Supporting information for

Self-Powered Aluminium Batteries for Sustainable Water Treatment: Performance, Mechanisms, and Techno-Economic Assessment

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S1. Parameters, calculation, and sensitivity analysis of TEA

S1.1 Capital expenditure and operational expenditure analysis

Table S1. Parameter selection for scene settings in TEA.

Parameter	Value	Unit	Ref
Daily processing capacity*	0.4	$m^3 \cdot d^{-1}$	[1]
Unit price of waste aluminium	1.49	$\$ \cdot kg^{-1}$	[2]
Unit price of waste aluminium processing	0.2	$\$ \cdot kg^{-1}$	[3]
Al content in waste aluminium	95.17	%	[2]
Unit price of commercial aluminium	79.7	$\$ \cdot kg^{-1}$	[2]
Unit price of commercial aluminium processing	2.5	$\$ \cdot kg^{-1}$	[3]
Al content in commercial aluminium	74.07	%	[2]
Lifespan of battery	1	year	-
Unit price of aluminium phosphate	1.3	$\$ \cdot kg^{-1}$	[4]
Unit output of aluminium phosphate**	0.354	$kg \cdot m^{-3}$	[2]
Maintenance and labour industry coefficients***	5	%	[5]
Electrolyte (NaCl) consumption	0.5	$kg \cdot m^{-3}$	[6]
Unit price of electrolyte (NaCl)	0.025	$\$ \cdot kg^{-1}$	[7]
Reactor area	10	m^2	-
Power density of waste aluminium	23.02	$mW \cdot g^{-1}$	[2]
Power density of commercial aluminium	0.613	$mW \cdot g^{-1}$	[2]
Unit price of electricity	0.1	$\$ \cdot kWh^{-1}$	[8]

Table S2. Parameter selection for waste aluminium self-powered system in TEA.

Parameter	Value	Unit	Ref
Waste aluminium consumption	0.03	$kg \cdot m^{-3}$	[9]
Cost proportion of motor components	10	%	[10]
Cost proportion of installation	30	%	[11]
Indirect cost proportion	5	%	[12]
Reactor equipment factor	800	$\$ \cdot d \cdot m^{-3}$	-
Quality of waste aluminium in the reactor	30.76	g	[2]

Table S3. Parameter selection for commercial aluminium self-powered system in TEA.

Parameter	Value	Unit	Ref
Commercial aluminium consumption	0.03	$kg \cdot m^{-3}$	[9]
Cost proportion of motor components	15	%	[10]
Cost proportion of installation	35	%	[11]
Indirect cost proportion	8	%	[12]
Reactor equipment factor	1000	$\$ \cdot d \cdot m^{-3}$	-
Quality of commercial aluminium in the reactor	76530.61	g	[2]

Table S4. Parameter selection for conventional electrocoagulation system in TEA.

Parameter	Value	Unit	Ref
Waste aluminium consumption	0.0943	$kg \cdot m^{-3}$	[13]
Cost proportion of motor components*	20	%	[10]
Cost proportion of installation**	40	%	[11]
Indirect cost proportion***	10	%	[12]
Specific energy consumption	1	$kWh \cdot m^{-3}$	[14]
Reactor equipment factor	1200	$\$ \cdot d \cdot m^{-3}$	-

Table S5. Summary of computation and result used for TEA.

