ARPA-E Review: TEA Update

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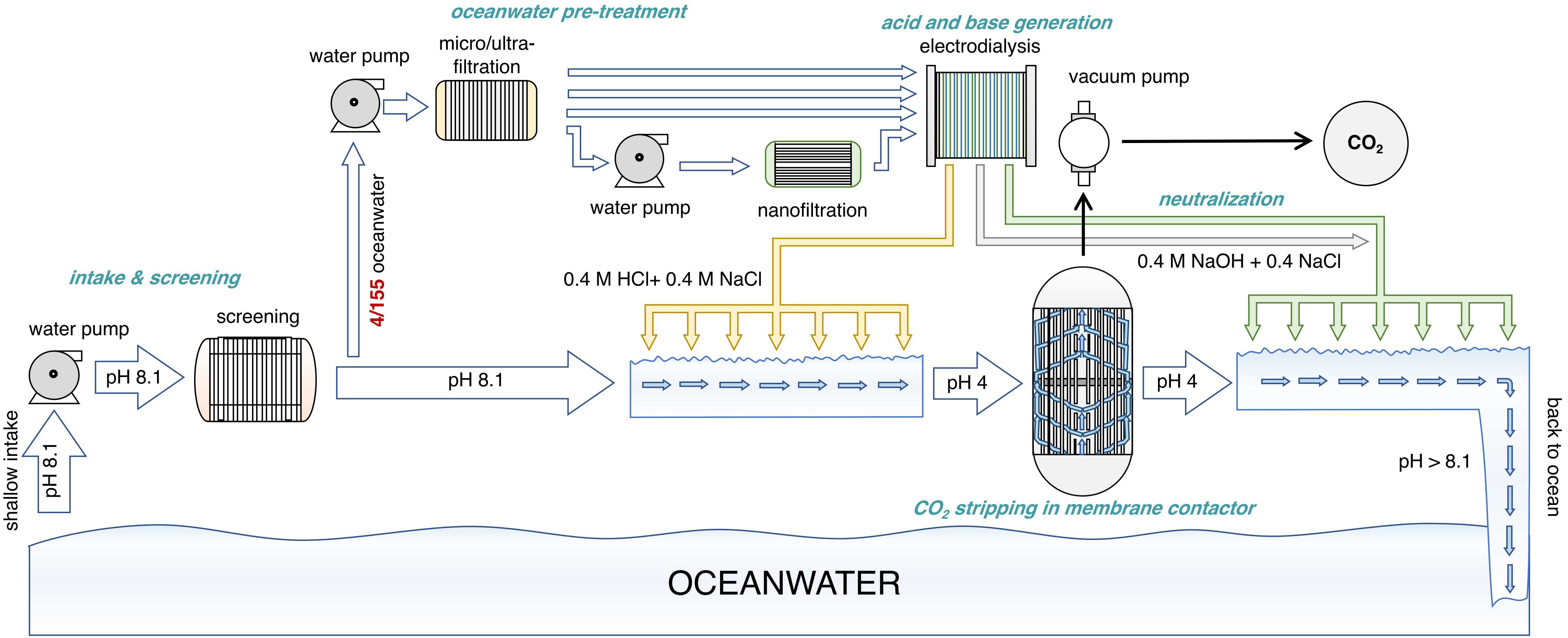
November 11, 2021

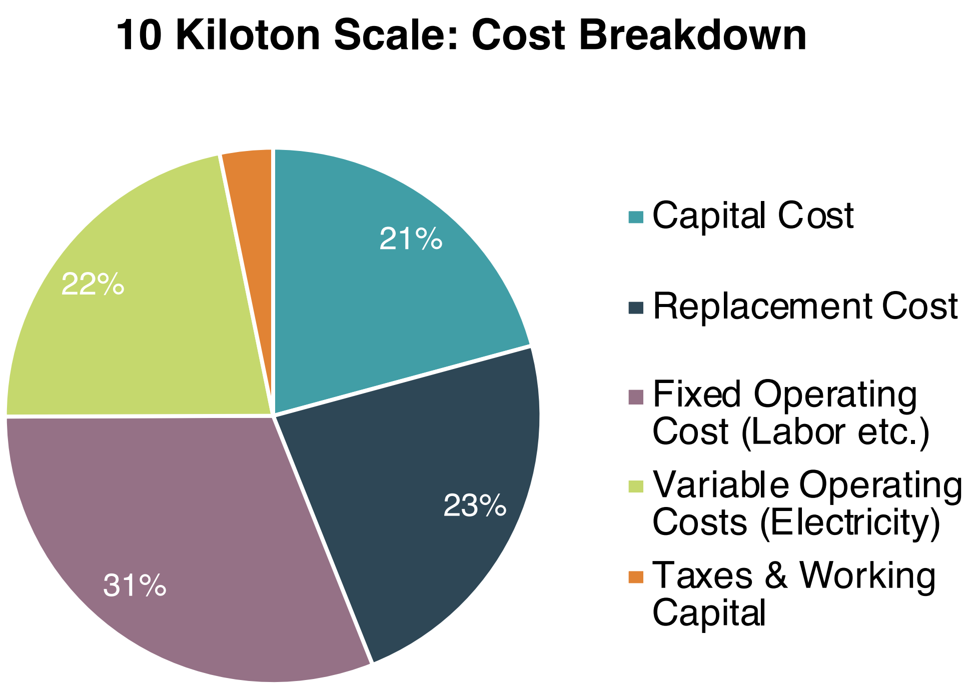
Current TEA is based on this system

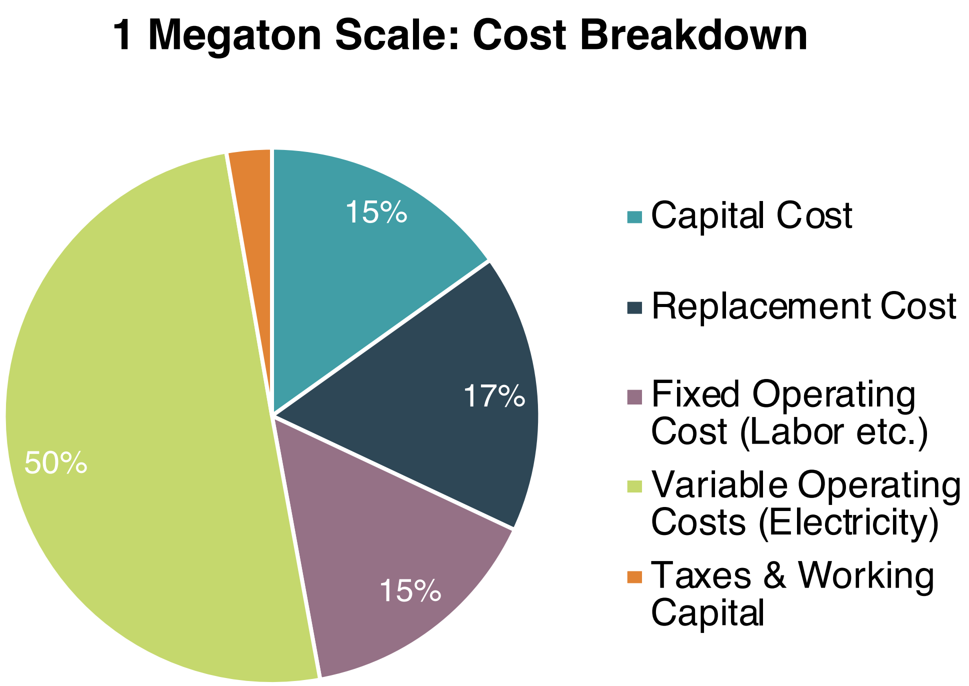


Key costs and parameter values

Item	Cost	Parameter	Value
Centrifugal pump (27,000 m^3/day)	$42,000	Oceanwater target pH**	4
Electrodialysis membrane cost	$0.05/$cm^2$	Membrane contactor efficiency	90%
Membrane contactor cost (1,920 m^3 oceanwater/day)	$6600	Electrodialyzer current density**	500 mA/cm^2
Vacuum pump cost (240,000 m^3/day)	$252,000	Electrodialyzer voltage**	2.5 V per cell
Intake piping* (400,000 m^3/day)	$420,000	Liquid ring vacuum pump base pressure**	35 Torr
Microscreening* (400,000 m^3/day)	$3,247,000	Scale	10 kiloton/yr (**current**) 1 megaton/yr (**future**)
Microfiltration* (10,000 m^3/day)	$1,555,000	Electricity price	$0.04/kWh (**current**) $0.02/kWh (**future**)
Nanofiltration (3,000 m^3/day)	$135,000	Labor cost (12.5 full-time employees at 10-kiloton/yr scale)	$40,000/year average salary

