Supporting Information

Prospective life cycle assessment based on SD approach: a case study on the large-scale centrifugal compressor

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This document contains 2 figures and 4 tables.

1. Information on the research object

The survey of PCL803 large-scale centrifugal compressor was conducted at the Shenyang Blower Work Group Co., Ltd (SBW), a leading compressor corporation in China. Relevant technical parameters of operation are presented in Table S1. Table S2 lists basic information on the core components.

Table S1 Technical parameters of PCL803 centrifugal compressor

Parameters	Quantity	Unit
Mass flow	239.93	kg/s
Inlet pressure	7.1	Mpa
Outlet pressure	11.95	Mpa
Inlet temperature	20	℃
Outlet temperature	63	℃
Impeller progression	3	/
Rated power	18,404	kW
Rated speed	6,100	rpm

Table S2 Basic information on the primary components of the compressor

Main components	Mass (kg)	Material
Impellers*	379	alloy steel
Spindle	952.7	alloy steel
Spacer sleeves*	116.6	stainless steel
Balance plate	182.4	stainless steel
Thrust plate	25.65	carbon steel
Inlet wind tunnel	2,255	stainless steel
Outlet wind tunnel	2,335	stainless steel
Lifting screws	116	alloy steel
Steel plates*	9,492.8	alloy steel

*Multiple components with the same type in a centrifugal compressor and the corresponding mass refers to the total weight.

2. Emissions and extractions of unit power

This study investigated the structural variation of grid power. To further understand changes of environmental burden, the emissions and extractions of specific energy sources (Table S3) reflecting the average situation in China were identified in Ecoinvent 3.1.

Table S3 Emissions and extractions (excerpt) involved in unit energy sources (unit: kg/kWh)

Extraction/ Emission	Cleaner energy					Thermal power		
	nuclear	wind	solar PV	hydro	biomass	coal	gas	oil
coal	4.641E-03	3.514E-03	2.258E-02	1.050E-03	3.501E-03	5.893E-01	3.658E-03	1.639E-02
crude oil	9.820E-04	1.280E-03	4.060E-03	5.710E-04	1.100E-02	2.350E-03	9.390E-04	3.680E-01
natural gas	1.284E-03	9.972E-04	5.474E-03	1.794E-04	1.062E-03	4.685E-04	2.289E-01	1.542E-02
CO	3.075E-05	8.503E-05	1.647E-04	1.791E-05	3.483E-03	1.898E-04	2.046E-04	4.668E-04
CO_2	1.499E-02	1.601E-02	6.682E-02	6.686E-03	1.571E+00	1.178E+00	6.870E-01	1.187E+00
SO_2	6.592E-05	6.065E-05	3.929E-04	1.399E-05	1.212E-04	9.820E-03	2.108E-03	6.873E-03
NO_X	5.344E-05	4.254E-05	1.875E-04	2.004E-05	2.640E-03	4.433E-03	6.992E-04	4.076E-03
CH_4	3.729E-05	4.683E-05	2.261E-04	2.968E-04	8.357E-05	8.106E-03	1.664E-03	7.959E-04
H_2S	9.090E-08	2.806E-07	7.183E-07	9.513E-07	2.303E-07	4.940E-07	1.014E-05	1.457E-06
HCL	1.933E-06	1.266E-06	8.949E-06	3.620E-07	1.450E-06	3.256E-04	1.435E-06	8.564E-06
CFC-11	8.290E-14	1.840E-13	2.980E-11	3.160E-14	1.240E-13	1.730E-13	5.250E-14	3.180E-13
CFC-12	4.087E-11	1.740E-10	3.370E-09	7.808E-12	1.580E-09	6.512E-11	2.851E-11	1.172E-10
CFC-113	3.060E-11	6.192E-11	3.234E-10	1.534E-11	9.521E-08	9.671E-11	2.458E-11	1.324E-10
COD	3.156E-05	1.147E-04	3.417E-04	2.310E-05	1.863E-04	4.471E-04	1.449E-04	3.814E-03
NH_3	4.626E-07	2.105E-06	7.313E-06	3.822E-07	1.715E-06	1.700E-06	3.918E-07	1.092E-04

With the ratio variation of energy sources and the data in Table S3, we determined the variation of emissions and extractions per unit electric power. Fig. S1 illustrates the changes of some representative atmospheric emissions or effluents including CO_2, SO_2, CH_4, and COD.

