
Additional Data Required

To build the surrogate and test with UK data, we will require data for:

- recovery vs pH,
- recovery vs acid dosage
- recovery vs reaction time

Need multivariable data set where (pH, dosage, reaction time, contaminants) are varied





A Hybrid Experimental and Theoretical Approach to Optimize Recovery of Rare Earth Elements from Acid Mine Drainage Precipitates by Oxalic Acid Precipitation, Y. Wang, P. Ziemkiewicz, and A. Noble, Minerals 2022

REE Oxalate Roaster Summary

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Feed Composition Data Used

- Solid feed: PrecipitateParametersData, with optional moisture content
- Gas feed: Generic ideal gas mixture (N_2, O_2, CO_2, H_2O)

Model Equations and Data for Unit Process

- Currently 100% conversion to oxides
- Full species mass balance and energy balance
- User specified solid recovery (default 95%)

Validation Data Used

- UKy REESim excel spreadsheet

Additional Data Required

- Conversion and recovery for individual species as functions of temperature and other operation conditions, if available

- $RE_2(C_2O_4)_3 \cdot xH_2O + 1.5O_2 \rightarrow RE_2O_3 + 6CO_2(g) + xH_2O(g)$
- **Impurities:**
  - $Fe_2(C_2O_4)_3 \cdot 2H_2O \rightarrow Fe_2O_3$
  - $Al_2(C_2O_4)_3 \cdot H_2O \rightarrow Al_2O_3$

Ion Exchange Summary

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Feed Composition Data Used

- Leaching process outlet from UKy flowsheet

Model Equations and Data for Unit Process

- Modified version of unit model from WaterTAP platform
- Data for unit operation and resin from references [1] and [2]

Validation Data Used

- No validation available, but model was tested using batch experimental data from literature (references in unit model)

Additional Data Required

- No additional data required

References:
[1] S. Mondal, A. Ghar, A.K. Satpati, P. Sinharoy, D. K. Singh, J.N. Sharma, T. Sreenivas, and V. Kain, Recovery of rare earth elements from coal fly ash using TEHDGA impregnated resin, Hydrometallurgy 185, 2019, 93-101.

[2] Dupont Amberlite XAD(TM)7HP Polymeric Adsorbent. Product Data Sheet Polymeric Adsorbent. February 2023. URL:

https://www.dupont.com/content/dam/dupont/amer/us/en/water-solutions/public/documents/en/IER-AmberLite-XAD7HP-PDS-45-D00782-en.pdf

Framework Development

PROMMIS
Process Optimization and Modeling for Minerals Sustainability

- What is it?
  - Libraries of models for common unit operations.
  - Includes thermodynamic properties, unit operations and cost estimation.
  - Different levels of rigor to support analyses from conceptual design through to high-fidelity simulations.

- Why do we care?
  - Facilitates rapid assemble of process models from modular components.
  - Will support full optimal design workflow from process synthesis to process control.

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A New Domain

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Process Optimization and Modeling for Minerals Sustainability

- Need new library of models for minerals processing
  - Need both current and future technologies

- Reviewed literature for REE recovery processes
  - Focus on unconventional resources
    - Coal Waste Products
    - Acid Mine Drainage
    - Brines and Produced Water
    - Phosphates and Gypsum
    - End-of-Life Recycling
      - Batteries
      - Magnets

- Learning by Doing
  - DOE wants immediate results

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Unit and Property Model Libraries

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Process Optimization and Modeling for Minerals Sustainability

- Goal: Develop a comprehensive library of models for CM & REE processing operations.