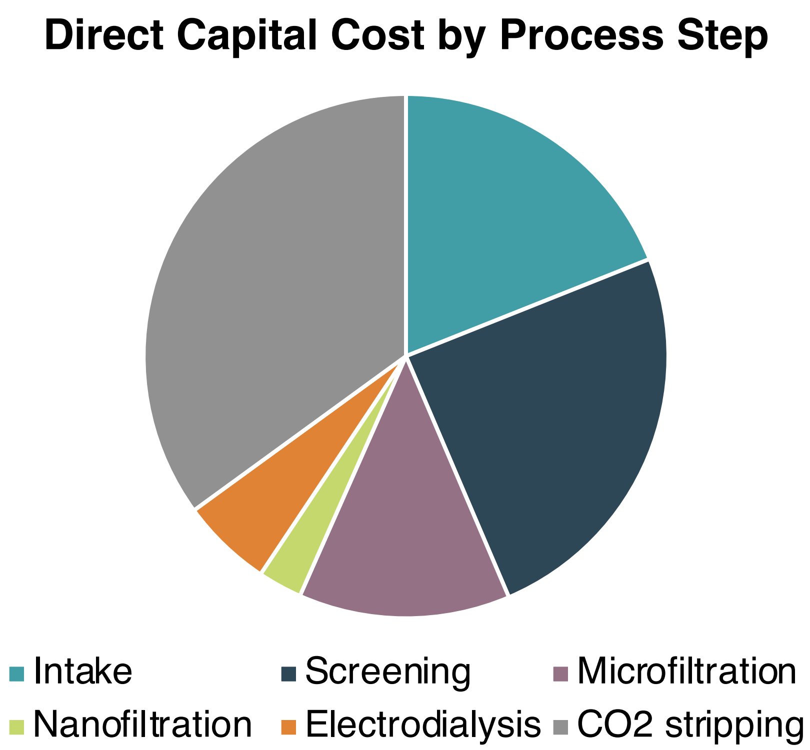
Current cost is **$537/ton,** future cost is **$117/ton CO_2**

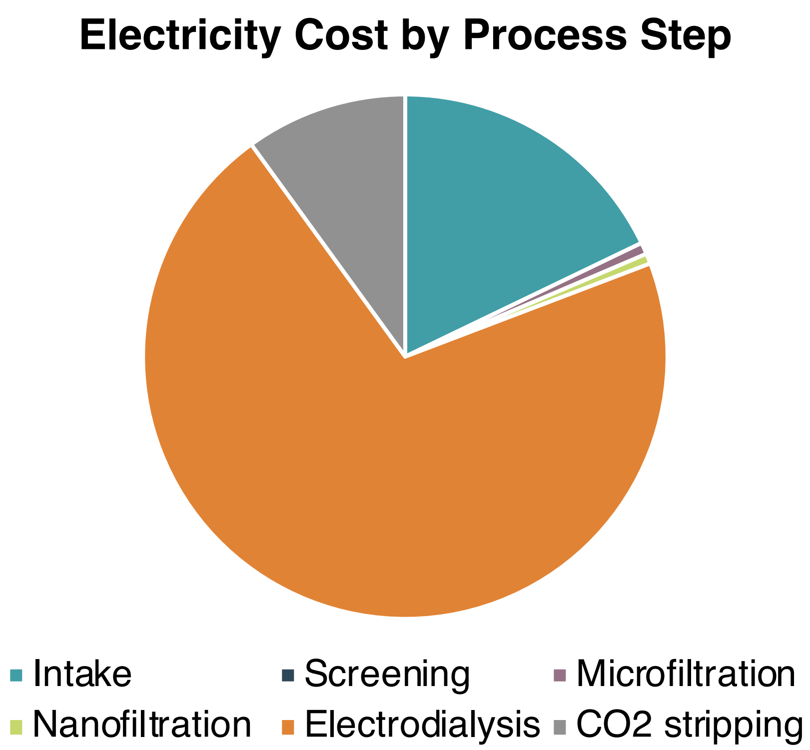




→ CapEx scales according to 6/10 rule, so becomes less significant at larger scales

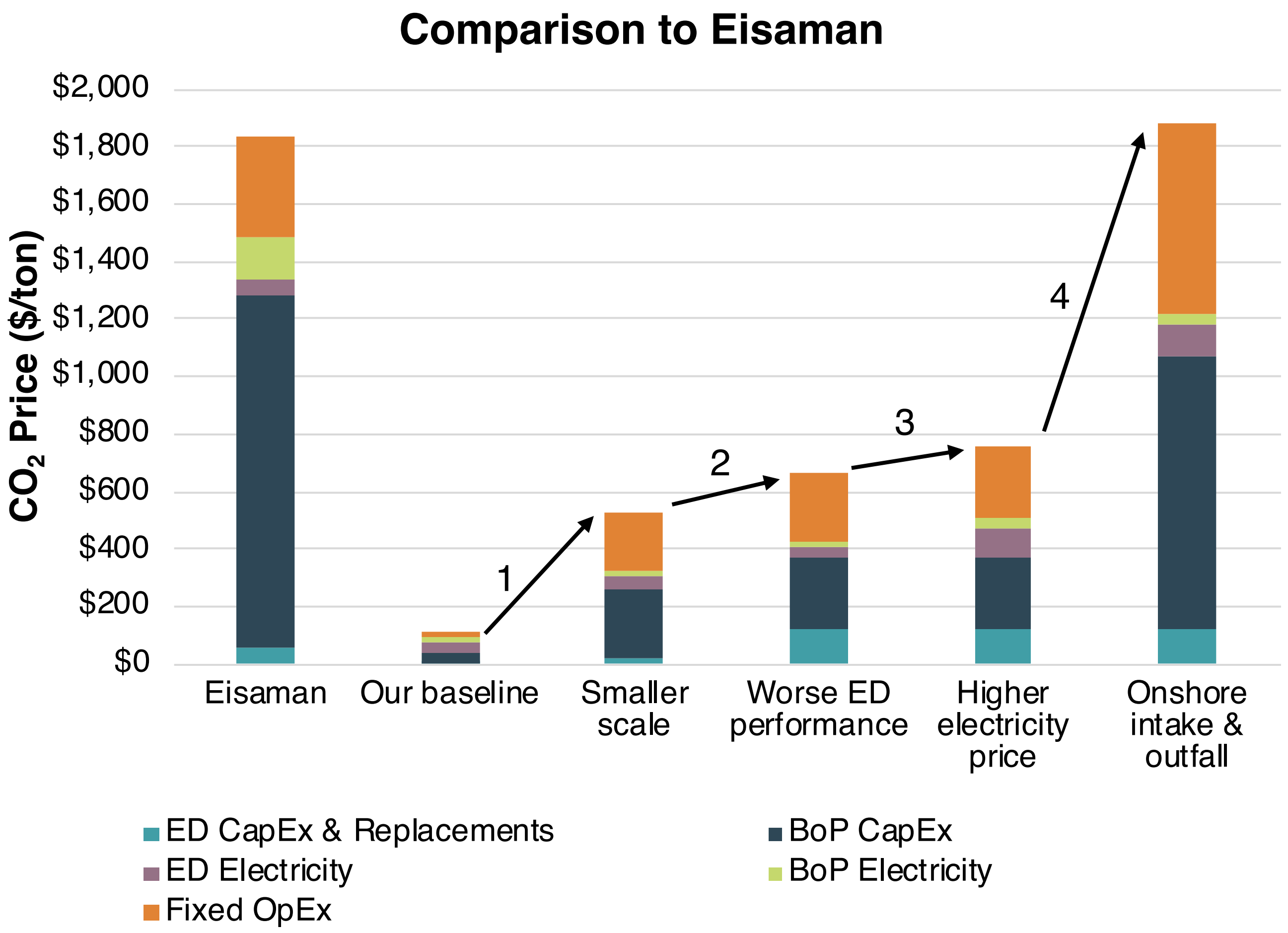
CO_2 stripping dominates CapEx, electrodialysis electricity dominates OpEx





→ Within each category (CapEx vs. electricity), breakdown by process step is the same at different scales

We achieve much lower CO_2 prices than previous papers (Eisaman *et al*) mostly due to larger scale, offshore intake



1. **Scale**
   1 megaton/year (us) → 7700 tons/year (them)

2. **Electrodialyzer current density**
   500 mA/cm^2 (us) → 100 mA/cm^2 (them)

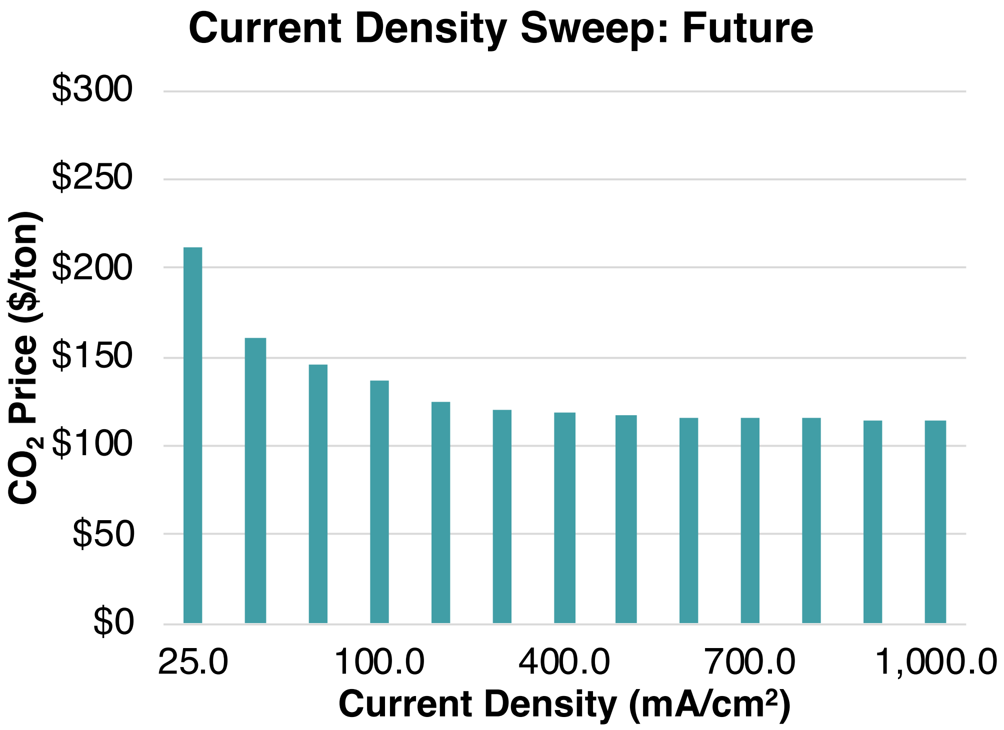
3. **Electricity cost**
   $0.02/kWh (us) → $0.04/kWh (them)

