ACCSCIENCE PUBLISHING

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ORIGINAL RESEARCH ARTICLE

Integrating factor decomposition and scenario decoupling into a modified STIRPAT model for regional carbon emission forecasting

Supplementary Files

Table S1. Calculation data of carbon emission factors for different types of energy consumption

Energy	Average low calorific value (kJ/kg, kJ/m^3)	Carbon content per unit of calorific value (kg/GJ)	Carbon dioxide emission factor
Raw coal	20908	25.8	1
Crude oil	41816	20	1
Natural gas	32238	15.3	1

Source: Data from the Intergovernmental Panel on Climate Change National Greenhouse Gas Inventory Guidelines[1] and the China Energy Statistical Yearbook.[2]

Table S2. Carbon emission factor of electricity

Energy	Carbon emission factor (kg CO_2/kWh)
Electricity	0.0921

Source: Data from the Ministry of Ecology and Environment issued directives requiring provincial-level governments to submit self-assessment reports on the implementation of greenhouse gas emission reduction targets in 2018.[3]

Table S3. Types and consumption of energy in Yunnan from 2005 to 2021

Year	Raw coal (million t)	Crude oil (t)	Natural gas (billion m^3)	Electricity output (billion kWh)
2005	65.51	7.0×10^2	6.12	68.27
2006	73.55	7.0×10^2	5.45	116.93
2007	74.54	1.1×10^3	5.49	165.86
2008	78.53	6.0×10^2	5.28	212.56
2009	85.22	7.0×10^2	4.52	260.14
2010	90.28	6.0×10^2	3.64	325.71
2011	95.35	2.0×10^2	4.20	330.35
2012	98.43	2.0×10^2	4.30	425.81
2013	96.81	3.0×10^2	4.26	669.11
2014	91.23	4.0×10^2	4.58	1012.40
2015	88.40	3.0×10^2	6.28	1109.17
2016	87.49	4.0×10^2	7.63	1277.75
2017	82.45	4.0×10^6	9.57	1418.95
2018	77.94	1.0×10^7	12.80	1558.47

(*Cont'd...*)

Table S3. (*Continued*)

Year	Raw coal (million t)	Crude oil (t)	Natural gas (billion m^3)	Electricity output (billion kWh)
2019	77.27	1.1×10^7	16.07	1636.64
2020	77.12	1.0×10^7	18.70	1636.22
2021	79.26	9.8×10^6	21.14	1848.67

Source: Data from the Yunnan Statistical Yearbook and the China Energy Statistical Yearbook for the years 2006–2022.[4]

Table S4. Data on various factor variables in the model from 2005 to 2021

Year	IY (million t)	B (million people)	C (CNY 10,000 per person)	D (%)	E (%)	F (CNY 10,000 per ton of standard coal)	G (%)	H (%)	J (tons of standard coal per CNY 10,000)	L (%)	U (CNY per kWh)
2005	35.62	44.50	0.79	62.48	29.50	0.74	39.66	0.00	1.74	41.86	6.28
2006	39.92	44.83	0.92	67.70	30.50	0.84	40.93	0.00	1.66	41.85	6.34
2007	40.44	45.14	1.13	66.47	31.60	0.97	40.52	0.00	1.49	42.75	6.81
2008	42.57	45.43	1.33	60.83	33.00	1.03	41.15	0.00	1.32	42.19	7.25
2009	46.13	45.71	1.44	62.62	34.00	1.07	39.63	0.00	1.30	44.40	7.38
2010	48.80	46.02	1.69	56.73	34.70	1.29	42.24	0.34	1.20	43.66	7.70
2011	51.56	46.31	2.07	55.97	36.80	1.38	40.02	0.75	1.09	45.31	7.91
2012	53.20	46.59	2.40	53.16	38.74	1.53	40.18	1.56	1.01	45.04	8.45
2013	52.26	46.87	2.77	50.63	39.99	1.76	38.99	2.08	0.85	46.36	8.79
2014	49.19	47.14	3.02	43.07	41.21	1.77	38.29	2.55	0.82	47.41	9.18
2015	47.72	47.42	3.21	40.99	42.93	1.75	36.71	3.82	0.70	49.39	10.40
2016	47.25	46.77	3.51	39.93	44.64	1.81	35.11	6.57	0.66	51.29	11.60
2017	47.95	46.93	3.95	38.06	46.29	1.76	34.18	7.46	0.60	53.17	12.02
2018	50.73	47.03	4.44	36.30	47.44	1.91	34.80	7.86	0.56	53.23	12.44
2019	51.15	47.14	4.93	34.57	48.67	2.11	34.71	8.48	0.52	52.21	12.82
2020	50.71	47.22	5.20	34.87	50.05	1.93	34.16	8.15	0.53	51.13	12.13
2021	51.50	46.90	5.77	34.23	51.05	1.93	35.32	7.60	0.49	50.42	12.70

Source: Data from the China Statistical Yearbook[5], Yunnan Statistical Yearbook[4], and the China Energy Statistical Yearbook[2] for the years 2006–2022.
Notes: B: Population size; C: Per capita gross domestic product; D: Energy structure; E: Urbanization size; F: Energy utilization efficiency; G: Secondary industry structure; H: Proportion of renewable energy generation; IY: Carbon emission; J: Energy intensity; L: Tertiary industry structure; U: Gross domestic product per kWh.

