Electronic Supplementary Material

Table S1 Reservoir and wellbore geometries and input characteristics for base case geothermal heat mining modeling using CO_2

Parameter	Value
Injection well depth/m	2500
Production well depth/m	2150
Reservoir depth/m	500
Single reservoir length and width/m	4000
Well distance range (*R*)/m	500

Table S2 Input characteristics and initial values for geothermal CO_2 heat mining model

	Parameter	Value
Reservoir characteristics	Reservoir porosity	0.1
	Reservoir permeability/mD	30
	Rock specific heat/(J·(kg·K)$^{-1}$)	920
	Rock thermal conductivity/(W·(m·K)$^{-1}$)	2.51
Parameters for relative permeability	Residual gas saturation	0.01
	m_{VG}	0.65
	Residual liquid saturation	0.05
	Saturated liquid saturation	1.00
Parameters for capillary pressure	Residual liquid saturation	0.03
	m_{VG}	0.4118
	Alpha/(Pa^{-1})	6.08×10^{-5}
	Maximum capillary pressure/Pa	6.40×10^{7}
	Saturated liquid saturation	1.00
Reservoir and injection well initial conditions	Reservoir initial fluid	Water
	Reservoir initial temperature/°C	225
	Reservoir initial pressure/MPa	20–25

Table S3 Estimated regression coefficients for geothermal heat mining predictive model

Term	Y_1	Y_2	Y_3	Y_4
r^2	0.9948	0.9986	0.9985	0.9979
1	55.2179	210.38483	53.919644	30.013414
X_1	0.1694	–0.10114	–0.142205	–0.051513
X_2	–0.54942	–1.8563	–0.134511	–0.552746
X_3	–0.52102	0.49904	–0.400002	0.130806

X_4	–4.82609	1.32471	–0.925185	–1.244107
X_1X_2	0.00030963	0.00650813	0.000672704	0.000698963
X_1X_3	–0.00277302	–0.000117044	0.000216836	–0.000380902
X_1X_4	0.0041037	–0.00509837	0.0043135	0.0029802
X_2X_3	–0.000568	–0.000313333	0.0069015	–0.000657733
X_2X_4	0.039778	0.0025	–0.020094	0.013328
X_3X_4	–0.0013	0.000466667	–0.00015	–0.0027767
X_1^2	–0.000253026	0.000130108	8.17226E–05	1.72619E–05
X_2^2	0.016636	–0.016164	0.0022774	0.0039844
X_3^2	0.023617	–0.00807104	0.0035299	0.0029863
X_4^2	0.04838	0.012943	0.022426	0.013491
$X_1^2X_2$	–2.96296E–08	–5.77778E–06	2.96296E-09	–3.91852E–07
$X_1^2X_3$	5.74222E–06	–9.64444E–07	2.08444E-07	8.30222E–07
$X_1^2X_4$	–3.37037E–06	3.45481E–06	–3.36296E–06	–2.20741E–06
$X_1X_2^2$	–7.11111E–06	0.00002328	–6.6963E–06	–7.77778E–07
$X_1X_3^2$	–3.56533E–05	1.20075E–05	–0.000004088	–0.000005232
$X_2^2X_3$	4.31111E–05	–4.44444E–07	–5.77778E–05	–1.95556E–06
$X_2^2X_4$	–0.000396296	–1.11111E–05	0.000174074	–0.000111852
$X_2X_3^2$	–3.25333E–05	2.66667E–06	–0.00002288	3.30667E–06

Table S4 Comparison between predicted results of RSM model and simulation results of TOUGH2-T2Well/ECO2N

No.	X_1/m	X_2/(kg·s^{-1})	X_3/°C	X_4/MPa	Y_1/(kg·s^{-1})		Y_2/°C		Y_3/MPa		Y_4/MPa	
					TOUGH2	RSM	TOUGH2	RSM	TOUGH2	RSM	TOUGH2	RSM
1	650	30	80	27	23.99	23.27	193.98	193.84	19.39	19.52	19.57	19.46
2	650	60	80	27	50.64	49.92	190.06	189.92	19.01	19.14	22.32	22.21
3	500	45	55	30	38.82	38.10	189.77	189.63	24.02	24.16	19.85	19.74
4	650	60	55	30	49.46	50.49	191.12	191.11	23.57	23.50	22.28	22.45
5	800	45	30	27	20.67	21.70	194.36	194.35	18.27	18.20	14.57	14.73
6	650	60	55	24	49.95	50.98	189.29	189.28	17.08	17.01	17.88	18.05
7	650	30	55	30	21.63	22.66	194.91	194.90	23.30	23.24	18.95	19.12
8	650	45	30	30	35.36	35.05	193.12	193.27	23.33	23.26	18.47	18.41
9	800	45	55	24	33.89	33.17	191.96	191.82	15.97	16.10	16.92	16.82
10	650	30	55	24	22.86	23.89	193.35	193.34	16.02	15.95	15.14	15.30