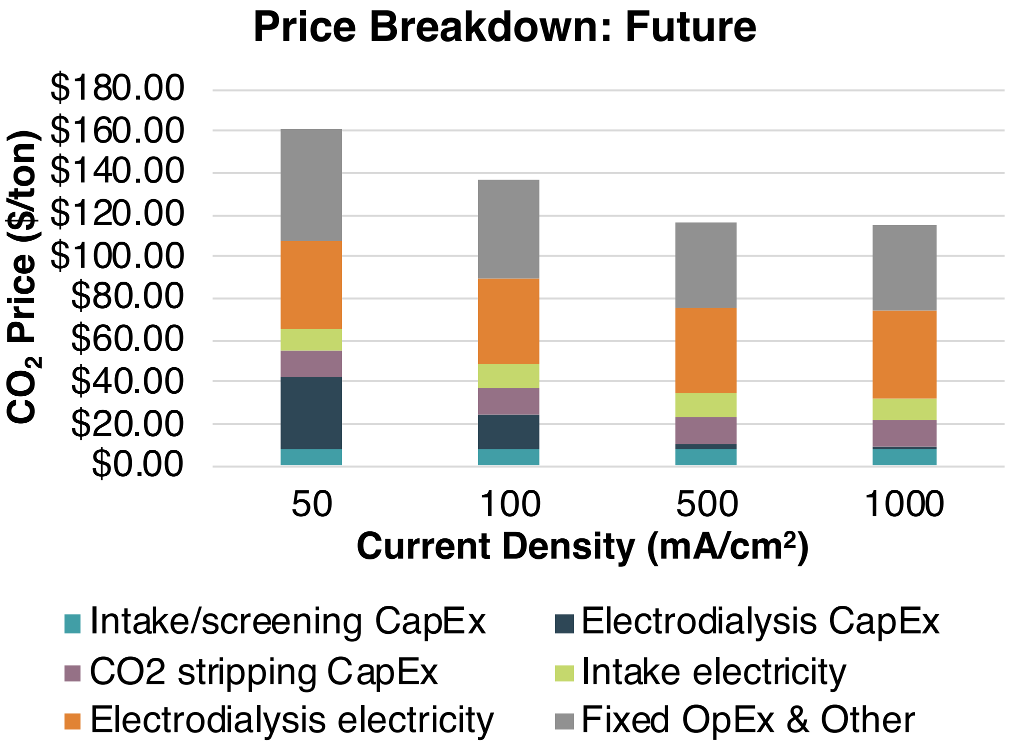
4. **Intake/outfall**
   20x higher intake/outfall costs due to onshore intake & outfall

Diminishing returns to increasing current density above 500 mA/cm^2 at megaton scale

Current density only affects electrodialyzer CapEx, not OpEx

Above 500 mA/cm^2, electrodialyzer CapEx (dark blue bars) becomes negligible (same finding holds at 10-kiloton scale)