Table S5. Average growth rates of each variable over five-year intervals

Variable speed	Variable	2021–2025	2026–2030	2031–2035	2035–2040
Baseline	B	0.32%	0.32%	0.32%	0.32%
	C	5.40%	5.40%	5.40%	5.40%
	D	0.00%	0.00%	0.00%	0.00%
	E	2.64%	2.64%	2.64%	2.64%
	G	−0.77%	−0.77%	−0.77%	−0.77%
	J	0.00%	0.00%	0.00%	0.00%
Low-speed	B	0.20%	0.20%	−0.03%	−0.03%
	C	4.00%	3.00%	2.00%	2.00%
	D	−1.00%	−1.00%	−0.50%	−0.50%
	E	3.00%	1.00%	1.00%	0.20%
	G	−0.35%	−0.35%	−0.35%	−0.35%
	J	−2.00%	−1.00%	−1.00%	−0.50%
Medium-speed	B	0.32%	0.32%	−0.10%	−0.10%
	C	6.00%	5.00%	3.00%	3.00%
	D	−2.00%	−2.00%	−3.00%	−1.50%
	E	4.38%	1.67%	1.67%	0.30%
	G	−0.80%	−0.80%	−1.50%	−0.60%
	J	−3.38%	−3.38%	−5.00%	−2.00%
High-speed	B	0.40%	0.40%	−0.15%	−0.15%
	C	7.00%	6.00%	5.00%	5.00%
	D	−3.00%	−3.00%	−4.00%	−2.00%
	E	5.00%	2.00%	2.00%	0.50%
	G	−1.60%	−1.60%	−1.60%	−1.60%
	J	−5.00%	−4.00%	−6.00%	−3.00%

Notes: B: Population size; C: Per capita gross domestic product; D: Energy structure; E: Urbanization size; G: Secondary industry structure; J: Energy intensity.

Table S6. Carbon emissions in Yunnan Province (2005–2021)

Year	Carbon emissions (million t)	Year	Carbon emissions (million t)
2005	35.62	2014	49.19
2006	39.92	2015	47.72
2007	40.44	2016	47.25
2008	42.57	2017	47.95
2009	46.13	2018	50.73
2010	48.80	2019	51.15
2011	51.56	2020	50.71
2012	53.20	2021	51.50
2013	52.26		

Table S7. The results of logarithmic transformation for each parameter

Year	ln*IY*	ln*B*	ln*C*	ln*D*	ln*E*	ln*F*	ln*G*	ln*H*	ln*J*	ln*L*	ln*U*
2005	8.18	8.40	−0.24	−0.47	−1.22	−0.30	−0.92	−11.51	0.55	−0.87	1.84
2006	8.29	8.41	−0.09	−0.39	−1.19	−0.17	−0.89	−10.82	0.51	−0.87	1.85
2007	8.31	8.41	0.12	−0.41	−1.15	−0.03	−0.90	−10.41	0.40	−0.85	1.92
2008	8.36	8.42	0.28	−0.50	−1.11	0.03	−0.89	−10.13	0.28	−0.86	1.98
2009	8.44	8.43	0.37	−0.47	−1.08	0.07	−0.93	−9.90	0.26	−0.81	2.00
2010	8.49	8.43	0.52	−0.57	−1.06	0.25	−0.86	−5.68	0.18	−0.83	2.04
2011	8.55	8.44	0.73	−0.58	−1.00	0.32	−0.92	−4.90	0.09	−0.79	2.07
2012	8.58	8.45	0.88	−0.63	−0.95	0.43	−0.91	−4.16	0.01	−0.80	2.13
2013	8.56	8.45	1.02	−0.68	−0.92	0.57	−0.94	−3.87	−0.16	−0.77	2.17
2014	8.50	8.46	1.11	−0.84	−0.89	0.57	−0.96	−3.67	−0.20	−0.75	2.22
2015	8.47	8.46	1.17	−0.89	−0.85	0.56	−1.00	−3.26	−0.36	−0.71	2.34
2016	8.46	8.45	1.25	−0.92	−0.81	0.59	−1.05	−2.72	−0.42	−0.67	2.45
2017	8.48	8.45	1.37	−0.97	−0.77	0.57	−1.07	−2.60	−0.50	−0.63	2.49
2018	8.53	8.46	1.49	−1.01	−0.75	0.65	−1.06	−2.54	−0.59	−0.63	2.52
2019	8.54	8.46	1.60	−1.06	−0.72	0.75	−1.06	−2.47	−0.65	−0.65	2.55
2020	8.53	8.46	1.65	−1.05	−0.69	0.66	−1.07	−2.51	−0.63	−0.67	2.50
2021	8.55	8.45	1.75	−1.07	−0.67	0.66	−1.04	−2.58	−0.71	−0.68	2.54