11	500	45	80	27	40.37	41.40	186.51	186.50	21.19	21.12	20.26	20.43
12	800	45	80	27	33.75	34.78	192.75	192.74	18.85	18.79	21.24	21.40
13	800	45	55	30	32.86	32.14	193.59	193.45	22.11	22.25	20.98	20.87
14	650	45	55	27	35.74	35.74	192.35	192.35	19.85	19.85	18.53	18.53
15	650	45	80	30	36.01	35.70	193.04	193.19	23.37	23.30	22.87	22.81
16	500	60	55	27	53.86	53.55	180.54	180.69	21.17	21.10	18.97	18.91
17	800	30	55	27	20.23	19.92	194.30	194.45	18.20	18.13	17.18	17.12
18	500	45	30	27	38.84	39.87	187.37	187.36	21.18	21.11	15.44	15.60
19	800	60	55	27	46.01	45.70	191.39	191.54	19.19	19.12	20.49	20.43
20	650	60	30	27	49.51	48.79	190.26	190.12	20.20	20.34	17.88	17.77
21	650	30	30	27	22.46	21.74	194.09	193.95	19.36	19.50	14.43	14.32
22	500	30	55	27	24.76	24.45	193.28	193.43	20.84	20.77	16.73	16.68
23	500	45	55	24	39.35	38.63	187.05	186.91	17.77	17.91	15.99	15.88
24	650	45	30	24	35.49	35.18	191.48	191.63	16.65	16.58	13.80	13.74
25	650	45	80	24	36.53	36.22	191.26	191.41	16.74	16.67	19.03	18.97
26	500	30	30	27	24.54	24.57	190.31	192.23	20.83	20.77	14.08	14.00
27	500	45	30	27	39.02	38.19	187.26	187.49	21.18	21.03	15.43	15.49
28	500	60	30	27	52.97	51.82	181.30	182.15	21.49	21.29	16.73	16.97
29	500	30	50	27	24.79	25.83	190.31	192.28	20.84	20.74	16.20	16.05
30	600	30	30	27	22.70	21.87	194.01	194.39	19.75	20.02	14.34	14.23

Table S5 Annual CEPCI data from 2000 to Feb, 2019

Year	Annual CEPCI
2000	394.1
2001	394.3
2002	395.6
2003	402.0
2004	444.2
2005	468.2
2006	499.6
2007	525.4
2008	575.4
2009	521.9
2010	550.8
2011	585.7
2012	584.6
2013	567.3
2014	576.1
2015	556.8
2016	541.7
2017	567.5
2018	603.1

S1 Cost factors

Cost Factors for estimating the plant cost, including pressure factor, bare module factor, and material factor are introduced and presented. Additionally, factors considering additional cost and contingency are also introduced in this section. These cost factors reflect the effects which are critical and significant to the plant capital cost.

Pressure factor F_p

Equipment costs increase when the operating pressures rise, which can be predicted and covered by using pressure factors. The pressure factor for all components used in the direct sCO_2 expansion power generation system can be expressed as [40]

$$F_p = 10^{C_1 + C_2 \log P + C_3 (\log P)^2}, \quad \text{(S1)}$$

where F_p is the pressure factor and P is the operating pressure in the unit of bar. The pressure of the hot produced sCO_2 from geothermal reservoirs ranges from 100 to 250 bar, which determines the pressure for the compressors, turbines, and heat exchanger tubes. Accordingly, the adapted pressure factor whose pressure is over 140 bar, is only compatible for tube. The pressure factor then can be extrapolated and adapted from Eq. (S1) as

$$F_{p,\mathrm{HX}} = \begin{cases} 10^{C_1 + C_2 \log P + C_3 (\log P)^2}, & \text{For tube and shell,} \quad P \le 140 \\ 0.8966 P^{0.0413}, & \text{Only for tube,} \quad P > 140 \end{cases} \quad \text{(S2)}$$

where F_p is the pressure factor, P stands for the operating pressure of equipment in the unit of bar, and C is the constant with values for different components, as listed in Table S6.