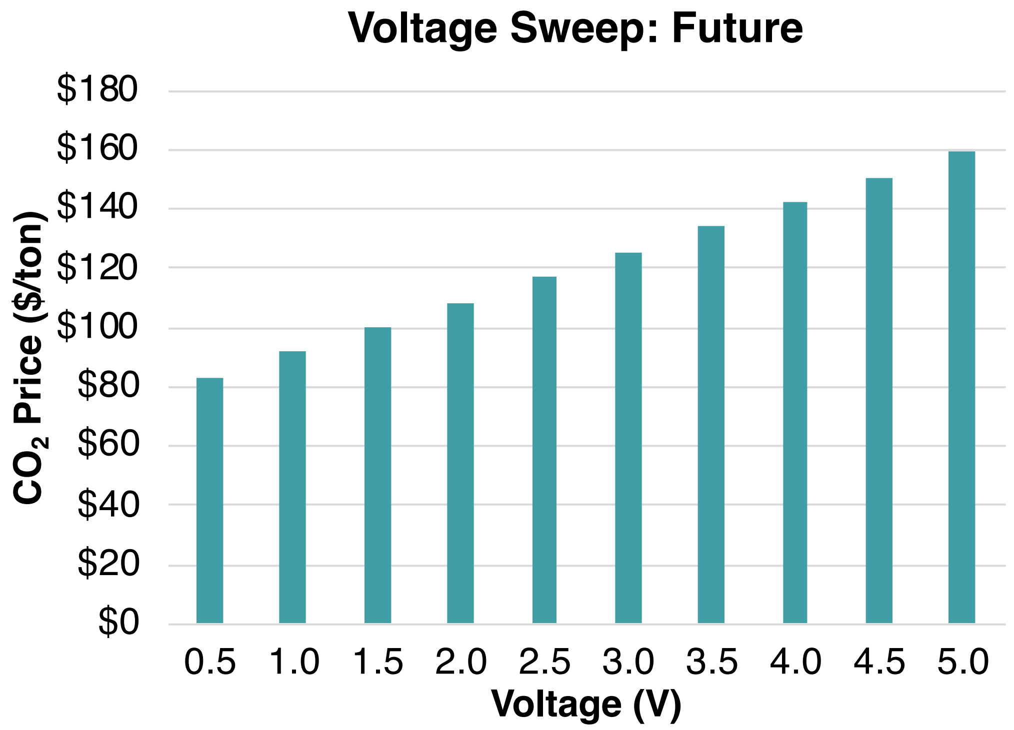


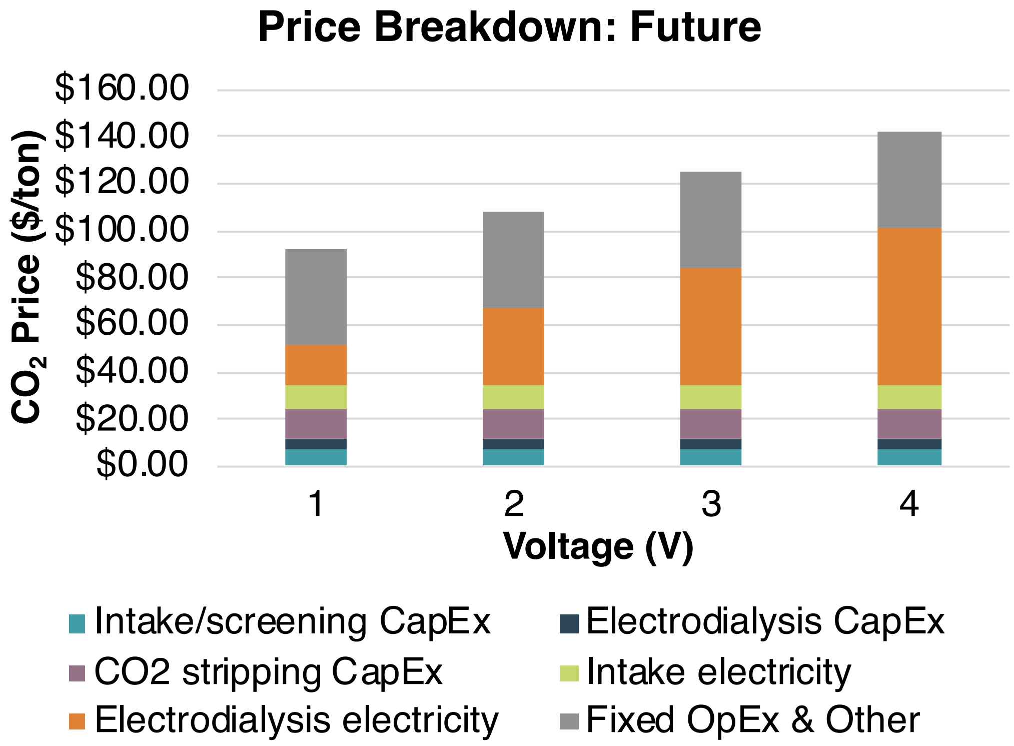


At megaton scale, reducing voltage reduces CO_2 price monotonically

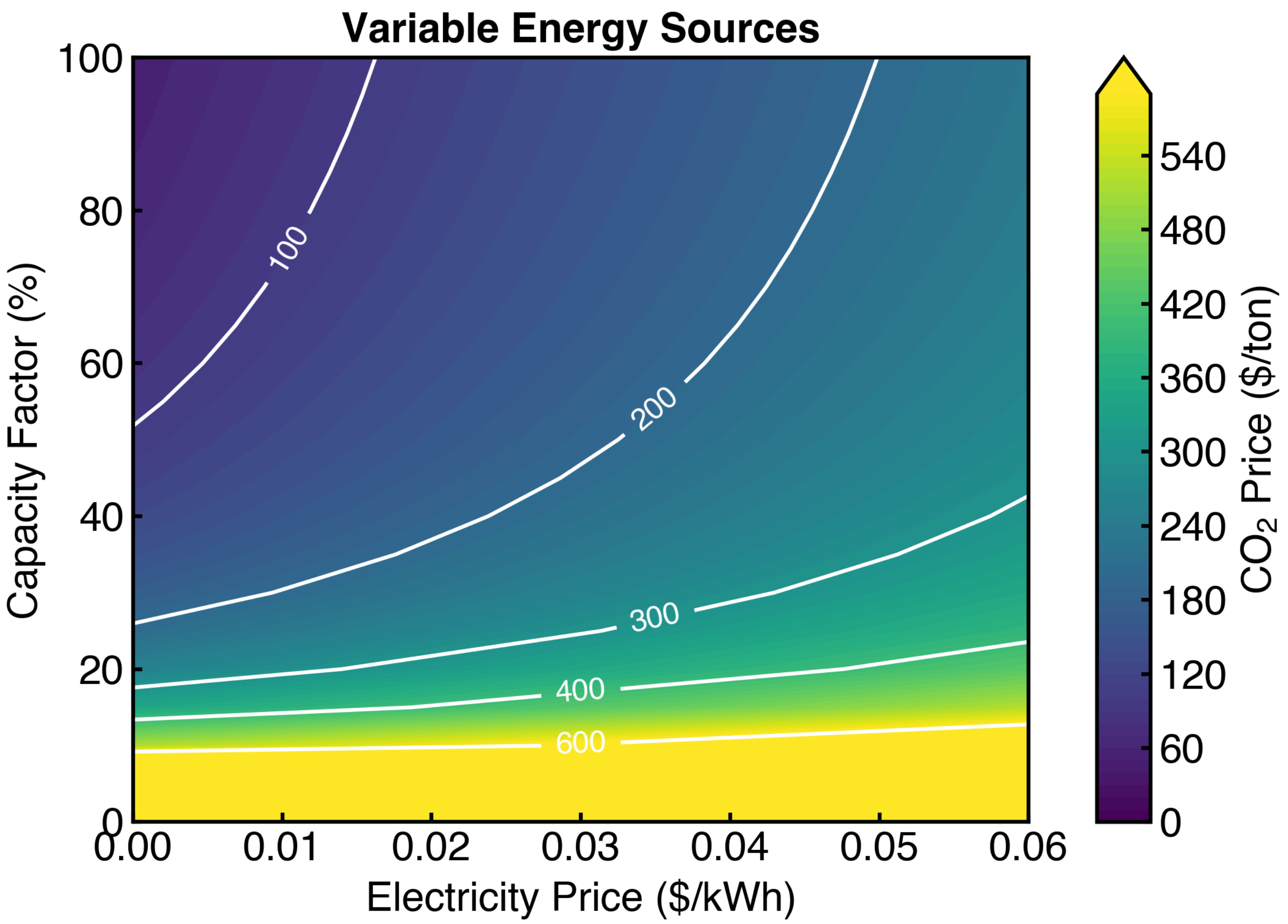
Voltage only affects electrodialyzer OpEx, not CapEx

Electrodialyzer electricity price alone varies with voltage & remains significant down to 1 V (same finding holds at 10-kiloton scale)





What if we have an electricity source that's almost free, but with a lower capacity factor?



- Renewables on grid may eventually lead to need for curtailment: using extra electricity when wind/solar are overproducing
- If electricity is free, we can have capacity factors as low as 50% and achieve less than $100/ton
- If we are paid to use electricity for optimizing grid load, we can have even lower capacity factors

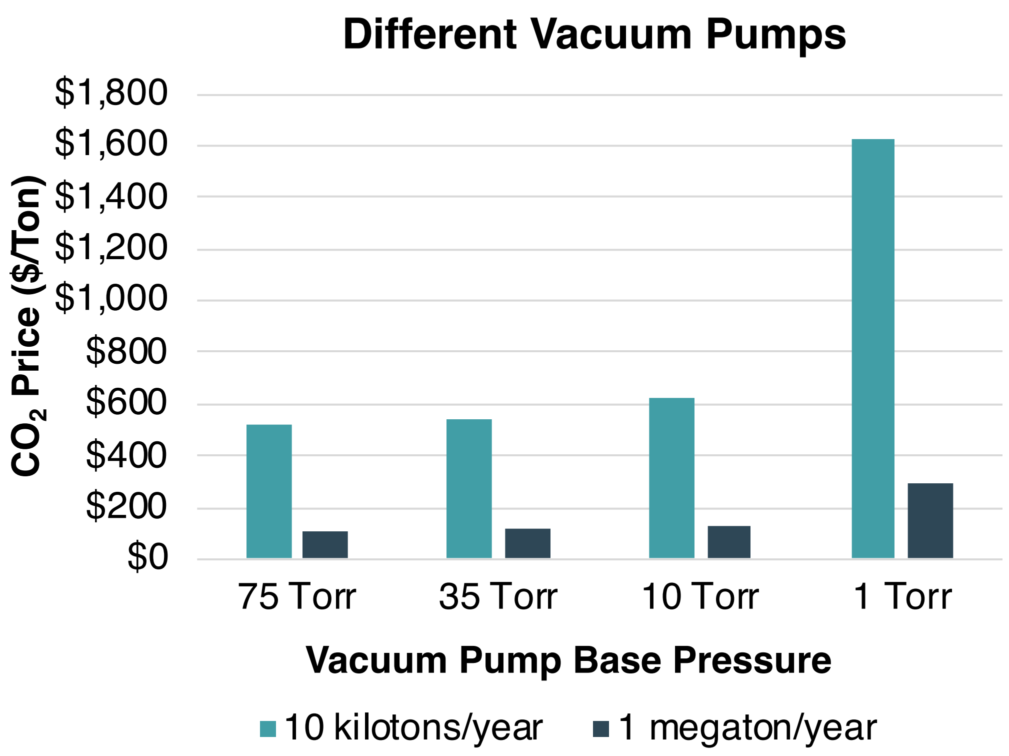
CO_2 cost is very sensitive to level of vacuum, because vacuum pumps have a maximum volumetric flow rate

- Most pumps have a maximum volumetric flow rate, since they are positive displacement pumps (remove a volume of gas over and over)

- At lower base pressures and the same **volumetric** flow rate, our **molar** flow rate becomes much smaller

- We need 10x as many pumps with the same max flow rate to get the same CO_2 throughput if we go from 10 Torr to 1 Torr

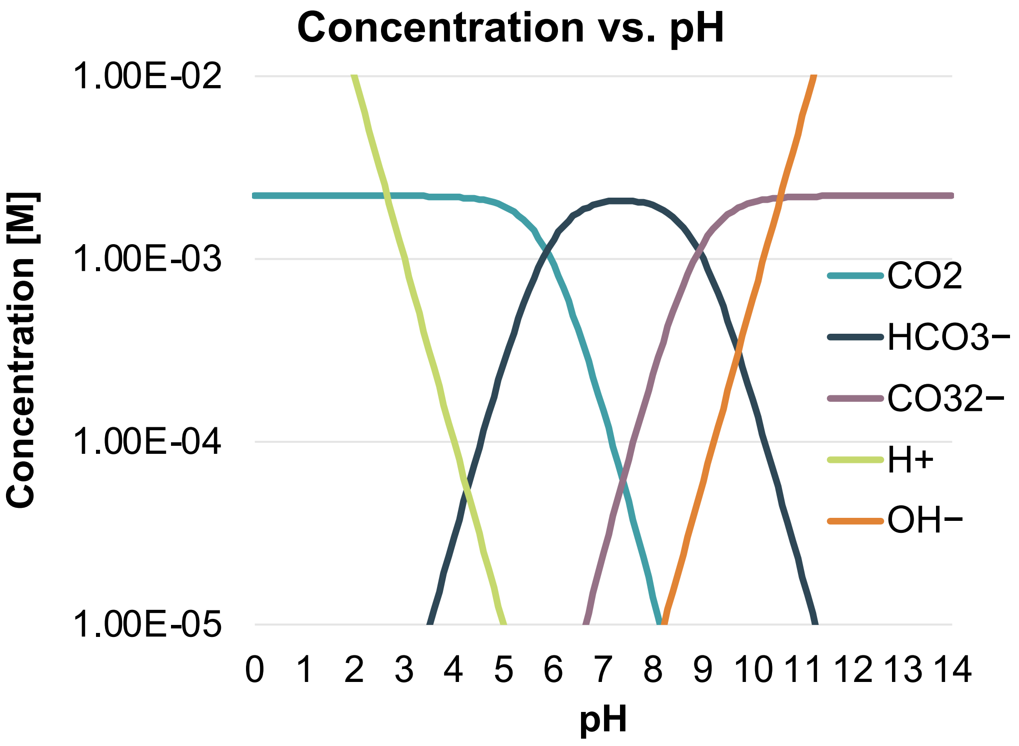
- Effect of increasing number of pumps becomes significant around 1 Torr