Method	Description	Computation and result
Waste aluminium self-powered system	Reactor equipment costs	= 800 ($\$\cdot d\cdot m^{-3}$) × 0.4 ($m^3\cdot d^{-1}$) = 320 $
	Other capital expenditure costs	= 320 (\$) × 10% + 320 (\$) × 30% + 320 (\$) × 5% = 144 $
	Aluminium consumption costs	= 0.03 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × (1.49+0.2) ($\$\cdot kg^{-1}$) / 95.17% = 7.778 $
	Electrolyte (NaCl) costs	= 0.5 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × 0.025 ($\$\cdot kg^{-1}$) = 1.825 $
	Maintenance, repairs and labour costs	= (320 + 144) (\$) × 5% = 23.200 $
	Aluminium phosphate revenue	= 0.354 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × 1.3 ($\$\cdot kg^{-1}$) × (1+28%) = 86.002 $
	Electricity revenue	= 30.76 (g) × 23.02 ($mW\cdot g^{-1}$) × 8760 ($h\cdot y^{-1}$) / 10^6 × 0.1 ($\$\cdot kWh^{-1}$) = 0.620 $
Commercial aluminium self-powered system	Reactor equipment costs	= 1000 ($\$\cdot d\cdot m^{-3}$) × 0.4 ($m^3\cdot d^{-1}$) = 400 $
	Other capital expenditure costs	= 400 (\$) × 15% + 400 (\$) × 35% + 400 (\$) × 8% = 232 $
	Aluminium consumption costs	= 0.03 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × (79.7+2.5) ($\$\cdot kg^{-1}$) / 74.07% = 486.075 $
	Electrolyte (NaCl) costs	= 0.5 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × 0.025 ($\$\cdot kg^{-1}$) = 1.825 $
	Maintenance, repairs and labour costs	= (400 + 232) (\$) × 5% = 31.600 $
	Aluminium phosphate revenue	= 0.354 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × 1.3 ($\$\cdot kg^{-1}$) = 67.189 $
	Electricity revenue	= 76530.61 (g) × 0.613 ($mW\cdot g^{-1}$) × 8760 ($h\cdot y^{-1}$) / 10^6 × 0.1 ($\$\cdot kWh^{-1}$) = 41.096 $
Conventional electrocoagulation system	Reactor equipment costs	= 1200 ($\$\cdot d\cdot m^{-3}$) × 0.4 ($m^3\cdot d^{-1}$) = 480 $
	Other capital expenditure costs	= 480 (\$) × 20% + 480 (\$) × 40% + 480 (\$) × 10% = 336 $
	Aluminium consumption costs	= 0.0943 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × (1.49+0.2) ($\$\cdot kg^{-1}$) / 95.17% = 24.448 $
	Electrolyte (NaCl) costs	= 0.5 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × 0.025 ($\$\cdot kg^{-1}$) = 1.825 $
	Maintenance, repairs and labour costs	= (480 + 336) (\$) × 5% = 40.800 $
	Aluminium phosphate revenue	= 0.354 ($kg\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × 1.3 ($\$\cdot kg^{-1}$) × (1+28%) = 86.002 $
	Electricity costs	= 1.0 ($kWh\cdot m^{-3}$) × 365 (d) × 0.4 ($m^3\cdot d^{-1}$) × 0.1 ($\$\cdot kWh^{-1}$) = 14.6 $

S1.2 The calculation of levelized cost of treatment (LCOT)

Levelized cost of treatment (LCOT) is calculated based on the TEA benchmark parameters (annualised CAPEX + OPEX), as well as the calculation formula. The TEA model is assumed to adopt a standard linear structure and will be verified later. And the results of the calculation of LCOT are shown in **Table S6**.

$$LCOT = \frac{\sum \mathit{(Annualized\ CAPEX + OPEX) - Byproduct\ revenue}}{\mathit{Annual\ water\ volume}}$$

* MERGEFORMAT (S1)

$$\mathit{Annualized\ CAPEX} = \mathit{CAPEX} \times \mathit{CRF}$$

* MERGEFORMAT (S2)

Capital recovery factor (CRF) is used to amortise the initial investment (CAPEX) over the project's lifespan in an equal annualised manner.

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{S3}$$

where:

i: Annual discount rate. In this study, it is calculated as 0.1;

n: Economic lifespan of the project (year). In this study, it is calculated as 1 year.

Among them, each cost item (such as equipment, electrodes, and maintenance) is directly and linearly added up to the total cost, without any nonlinear interactions (such as exponential decay or threshold effects).

Table S6. Baseline of LCOT in different systems in TEA.

System	LCOT ($\$\cdot m^{-3}$)
Waste aluminium self-powered system	3.127
Commercial aluminium self-powered system	7.578
Conventional electrocoagulation system	6.118

S1.3 Sensitivity analysis

The sensitivity analysis assumes that each cost item has a linear relationship with the total cost, and this holds true under small range perturbations (±20%). This method is simple in calculation and has a clear physical meaning, and is widely used in TEA sensitivity analysis, especially suitable for evaluating the impact of parameter uncertainty on LCOT [15–17].