Notes: B: Population size; C: Per capita gross domestic product; D: Energy structure; E: Urbanization size; F: Energy utilization efficiency; G: Secondary industry structure; H: Proportion of renewable energy generation; IY: Carbon emission; J: Energy intensity; L: Tertiary industry structure; U: Gross domestic product per kWh.

In **Table S5**, baseline settings maintain Yunnan's economic and social development without implementing energy conservation and emission-reduction measures; medium-speed settings set parameters based on relevant development planning and programs in Yunnan. The basis setting for the relevant parameters is as follows:

(i) Population parameter setting: According to the National Population Development Plan (2016–2030)[6], China's population is projected to peak around 2030. It is assumed that Yunnan's population will also peak in 2030 and gradually decrease thereafter.

(ii) Per capita gross domestic product (GDP) parameter setting: According to the Outline of the 14th Five-Year Plan for Economic and Social Development and Long-Range Objectives for the Year 2035 in Yunnan Province[7], Yunnan aims to have a per capita regional GDP exceeding USD 10,000 by 2025 and to reach the national average per capita regional GDP by 2035. It is assumed that the per capita GDP will peak at CNY 71,500 in 2025, with the growth rate gradually decreasing thereafter.

(iii) Setting of energy structure parameters: By 2025, Yunnan aims to increase the share of non-fossil energy consumption in primary energy consumption to over 46%, according to the 14th Five-Year Plan for Green Energy Development in Yunnan Province.[8] By 2035, it is projected that the share of fossil energy consumption in primary energy consumption will reach 60%, with the proportion of raw coal consumption in Yunnan decreasing annually.

(iv) Urbanization rate parameter setting: According to the Yunnan Provincial Plan for New-Type Urbanization (2021-2035)[9], Yunnan aims to achieve an urbanization rate of 60% for its permanent resident population by 2025 and 70% by 2035. Therefore, it is assumed that the urbanization rate will reach 60% in 2025 and 70% in 2035.

(v) Industrial structure parameter setting: According to the 14th Five-Year Plan for High-Quality Development of the Manufacturing Industry in Yunnan Province[10] and the Outline of the 14th Five-Year Plan for Economic and Social Development and Long-Range Objectives for the Year 2035 in Yunnan Province[7], Yunnan aims to increase the share of industrial added value in its GDP to 30% by 2025 and to establish a modern economic system by 2035. Therefore, it is

assumed that the share of the secondary industry will gradually decline.

(vi) Energy intensity parameter setting: Based on the 14th Five-Year Plan for Economic and Social Development and Long-Range Objectives for the Year 2035 in Yunnan Province[7] it is assumed that Yunnan's energy intensity will decrease annually in the future.

Low-speed settings are based on medium-speed development, with all parameters growing more slowly. In contrast, high-speed settings accelerate all parameters from medium-speed development.

The ridge trace plot of each parameter in Model M1 is presented in **Figure S1**. Based on the ridge trace plot, the ridge parameter K for Model M1 was determined to be 0.076. Using this ridge parameter as a constraint, a ridge regression analysis was re-conducted, and the detailed results are presented in **Table S8**. The specific expression of Model M1 is given in **Equation S1**. Further t-test results show that the regression coefficients and constant term corresponding to parameters ln$B$, ln$D$, ln$E$, ln$H$, ln$L$, *and* ln$U$ in Model M1 fail to pass the significance test at the 5% level. Consequently, the initially obtained Model M1 does not meet the validation criteria and requires further adjustment.