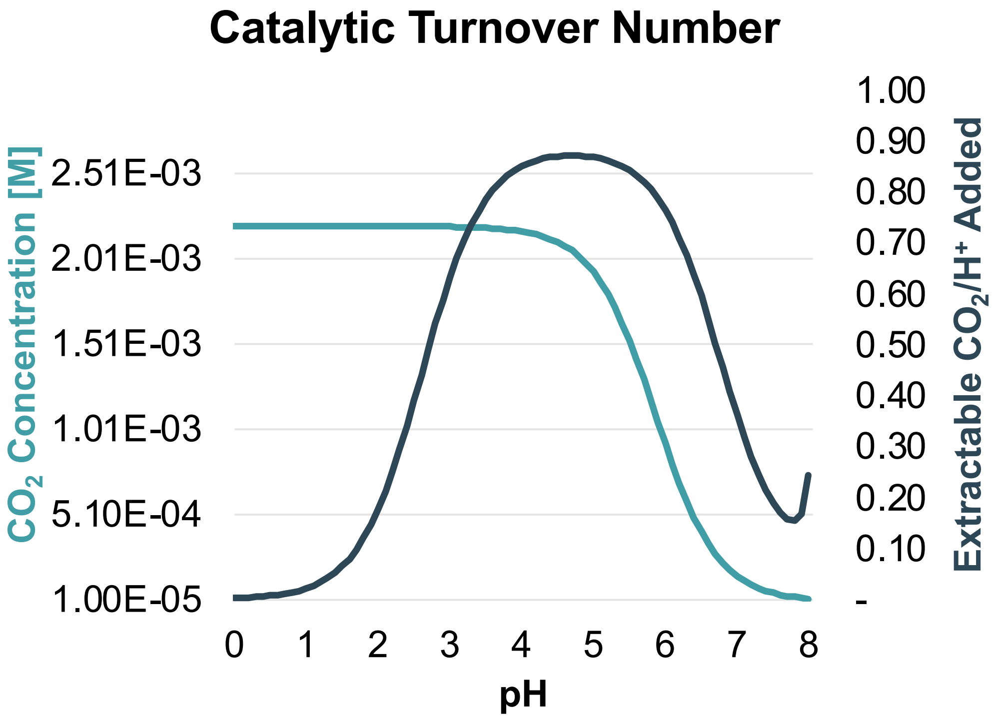


Key metric: catalytic turnover number, which is extractable CO_2 per H^+ added

Can also define a catalytic turnover factor $\mathrm{F_{CT}}$ that denotes the catalytic reaction rate enhancement

In equilibrium, $\mathrm{F_{CT}} = 1$. Out of equilibrium and catalyzed, $\mathrm{F_{CT}}$ could be greater than 1