Table S6 Constant values of pressure factor for different equipment

Equipment	C_1	C_2	C_3	Pressure range/bar
Compressor	0	0	0	-
Turbine	0	0	0	-
Tube shell heat exchanger	0	0	0	$P < 5$
	–0.00164	–0.00627	0.0123	$5 < P < 140$

Material factor F_M and bare module factor F_{BM}

The direct contacts between the hot produced sCO_2 from geothermal reservoirs containing minerals occur in the direct turbine expansion process which requires anti-corrosive materials to manufacture these components. It is necessary to apply the material factors for cost estimation of the components in which the produced sCO_2 contacts. In addition, bare module factors for turbines, compressors and heat exchangers are also presented for obtaining their bare module costs [40]. The bare module costs for compressors/turbines and heat exchangers can be respectively expressed as

$$C_{\mathrm{BM,t/comp}} = C_{\mathrm{p,t/comp}} \cdot F_{\mathrm{BM}} \cdot F_{\mathrm{P}}, \quad \text{(S3)}$$

$$C_{\mathrm{BM,HX}} = C_{\mathrm{p,HX}} \cdot F_{\mathrm{BM}} = C_{\mathrm{p,HX}} (B_1 + B_2 F_{\mathrm{M}} F_{\mathrm{p}}), \quad \text{(S4)}$$

where CBM is the bare module cost, C_p is the pressure factor, and B_1 and B_2 are constant values. Tables S8 and S9 present the parameter and constant values required to calculate the bare module factors of the turbine, the compressors, and the heat exchangers.

Table S7 Values of bare module factors in Eq. (S3)

Equipment	Material	F_{BM}
Centrifugal	Carbon steel	2.8
Compressors	Stainless steel	5.7
Turbines	Carbon steel	3.5
	Stainless Steel	6.1

Table S8 Values of material factors in Eq. (S4)

Equipment	Material	F_M
Tube shell HX	CS-Shell/CS-Tube	1
	CS-Shell/SS-Tube	1.8
	SS-Shell/SS-Tube	2.7

Table S9 Constant values for Eq. (S4)

Equipment	B_1	B_2
Fixed tube sheet HX	1.63	1.66

Conversion factor of chemical engineering plant index (CEPCI) $F_{\mathrm{CEPCI,yr}\,A\ \mathrm{to\ yr}\,B}$

CEPCI is employed to update capital costs from one period to another. The conversion factor can be defined as [41]

$$F_{\mathrm{CEPCI,yr}\,A\ \mathrm{to\ yr}\,B} = \frac{\text{CEPCI at year } B}{\text{CEPCI at year } A}. \quad \text{(S5)}$$

Factor considering the additional cost F_{add}

The piping, control system, installation labor, and other overhead costs were considered to multiply on the basis of bare module cost, which was assumed as $F_{\mathrm{add}} = 1.8$ in this paper.

Contingency factor F_{contcy}

The contingency factor is a factor that accounts for unforeseeable expenses during plant construction, which may be caused by design development changes, construction schedule adjustments, or differing site conditions for those expected, etc. The contingency factor is based on the previous experience and the predicted construction difficulty. In this analysis, for a power plant, a typical contingency rate of 15% is considered, leading to a contingency factor of

$$F_{\text{contcy}} = 1.15 .$$

S2 Equipment purchase cost and bare module cost model for direct sCO_2 expansion system

To be able to estimate the bare module cost, the purchase cost for each component in the power cycle has to be available which is presented in this section.

CO_2 turbine purchase cost

An economic analysis was performed by Atrens et al. for a CO_2-based EGS power plant in 2011 [19]. In terms of the compression work and the CO_2 density at the turbine outlet, Eq. (S6) can be used to calculate the CO_2 turbine purchase cost which is converted to the cost at 2019 through the CEPCI factor.

$$C_{\text{p,t}} = F_{\text{CEPCI,2011 to 2019}} \times 1.066 W_{\text{t}}^{0.5439} \rho_{\text{CO}_2,\text{out}}^{-0.1472}, \quad \text{(S6)}$$

where $C_{\text{p,t}}$ is the purchase cost of CO_2 turbine in M$, W_{t} is the turbine power output in MW_e, and $\rho_{\text{CO}_2,\text{out}}$ is the CO_2 density at turbine outlet in kg/m^3.