- First Year:
  - Identify key unit operations and properties from candidate case studies.
  - Focus on unconventional feedstocks:
    - Coal ash and waste
    - Acid mine drainage
    - Phosphates & gypsum
    - Brines
    - Battery recycling
    - End-of-life magnets

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Core Model Development

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Process Optimization and Modeling for Minerals Sustainability

- Models (contributed to GitHub)
  - Roaster (calcination)
  - Leaching
  - Solvent extraction
  - Solid liquid separation
  - Precipitation
  - Thickener
  - Crushing and Grinding
  - Evaporation
- Property Packages:
  - Case specific properties
  - Integration of PhreeqC / Mintec
- WaterTAP Models
  - RO
  - Ion exchange
  - Nanofiltration
  - Electrodialysis
  - Membrane Distillation

REEE Costing Framework

https://github.com/prommis/prommis/tree/main/src/prommis/uky/costing

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Current Framework Capabilities	Ongoing PrOMMiS Integration	Planned Capabilities

• Capital & Operating Costs
• Annualized Costs & Revenue
• Membrane Capital & Operating Costs via WaterTAP
• Custom Costing Models
• Objectives for TEA – Net Present Value and Cost of Recovery
	• Bottom-Up Costing for Hydrogen Decrepitation (WVU)
	• Economy of Numbers (WVU)
	• Costing for Li/Co diafiltration (ND)
	• Superstructure UI integration (LBNL)
	• Tutorial development (NETL)
		• For March 2025:
		  • Operation Labor Estimation
		  • Tax & Environmental Incentives
		  • Byproduct Recovery Value
		• For EY25:
		  • TEA of at least two processes
		  • Cost & Price UQ to supplement task 2.4 tools

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PrOMMiS Costing Library

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Front End Loader (2 yd^3)	Front End Loader (10 yd^3)	Bucket Elevator	Jaw Crusher	VSI Crusher	Roll Crusher
Vibrating Screen	Storage Bins	Dry Ball Mill	PE Tanks	Steel Tanks	Tank Mixer
Elevator Motor	Process/Slurry Pump	Thickener	Filter Press	Conveyor	Roaster
Gas Scrubber	Spray Chamber Quencher (77k-60k cfm)	Spray Chamber Quencher (60k-230k cfm)	Chiller	Solution Heater	Belt Filter
BioLeach Tanks	Blower	Mixer Settler	HDD Recycling Shredder (2700 drives/hour)	HDD Recycling Furnace	Hydrogen Decrepitation Furnace*
Diafiltration (Li/Co Separation)*	Nanofiltration**	Reverse Osmosis**	Ion Exchange**	Membranes**	

* Bottom-up Cost Models (users can write their own custom models)

** WaterTap library

PrOMMiS Costing Library:

$$SC_i = RC_i * \left(\frac{RP_i}{SP_i}\right)^{Exp_i}$$

- SC – scaled cost
- RC – reference cost
- SP – scaled parameter
- RP – reference parameter
- Exp – exponential factor
- i – i^{th} unit cost account

References:

[1] Keim, Steven Anthony, and Naumann, Hans. Production of Salable Rare Earths Products from Coal and Coal Byproducts in the U.S. Using Advanced Separation Processes (Final Technical Report). United States: N. p., 2019. Web. doi:10.2172/1569277.

[2] Honaker, Rick, Werner, Joshua, Yang, Xinbo, Zhang, Wencai, Noble, Aaron, Yoon, Roe-Hoan, Luttrell, Gerald, and Huang, Qingqing. **Pilot-Scale Testing of an Integrated Circuit for the Extraction of Rare Earth Minerals and Elements from Coal and Coal Byproducts Using Advanced Separation Technologies.** United States: N. p., 2021. Web.

[3] Honaker, Rick Q., Werner, Joshua, Nawab, Ahmad, Zhang, Wencai, Noble, Aaron, Free, Michael, and Yang, Xinbo. **Demonstration of Scaled-Production of Rare Earth Oxides and Critical Materials from U. S. Coal-Based Sources (Final Report).** United States: N. p., 2023. Web. doi:10.2172/1971736.

[4] Garrett, D.E. (1989). Chemical Engineering Economics.

[5] Ames National Laboratory. (2020, March 26). It's all part of the Grind: CMI's new hard drive Shredder serves up plenty of material for recycling science. Ames Laboratory. https://www.ameslab.gov/news/it-s-all-part-of-the-grind-cmi-s-new-hard-drive-shredder-serves-up-plenty-of-material-for

[6] Loh, H.P., Lyons, Jennifer, White, Charles W.. Process Equipment Cost Estimation Final Report. United States: N. P., 2002. Web.

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