1. Sensitivity Coefficient (SC):

$$SC = \frac{Annual\ cost\ of\ each\ indicator}{CAPEX_{total} + OPEX_{total}} \tag{S4}$$

2. LCOT disturbance value:

$$LCOT \pm 20\% = LCOT_{baseline} \pm (LCOT_{baseline} \times SC \times 0.2) \tag{S5}$$

3. The variation range of LCOT:

$$\Delta LCOT_i(\%) = \pm\left(SC \times 20\%\right) \tag{S6}$$

To verify the relationship assumed above, by perturbing the electrode cost by ±20% and comparing it with the baseline LCOT, the results show that ΔLCOT maintains a strict linear relationship with the input change, proving that the linear relationship between each cost item and the total cost holds under small perturbations. This conclusion was also consistent in other electrode types and treatment scenarios [18,19].

If the model incorporates nonlinearity (such as economies of scale), it can switch to global sensitivity methods [20]. This study has a narrow parameter range, and the linear method is sufficient.

Table S7. Summary of results used for sensitivity analysis in TEA.

System	Expenditure	Indicator	Annualized cost ($\$\cdot y^{-1}$)	SC
Waste aluminium self-powered system	CAPEX	Reactor equipment	320.000	0.780
		Electrode assembly	32.000	0.078
		Installation	96.000	0.234
		Indirect costs	16.000	0.039
		Total	464.000	
	OPEX	Aluminium consumption	7.778	0.019
		NaCl consumption	1.825	0.004
		Labor	23.200	0.057
		Byproduct revenue	-86.622	-0.211
		Total	-53.819	
Commercial aluminium self-powered system	CAPEX	Reactor equipment	400.000	0.383
		Electrode assembly	60.000	0.058
		Installation	140.000	0.134
		Indirect costs	32.000	0.031
		Total	632.000	
	OPEX	Aluminium consumption	486.075	0.466
		NaCl consumption	1.825	0.002
		Labor	31.600	0.030
		Byproduct revenue	-108.285	-0.104
		Total	411.215	
Conventional electro-coagulation system	CAPEX	Reactor equipment	480.000	0.591
		Electrode assembly	96.000	0.118
		Installation	192.000	0.237
		Indirect costs	48.000	0.059
		Total	816.000	
	OPEX	Aluminium consumption	24.448	0.030
		NaCl consumption	1.825	0.002
		Labor	40.800	0.050
		Energy consumption	14.600	0.018
		Byproduct revenue	-86.002	-0.106
		Total	-4.329	

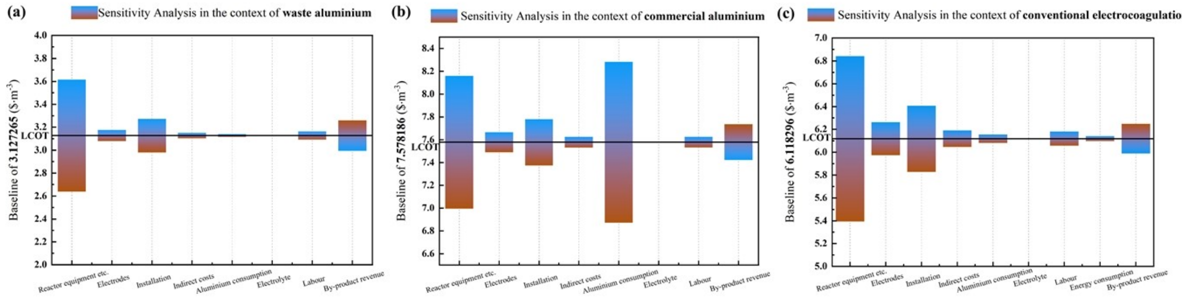

Fig. S1. Sensitivity analysis in the context of waste, commercial aluminium, and conventional electrocoagulation. **(a)** The sensitivity results of the system using waste aluminium as the anode material. **(b)** The sensitivity results of the system using commercial aluminium electrodes as raw materials. **(c)** The sensitivity results of the conventional electrocoagulation system.