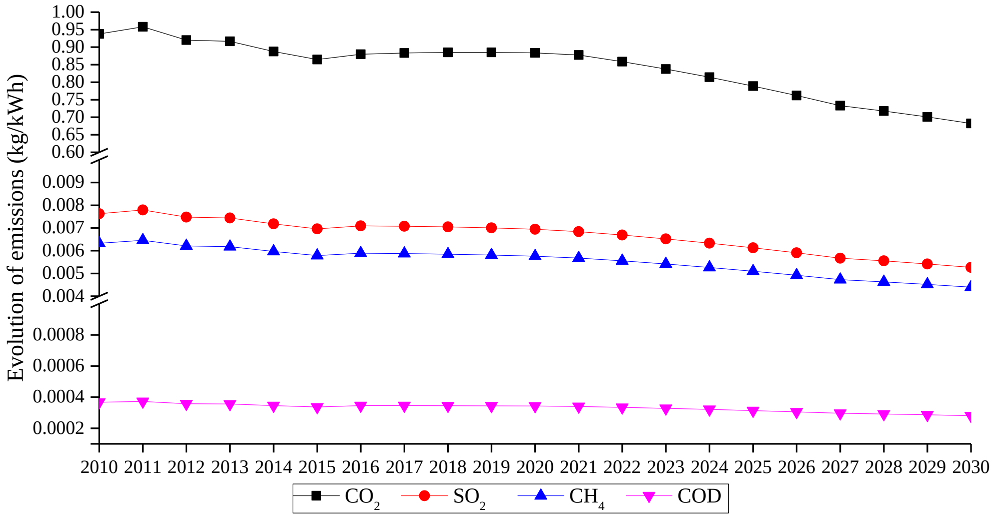

Fig. S1. Evolution of representative emissions per unit electric power

3. Authentic test

The results of system dynamics modeling should be validated with authentic data. We compared the simulation and actual data of each energy source generation from the year 2011 – 2015, as shown in Table S4.

Table S4 Authentic test results

Years	Hydro power (GWh)			Nuclear power (GWh)		
	Actual values	Simulation value	Error	Actual values	Simulation value	Error
2011	698,945	698,900	-0.01%	86,350	86,350	0.00%
2012	872,107	844,700	-3.14%	97,394	97,710	0.32%
2013	920,291	868,100	-5.67%	111,613	110,300	-1.18%
2014	1,064,337	978,000	-8.11%	132,538	129,900	-1.99%
2015	1,130,270	1,010,000	-10.64%	170,789	166,200	-2.69%
Years	Wind power (GWh)			Solar PV (GWh)		
	Actual values	Simulation value	Error	Actual values	Simulation value	Error
2011	70,331	70,330	0.00%	2,604	2,604	0.00%
2012	95,978	92,150	-3.99%	6,350	6,125	-3.54%
2013	141,197	133,100	-5.73%	15,451	14,690	-4.93%
2014	156,078	143,000	-8.38%	29,195	26,950	-7.69%
2015	185,766	167,700	-9.73%	45,225	40,910	-9.54%
Years	Other cleaner energy (GWh)			Installed capacity of Energy sources in 2030 (GW)		
	Actual values	Simulation value	Error		Values in [46]	Simulation value
2011	38407	35570	-7.39%	Hydro power	560	580.9
2012	41109	37610	-8.51%	Nuclear power	130	122.4
2013	49462	44580	-9.87%	Wind power	500	478.2
2014	57523	51370	-10.70%	Solar PV	300	322.4
2015	63889	56730	-11.21%	Others	41	44.9

4. Sensitivity analysis

A sensitivity analysis should be conducted to examine the robustness and viability of the prediction model by observing the result variation relative to the change of important factors. Fig. S2 presents the corresponding changes to the +10% variation of the price of hydropower, solar PV, wind, nuclear, and others.