CO_2 compressor purchase cost

The centrifugal CO_2 compressor purchase cost can be calculated by using Eq. (S7) [40]. It can be seen from Eq. (S7) that the compressor purchase cost is determined by the compression work of compressors. In addition, the predicted CO_2 compressor purchase costs calculated by using Eq. (19) are also comparable with the technical data of CO_2 compression, transport, and storage [42].

$$C_{\text{p,comp}} = \frac{F_{\text{CEPCI,2001 to 2019}}}{1\times10^6} \times \begin{cases} 10^{2.2897+1.3604\times\log W_{\text{comp}}-0.1027\times(\log W_{\text{comp}})^2}, & W_{\text{comp}} \le 3000 \\ \dfrac{W_{\text{comp}}}{3000}\times 10^{2.2897+1.3604\times\log 3000-0.1027\times(\log 3000)^2}, & W_{\text{comp}} > 3000 \end{cases}$$

(S7)

where $C_{\text{p,comp}}$ is the purchase cost of CO_2 compressor in 2019 in M$ and W_{comp} is the compression work in kW.

Heat exchangers (CO_2 coolers) purchase cost

The heat exchangers used in the direct sCO_2 expansion power generation system are CO_2 coolers, which use cold water to cool CO_2. The operating pressure and temperature ranges of different types of heat exchangers are presented in Fig. S1 [21]. Accordingly, shell tube HX, PCHE HX, and PMHE HX are applicable in this system for analysis. However, PMHE HXs and PCHE HXs are still under investigation with very limited cost information, and tend to have a higher cost than the conventional shell tube HX. As a result, a fixed tube-shell heat exchanger was selected for the cost estimation and optimization analysis in this paper. The design methods and correlations can be found in Appendix A4 in Ref. [21].

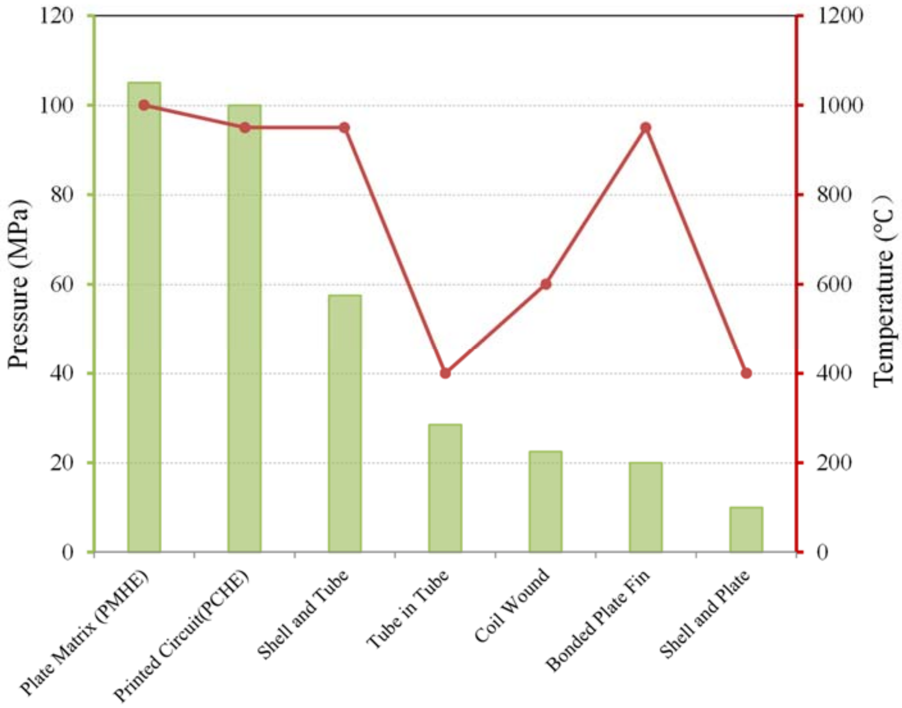

Fig. S1 Pressure and temperature working conditions for sCO_2 HXs [21].

The purchased cost of the fixed tube-sheet heat exchanger using carbon steel can be calculated by [40]

$$C_{p,\text{HX}} = \frac{F_{\text{CEPCI,2001 to 2019}}}{1\times10^6} \times \begin{cases} 10^{4.3247-0.3030\times\log A+0.1634\times(\log A)^2}, & A \le 1000 \\ \frac{A}{1000}\times10^{4.3247-0.3030\times\log 1000+0.1634\times(\log 1000)^2}, & A > 1000 \end{cases} \tag{S8}$$

where $C_{p,\text{HX}}$ is the purchase cost of heat exchangers used in the sCO_2 expansion power system in M$ and A is the heat transfer area of heat exchanger (m^2). For each heat exchanger considered in this analysis, the heat transfer area was calculated based on the optimal operating conditions. Additionally, the physical properties of all substances used in this analysis are obtained from the NIST REFPROP database [43].