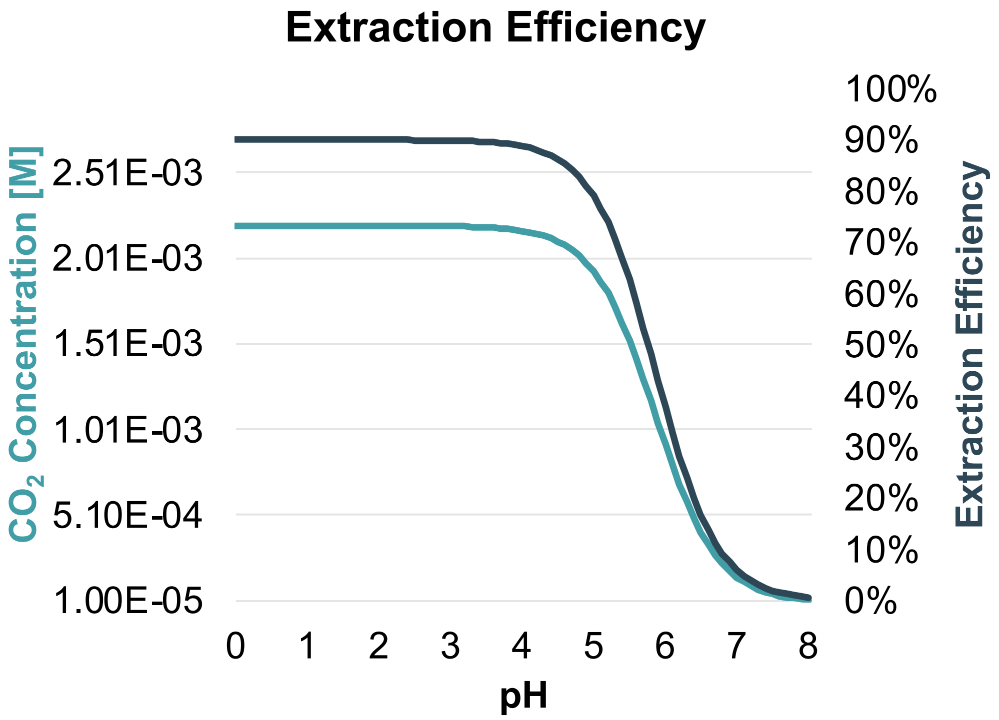


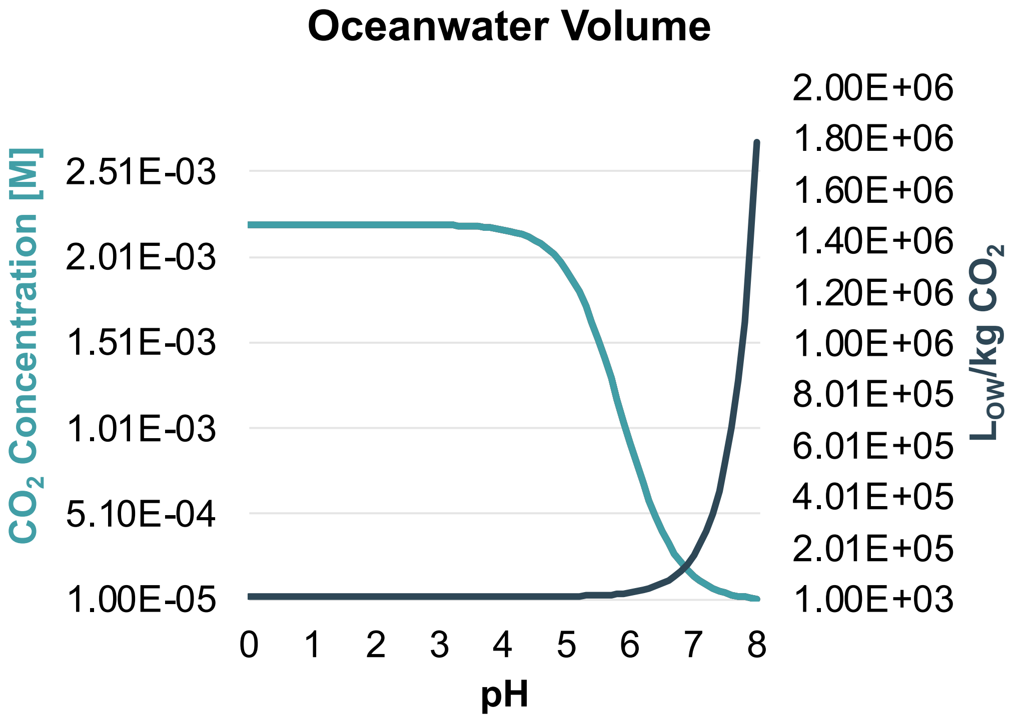


Extraction efficiency is CO_2 extracted per DIC in oceanwater

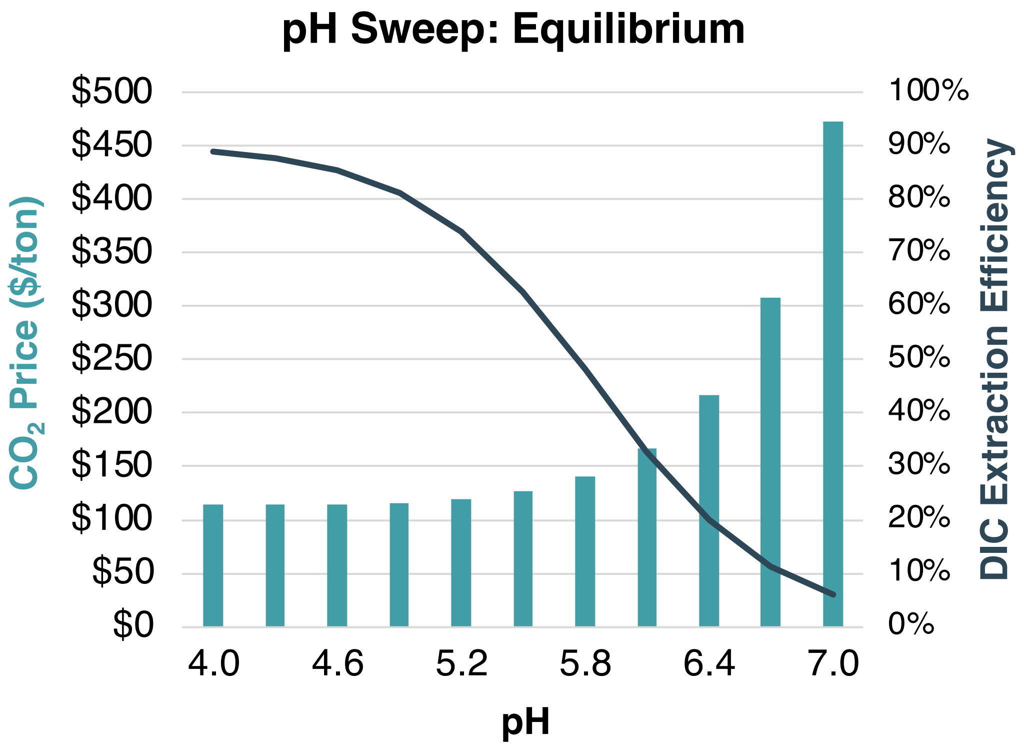
Equilibrium curves are shown here – clear why cost increases at higher pH (pumping huge oceanwater volumes)

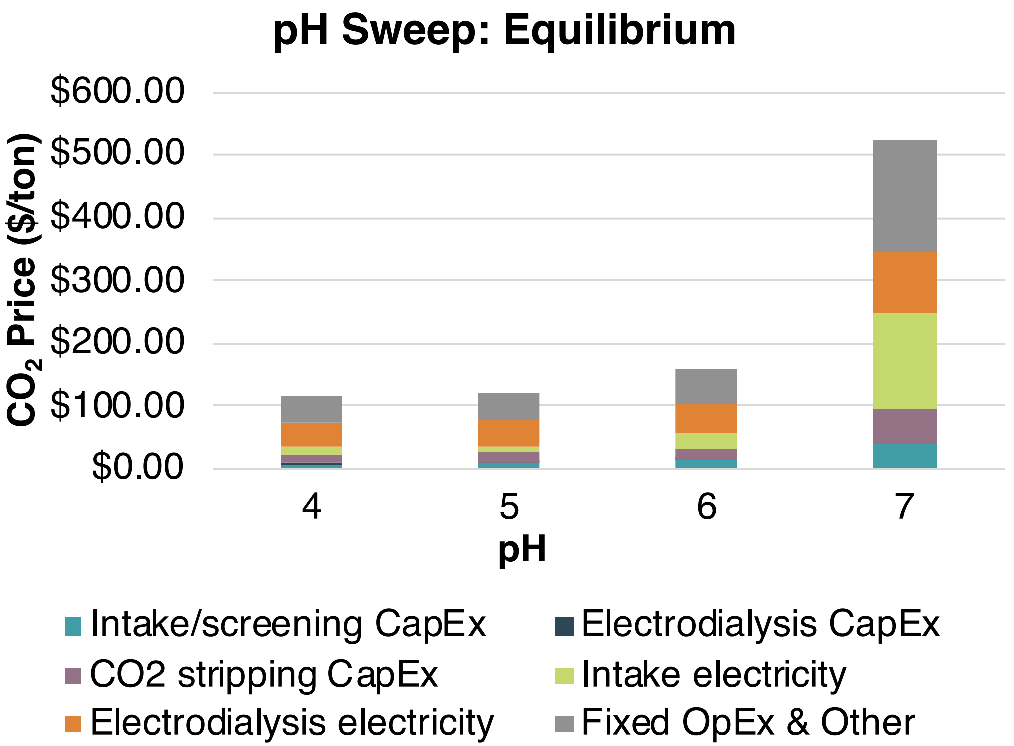
Out of equilibrium, extraction efficiency could be enhanced by a factor equal to the "catalytic turnover factor"





Assuming we can only extract the equilibrium concentration of CO_2 at a given pH, CO_2 price increases as pH increases

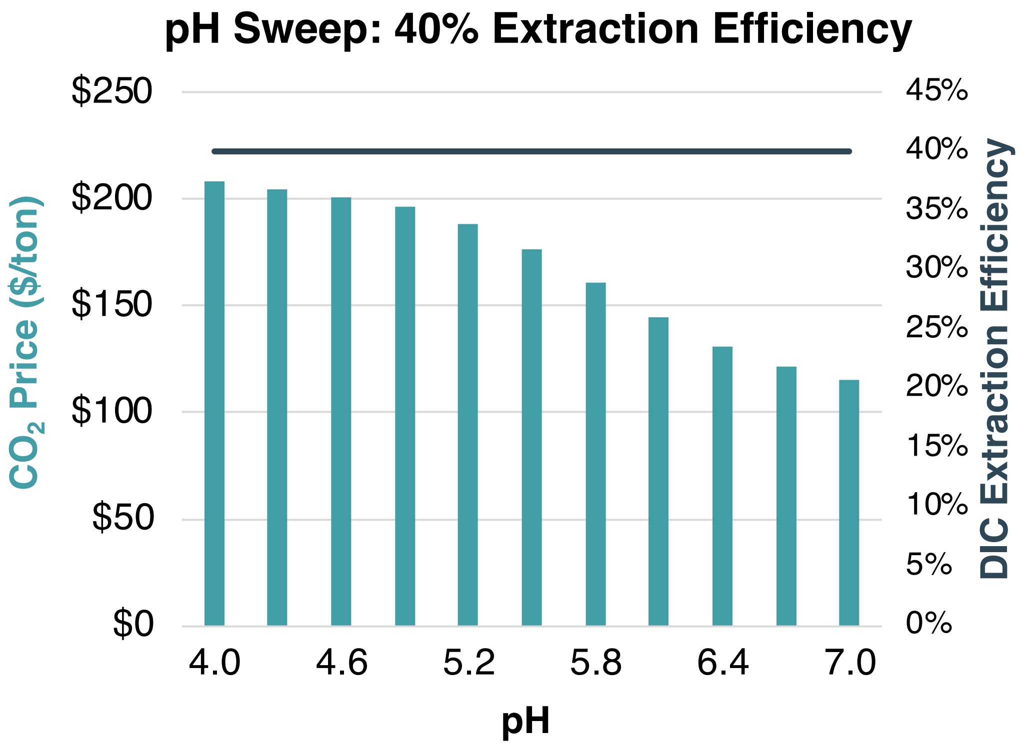


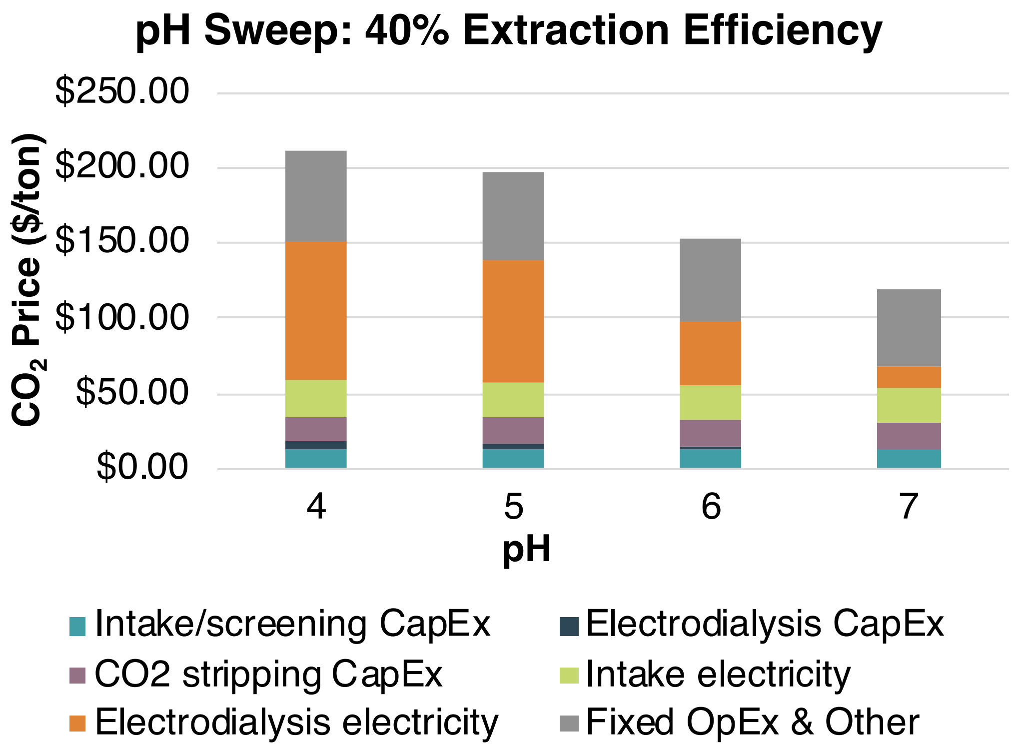


Due to decreased extraction efficiency

This mostly increases intake electricity costs (green bars) – at lower extraction efficiencies, we process more water