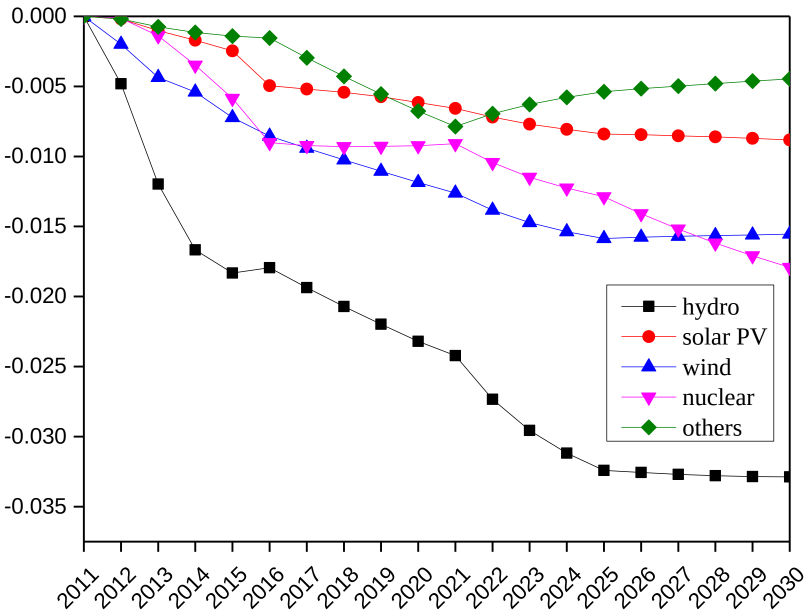

Fig. S2. Variation of cleaner energy ratio relative to the capital cost

5. Primary equations of system dynamics

In order to improve the transparency of the study, the primary equations and the relevant data of the three subsystems are illustrated in this section.

The primary equations in the electricity generation subsystem are presented as blow (A: Auxiliary variable, R: Rate variable, L: Level variable):

A gross thermal power production=gross electricity generation-gross cleaner energy generation, unit: GWh.

Lookup growth rate of gross domestic product (GDP)= [(2011,0)-(2030,0.1)], (2011,0.09536), (2012,0.07856), (2013,0.07758), (2014,0.07298), (2015,0.069), (2016,0.06689), (2017,0.066), (2018,0.065), (2019,0.063), (2020,0.061), (2021,0.059), (2022,0.058), (2023,0.056), (2024,0.055), (2025,0.053), (2026,0.052), (2027,0.05), (2028,0.049), (2029,0.048), (2030,0.047), unit: Dmnl.

Lookup electricity elasticity coefficient=[(2011,0.4)-(2030,1.3)], (2011,1.27), (2012,0.75), (2013,1.14), (2014,0.55), (2015,0.42), (2016,0.75), (2017,0.7), (2018,0.7), (2019,0.7), (2020,0.7), (2021,0.5), (2022,0.5), (2025,0.5), (2026,0.5), (2027,0.5), (2027,0.5), (2028,0.5), (2029,0.5), (2030,0.5), unit: Dmnl.

A increment rate of electricity consumption=growth rate of gross domestic product (GDP) (Time+1)*electricity elasticity coefficient (Time+1), unit: Dmnl, note: growth rate of GDP and electricity elasticity coefficient are table functions of simulate time.

R increment of electricity consumption=Gross electricity consumption*increment rate of electricity consumption, unit: GWh/Year.