Cooling water chiller bare module cost

The heat taken away by circulating water for cooling down CO_2 needs to be rejected by the cooling equipment. The packaged centrifugal water chiller was selected in the cost estimation. The bare module cost of centrifugal water chiller can be found with different tons of refrigeration [44]. A bare module cost for cooling water chiller based on cooling load was introduced in Ref. [21]. The bare module cost per kW cooling is around $100/kW$_{th}$ when the total cooling load for the power plant is over 4 MW$_{th}$. In this analysis, the power generation capacity is at least 10 MW$_e$, which indicates that this method is suitable for estimating the cooling water chiller bare module cost (see Eq. (S9)).

$$C_{\text{BM.chiller}} = F_{\text{CEPCI,2017 to 2019}} \times \frac{\$100}{\text{kW}_{\text{th}}} \times Q_{\text{cooling water}} \times 10^{-6}, \tag{S9}$$

where $C_{\text{BM.chiller}}$ is the water chiller bare module cost in 2019 in M$ and $Q_{\text{cooling water}}$ is the heat removed by the cooling water.

CO_2-H_2O separator bare module cost

The CO_2-H_2O separator is an essential component in this paper due to the existence of brine when the sCO_2 and brine mixture is produced from the geothermal wellbore (Fig. S2). However, there are no commercial products for large-scale application. A technique named the cost-to-capacity method is used to estimate the large-scale CO_2-H_2O separator. A quote for a Mueller helical separator of $50000 for a maximum CO_2 volume flow of 298 L/min is obtained [45,46].

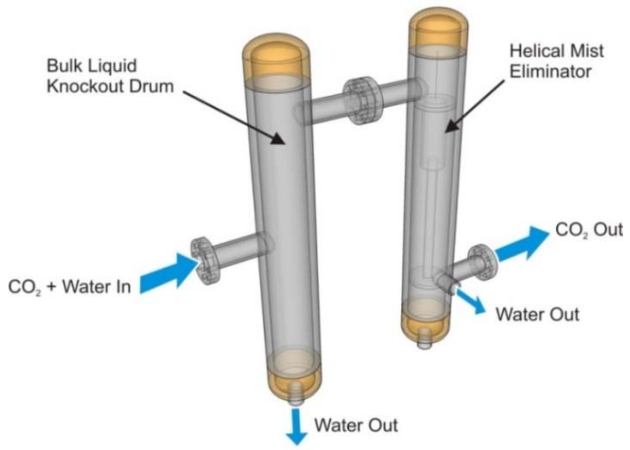

Fig. S2 Sketch of CO_2-H_2O separator.

In addition, a rule of thumb developed and validated over the years referred to as the rule of six-tenths can be used to get the satisfactory results. Therefore, the bare module cost for a full-scale CO_2-H_2O separator can be estimated by

$$C_{\text{BM,separator/wellset}} = F_{\text{CEPCI,2017 to 2019}} \times C_{\text{BM,separator,known}} \left(\frac{V_{\text{separator/wellset}}}{V_{\text{separator,known}}} \right)^{0.6} \times 10^{-6}, \tag{S10}$$

where $C_{\text{BM,separator/wellset}}$ is the bare module cost for CO_2-H_2O separator for each well-set in M$, $C_{\text{BM,separator,known}}$ is the known bare module cost for an existing commercial separator in M$, $V_{\text{separator/wellset}}$ is the CO_2 volume flowrate (L/min), and $V_{\text{separator,known}}$ is CO_2 volume flowrate of 298 L/min for the existing separator.

Accordingly, with obtaining the bare module cost for each component and the cost factors considering the additional cost for installation and contingency, the total capital cost for the direct sCO_2 expansion power generation system can be expressed as

$$C_{\text{tot captital, power system}} = F_{\text{contcy}} \cdot F_{\text{add}} \cdot \sum C_{\text{BM},i}, \quad \text{(S11)}$$

where $C_{\text{tot captital, power system}}$ is the total capital cost of the power generation system, F_{contcy} is contingency factor, F_{add} is additional cost factor, and $C_{\text{BM},i}$ is a bare module cost for each component.