If we can achieve higher extraction efficiency at higher pH via catalysis, cost drops substantially

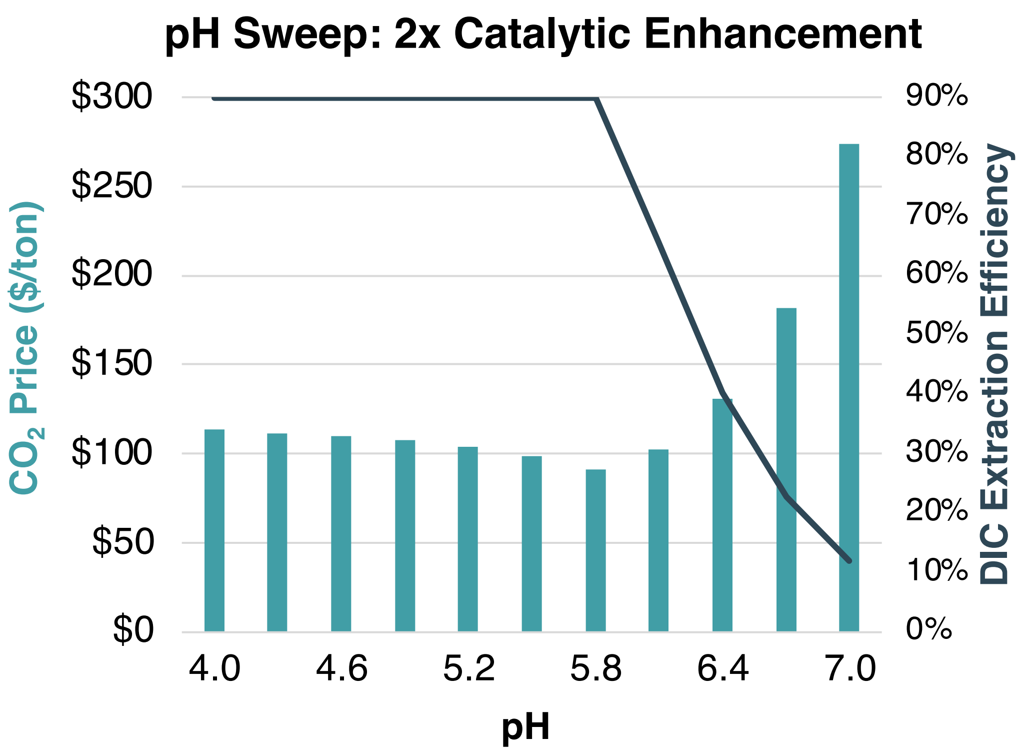


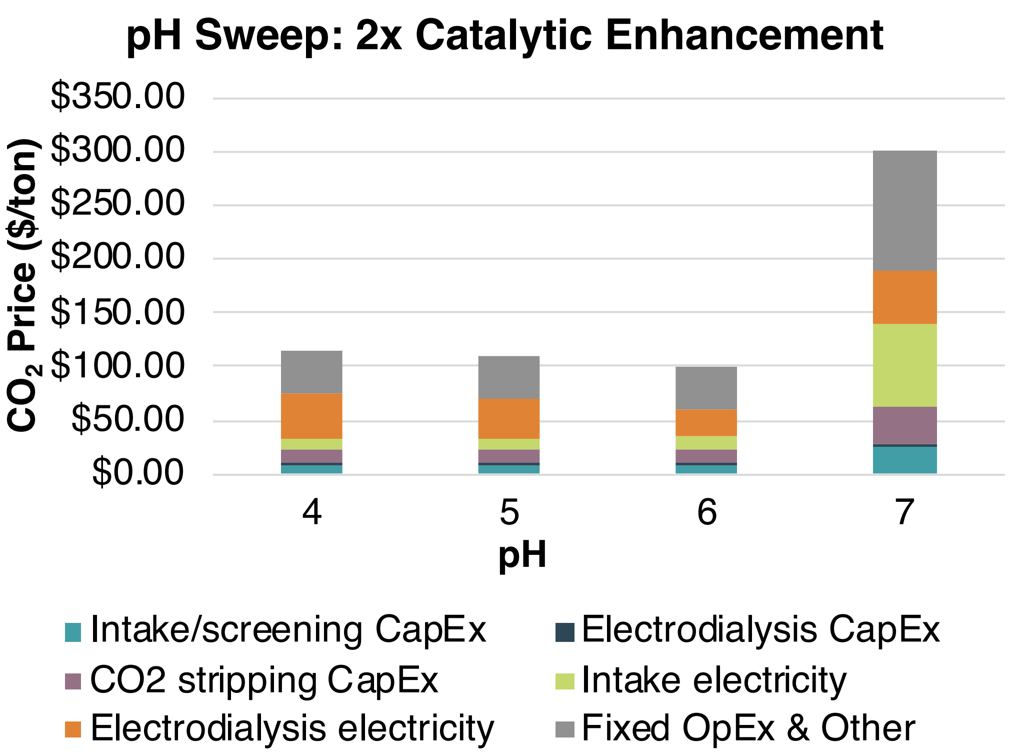


In this scenario, we have catalyzed CO_2 production (e.g. with a carbonic anhydrase mimic)

Price decreases as pH increases since we have to acidify a smaller fraction of the oceanwater through electrodialysis – leads to savings in electrodialysis electricity (orange bars)

Intermediate pH values between 4.0 and 8.1 are worth pursuing if we can achieve some small catalytic enhancement of CO_2 production





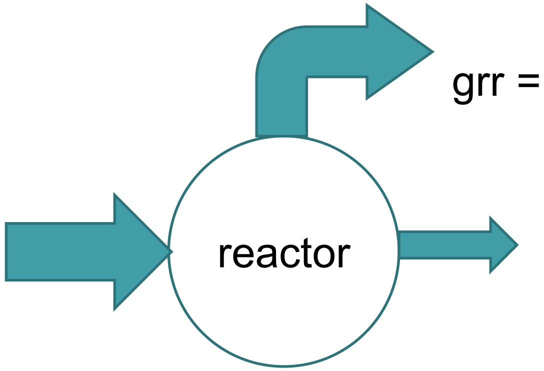
In this scenario, we have catalyzed CO_2 production by a factor of 2 (e.g. with a carbonic anhydrase mimic) and we can remove double the amount of CO_2 we could remove at equilibrium

This leads to lower CO_2 prices at intermediate pH (e.g. pH 6)

0D reactor model in COMSOL allows us to model steady-state operation of our system (developed by Leanna @ UCI)

$CO_2(g)$ flows out at
grr = gfr (s^{-1}) × $[CO_2(aq)]_{ss}$ (M)

H^+, $OH^–$, $CO_2(aq)$, H_2CO_3,
and $HCO_3^–$ flow in at
lfr (s^{-1}) × $[species]_{eq}$ (M)



H^+, $OH^–$, $CO_2(aq)$, H_2CO_3,
and $HCO_3^–$ flow out at
lfr (s^{-1}) × $[species]_{ss}$ (M)

Steady-state operation is important! Cannot assume we extract equilibrium concentration of CO_2

- Flowing oceanwater infinitely slowly → extract more DIC as CO_2, even at high pH
- Flowing oceanwater very quickly → cannot extract all dissolved $CO_2(aq)$

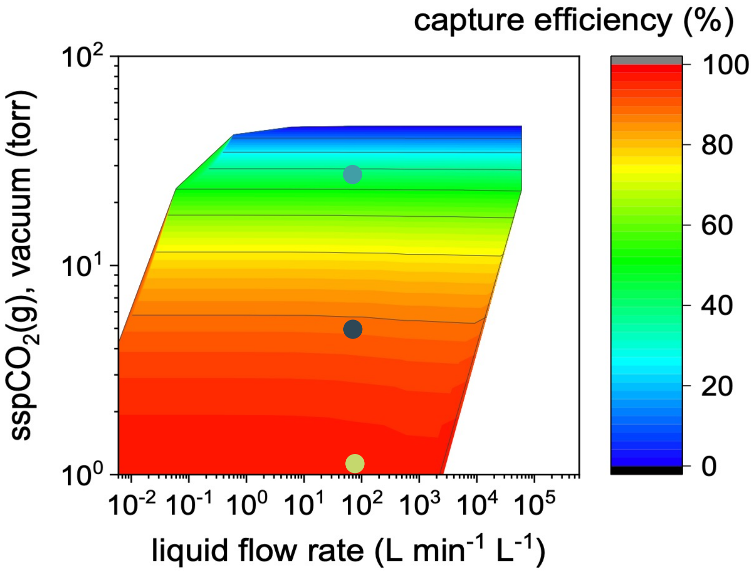
Lfr = liquid flow rate; Gfr = gas flow rate; Grr = gas reaction rate