L Gross electricity consumption=INTEG(increment of electricity consumption)+electricity production of the base year, unit: GWh, note: INTEG denotes the integral sign.

A gross electricity production=Gross electricity consumption, unit: GWh.

The primary equations in the investment subsystem are as follows:

A investment for renewable energy=total investment for renewable energy*modification factor, unit: Yuan/Year.

A modification factor=IF THEN ELSE(0.4-ratio of cleaner energy<=0, 0.65, 1), unit: Dmnl, note: the selection function IF THEN ELSE (*a*, *b*, *c*) means the function value is *b* when condition *a* is satisfied, otherwise, the value is *c*.

A capital cost (wind)=WITH LOOKUP (Time), Initial value ([(2010,0)-(2030,8e+009)], (2010,7.52e+009), (2015,6.016e+009), (2020,5.4144e+009), (2030,4.57216e+009)), unit: Yuan/GW.

A capital cost (solar PV)=WITH LOOKUP (Time), Initial value ([(2010,0)-(2030,3e+010)], (2010,2.6712e+010), (2020,1.20015e+010), (2030,8.001e+009)), unit: Yuan/GW.

A investment ratio for hydro=WITH LOOKUP (Time), Initial value ([(2011,0)-(2030,1)], (2011,0.3711), (2012,0.2865), (2013,0.276), (2014,0.1198), (2015,0.0828), (2016,0.2), (2020,0.2), (2021,0.28), (2030,0.28)), unit: Dmnl.

A investment ratio for wind=WITH LOOKUP (Time), Initial value ([(2011,0)-(2030,10)], (2011,0.4726), (2012,0.19846), (2013,0.2864), (2014,0.337), (2015,0.1277), (2016,0.28), (2020,0.28), (2021,0.3), (2030,0.3)), unit: Dmnl.

A investment ratio for solar=WITH LOOKUP (Time), Initial value ([(2011,0)-(2030,10)], (2011,0.1376), (2012,0.5052), (2013,0.4096), (2014,0.5271), (2015,0.7765), (2016,0.4), (2020,0.4), (2021,0.4), (2030,0.4)), unit: Dmnl.

A investment ratio for others=WITH LOOKUP (Time), Initial value ([(2011,0)-(2030,1)], (2011,0.0187), (2012,0.0238), (2013,0.028), (2014,0.016), (2015,0.013), (2016,0.12), (2020,0.12), (2021,0.02), (2030,0.02)), unit: Dmnl.

A investment for nuclear=WITH LOOKUP (Time), Initial value ([(2011,0)-(2030,9e+011)], (2011,3.25e+009), (2012,2.72e+010), (2013,7.05e+010), (2014,9.22e+010), (2015,8.41e+010), (2016,2.5e+010), (2020,2.5e+010), (2021,4.537e+010), (2030,2.287e+011)), unit: Yuan/Year.

The primary equations in the emission subsystem are as follows:

A ratio of cleaner energy=gross cleaner energy generation/gross electricity production, unit: Dmnl.

A ratio of thermal power=1-ratio of cleaner energy, unit: Dmnl.

A gas proportion in thermal power=WITH LOOKUP (Time), Initial value ([(2011,0)-(2030,0.2)], (2011,0.02512), (2012,0.02545), (2013,0.025331), (2014,0.027011), (2015,0.034087), (2030,0.034087)), unit: Dmnl.

A coal proportion in thermal power=WITH LOOKUP (Time), Initial value ([(2011,0)-(2030,2)], (2011,0.971704), (2012,0.971732), (2013,0.97229), (2014,0.970745), (2015,0.963643), (2030,0.963643)), unit: Dmnl.

A oil proportion in thermal power=WITH LOOKUP (Time), Initial value ([(2011,0)-(2030,0.01)], (2011,0.003176), (2012,0.002818), (2013,0.002379), (2014,0.002245), (2015,0.00227), (2030,0.00227)), unit: Dmnl.