The sensitivity analysis applies ±20% perturbations to key parameters (such as reactor equipment, electrode cost, current density, operation and maintenance costs, and byproduct revenue), and evaluates their relative impact on the LCOT one by one, presenting the results in a visual form (**Fig. S1a-c** and **Table S7**). This method is widely used in TEA [21,22], and the verification of the benchmark model confirmed that the cost items have a linear relationship with the total cost. The results show that the baseline LCOTs of the three systems are 3.127 $\$\cdot m^{-3}$, 7.572 $\$\cdot m^{-3}$, and 6.118 $\$\cdot m^{-3}$, respectively (**Table S6**), demonstrating a clear cost hierarchy among the three systems. Among them, the LCOT of the waste aluminium system is the most stable, indicating that it has significant advantages in both economic and operational stability, which is attributed to the dual buffering of low-cost raw materials and byproduct revenue.

In the waste aluminium self-powered system (**Fig. S1a)**, the most sensitive factor for LCOT is the cost of reactor equipment (SC = 0.780), while it is almost insensitive to operating parameters such as current density, power consumption, and electrolyte cost, revealing that its structure is mainly controlled by the one-time investment in equipment, and the operation is extremely stable, with negative buffering provided by byproduct revenues, enabling the overall economic performance to exhibit the strongest ability to resist fluctuations. In contrast, the LCOT of the commercial aluminium system (**Fig. S1b)** is most sensitive to the cost of aluminium raw materials (SC = 0.466), while it is least sensitive to current density, energy consumption, and electrolyte cost, indicating that its economic structure is dominated by the high price of commercial aluminium which makes it highly vulnerable to fluctuations in the material market and lacking a stable mechanism for resisting shocks. In conventional electrocoagulation systems (**Fig. S1c)**, LCOT is most sensitive to the cost of reactor equipment (SC = 0.591), while it is the least sensitive to operating parameters such as energy consumption and current density. This highly equipment-dominated cost structure implies that its economic performance is mainly limited by initial capital investment, with limited contribution from the operational side, which it difficult to reduce the overall cost by optimising the operation.

S2. Radar chart of three systems

Based on the calculations from **Table S5**, applying these results to the TEA analysis calculations and summaries yields outcomes for different systems (**Table S8**). To clearly grasp the economic advantages and disadvantages of different systems through radar charts, we standardised the data to eliminate interference from units of measurement and numerical ranges, ensuring fairness, objectivity, and intuitiveness in the analysis, as shown in **Eqn. (S7)** [23].

$$Normalization\ sustainability\ metrics = \frac{a_{max} - a_i}{a_{max} - a_{min}} \times 100\% \tag{S7}$$

Where a_i denotes the actual value of a given method for a specific metric, while a_{max} and a_{min} represent the highest and lowest observed values of that metric across all technologies being compared.

Table S8. Summary of water treatment parameters for different aluminium-based systems

System	Electricity revenue (%)	Electrode cost savings (%)	Capital investment Savings (%)	Byproduct revenue intensity (%)	Unit processing cost savings (%)
Waste aluminium self-powered system	27.33	100	100	97.22	100
Commercial aluminium self-powered system	100	0	52.27	0	0
Conventional electrocoagulation system	0	96.52	0	100	36.58

The electricity revenue indicator reflects the economic expenditure of electricity consumption or the economic benefits brought by power generation. Electrode Cost Savings represents the annual cost savings resulting from electrode wear, primarily evaluated based on aluminium consumable cost data. A higher value indicates more significant savings in electrode costs. Capital Investment Savings represents cost savings on initial equipment procurement, construction, and other related expenses, primarily evaluated based on capital expenditure cost data. The byproduct revenue intensity metric represents the revenue generated from byproduct sales per cubic meter of treated wastewater. A higher value indicates a stronger economic contribution from the byproduct, as shown in **Eqn. (S8)** [24].

$$Byproduct\ Revenue\ Intensity = \frac{(Y_P \times P_P)}{Q_{annual}} \tag{S8}$$

Where:

Y_p: Total annual aluminium phosphate recovered ($kg \cdot y^{-1}$);

P_p: Market price of aluminium phosphate ($\$ \cdot kg^{-1}$);

Q_{annual}: Annual wastewater treatment volume ($m^3 \cdot y^{-1}$).

Unit Processing Cost Savings represents the cost savings per cubic meter of wastewater treated, derived primarily from the total treatment cost and the volume treated.

Typically, a radar chart provides an intuitive comparison of the technical and economic competitiveness across five dimensions for the waste aluminium self-powered system, conventional electrocoagulation system, and commercial aluminium self-powered system. A larger area on the radar chart indicates superior overall performance in that dimension.

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