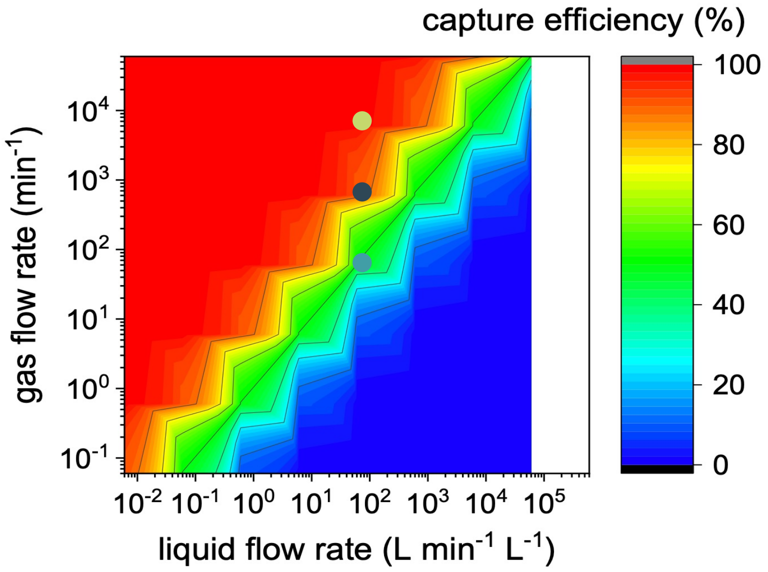
Output of the 0D reactor model can be used as input for our TEA

- **Extraction efficiency** (not liquid flow rate!) determines the necessary oceanwater flow rate for a given CO_2 scale
  - Want this to be high
- **CO_2 partial pressure** determines the vacuum base pressure in our membrane contactor
  - Want this to be high
- **Liquid flow rate** determines how many membrane contactors (MCs) we need
  - Want this to be within membrane contactor specs (10–50 $m^3/min/m^3$)

At pH 4, best operating point is close to 4 Torr, 91% extraction efficiency

Assuming equilibrium extraction, CO_2 price was lower ($115/ton)

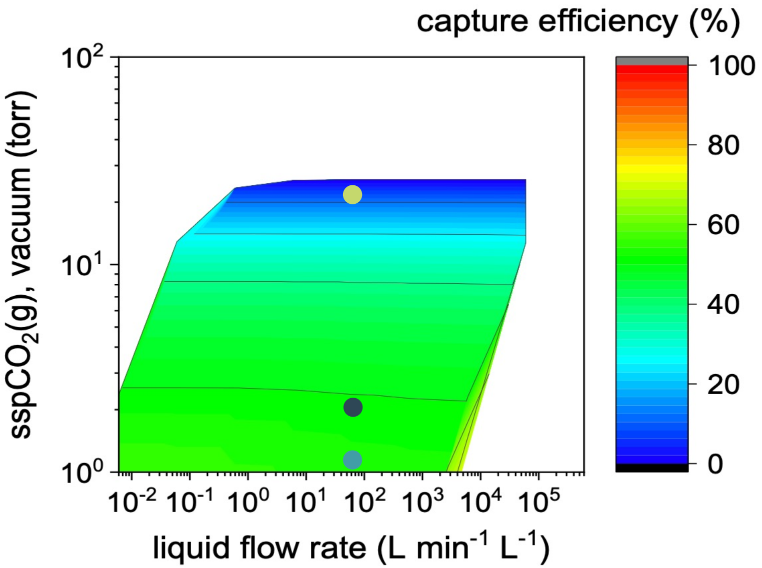


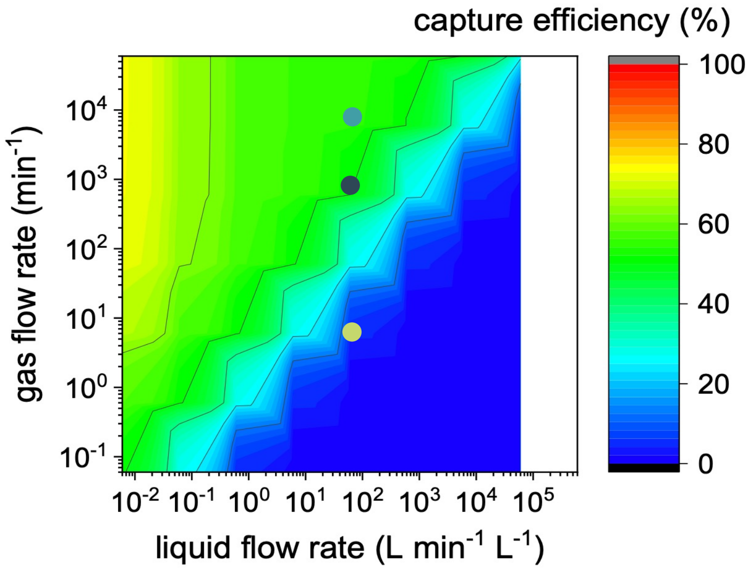


pCO_2 (torr)	Extraction efficiency (%)	lfr (min^{-1})	gfr (min^{-1})	CO_2 Price
23	50	60	60	$178
4	91	60	600	$158
0.5	99	60	6000	$479

At pH 6, best operating point is close to 2 Torr, 50% extraction efficiency

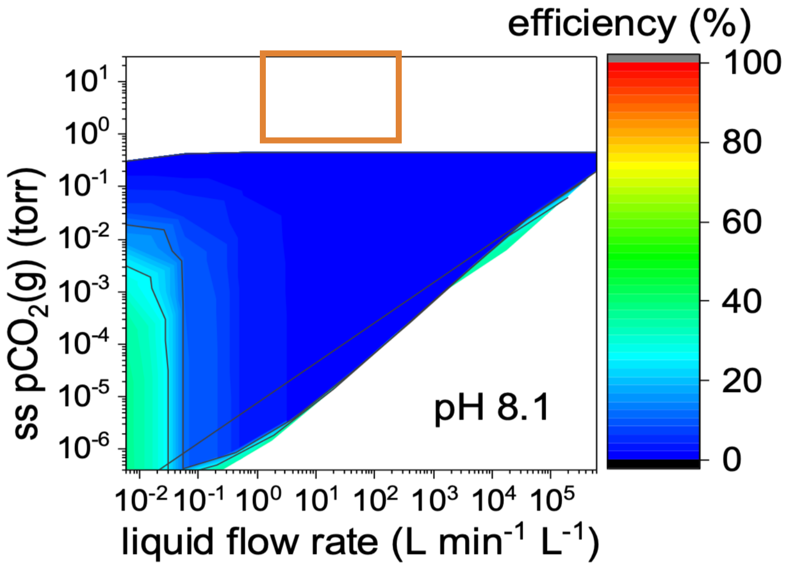
Assuming equilibrium extraction, CO_2 price was lower ($156/ton)

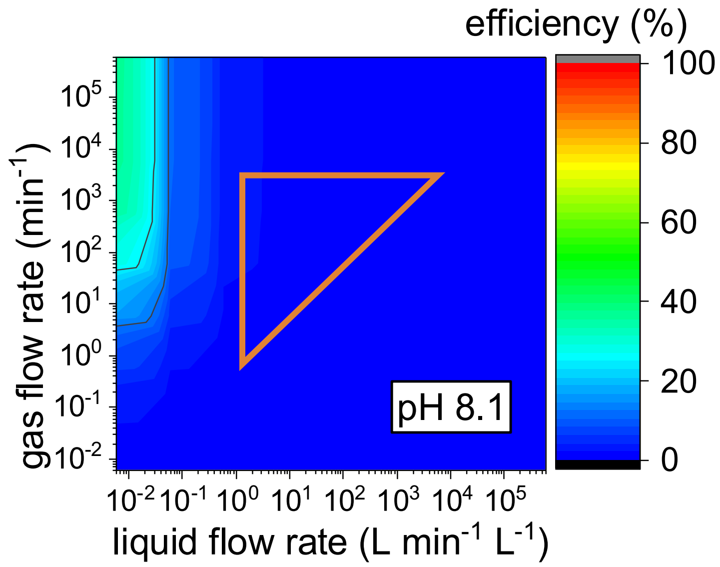




	pCO_2 (torr)	Extraction efficiency (%)	lfr (min^{-1})	gfr (min^{-1})	CO_2 Price
●	23	5	60	6	$805
●	2	50	60	600	$201
●	0.3	55	60	6000	$612

Operation at pH 8.1 is not realistic without catalysis





- Orange boxes mark target areas for low-cost operation
  - High pressure (equivalently, low gfr)
  - Gfr > lfr for high extraction efficiency
  - Lfr in membrane contactor operating range (1-100 min^{-1})
- Extraction efficiency low in those target areas – CO_2 price ends up being >$1000/ton

Main conclusions

- At 10 kiloton scale, CapEx and OpEx (mostly electricity) are both significant. At megaton scale, electricity cost dominates CO_2 cost.
- We achieve much lower costs than previous reports mostly due to 1) larger scale and 2) offshore floating platform reducing intake/outfall costs.
- CapEx is proportional to electrodialyzer current density, and OpEx is proportional to electrodialyzer voltage. Therefore, at megaton scale, we can tolerate lower current densities – diminishing returns to achieving greater than 500 mA/cm^2.
- If electricity is basically free, we can tolerate a lower capacity factor, as low as 50%.
- Vacuum level for pulling CO_2 off with membrane contactor must be greater than 1 Torr, otherwise we incur prohibitively large vacuum pump costs.
- Steady-state operation can yield different ideal operating points & a minimum cost operating point exists.