Since Model M1 failed validation, we eliminated certain parameters and performed model tests to efficiently screen models and developed a new one.

$$\ln IM1 = -2.925 + 1.44 \times \ln B + 0.065 \times \ln C + 0.147 \times \ln D + 0.148 \times \ln E + 0.119 \times \ln F + 0.631 \times \ln G + 0.01 \times \ln H - 0.035 \times \ln L + 0.005 \times \ln U \quad \text{(S1)}$$

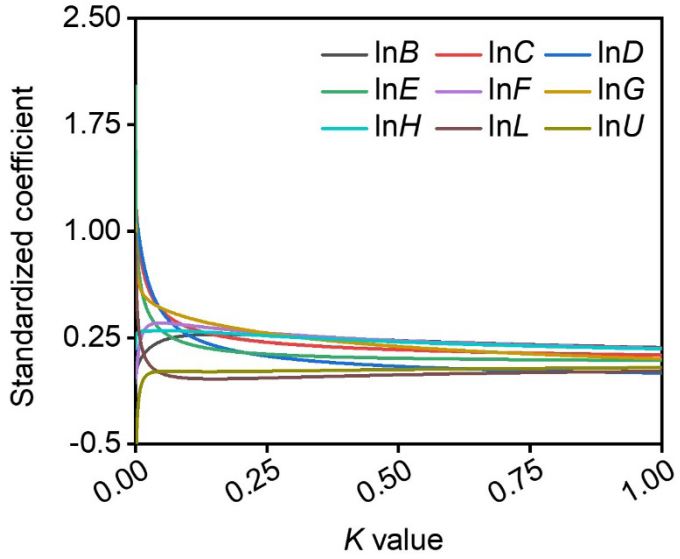

Figure S1. Ridge trace plot of each variable in Model M1

Table S8. Regression test of Model M1 (K = 0.076, t-test, F-test, and R^2)

Variable	Unstandardized coefficients		t-test	p	R^2	Adjusted R^2	F-test	p
	B	Standard error						
Constant	−2.925	7.717	−0.379	0.716				
ln$B$	1.44	0.915	1.575	0.159				
ln$C$	0.065	0.02	3.316	0.013**				
ln$D$	0.147	0.071	2.065	0.078*				
ln$E$	0.148	0.064	2.33	0.053*	0.916	0.876	8.411	0.005***
ln$F$	0.119	0.04	2.959	0.021**				
ln$G$	0.631	0.212	2.972	0.021**				
ln$H$	0.01	0.005	1.78	0.118				
ln$L$	−0.035	0.189	−0.183	0.860				
ln$U$	0.005	0.051	0.106	0.918				

Notes: *$p \le 0.1$; **$p \le 0.05$; ***$p \le 0.01$; B: Population size; C: Per capita gross domestic product; D: Energy structure; E: Urbanization size; F: Energy utilization efficiency; G: Secondary industry structure; H: Proportion of renewable energy generation; J: Energy intensity; L: Tertiary industry structure; U: Gross domestic product per kWh.

Table S9. Model selection using the ridge regression method with variable elimination

Model	Variable	Ridge parameter *K*	Variable test (*t*-test at a 5% significance level)	Variable test (*F*-test at a 5% significance level)
M1	BCDEFGHLU	*K* = 0.076	The variable BDEHLU and the constant term fail the test	
M2	BCDEFGHL	*K* = 0.093	The variable BDHL and the constant term fail the test	
M3	BCDEFGHU	*K* = 0.108	The variable BDHU and the constant term fail the statistical test	
M4	BCDEFGLU	*K* = 0.093	The variable DLU and the constant term fail the test	
M5	BCDEFGH	*K* = 0.133	The variable D and the constant term fail the test	
M6	BCDEFGL	*K* = 0.104	The variable DL and the constant term fail the test	
M7	BCDEFGU	*K* = 0.118	The variable DU and the constant term fail the test	
M8	BCDEFG	*K* = 0.060	The constant term fails the test	
M9	BCDEFU	*K* = 0.097	The variable E and the constant term fail the test	
M10	BCDEGU	*K* = 0.122	The variable DU fails the test	
M11	BCDFGU	*K* = 0.118	The variable DU and the constant term fail the test	
M12	BCEFGU	*K* = 0.138	The variable U and the constant term fail the test	
M13	BDEFGU	*K* = 0.111	The variable DU and the constant term fail the test	
M14	CDEFGU	*K* = 0.130	The variable DU fails the test	Validation passed
M15	BCDEFL	*K* = 0.094	The variable EL and the constant term fail the test	
M16	BCDEGL	*K* = 0.120	The variable DL fails the test	
M17	BCDFGL	*K* = 0.103	The variable DL and the constant term fail the test	
M18	BCEFGL	*K* = 0.123	The variable EL and the constant term fail the test	
M19	BDEFGL	*K* = 0.098	The variable DL and the constant term fail the test	
M20	CDEFGL	*K* = 0.120	The variable DL fails the test	
M21	BCDEFH	*K* = 0.085	The variable BEH and the constant term fail the test	
M22	BCDEGH	*K* = 0.133	The variable D and the constant term fail the test	
M23	BCDFGH	*K* = 0.144	The variable D and the constant term fail the test	
M24	BCEFGH	*K* = 0.169	The variable E and the constant term fail the test	
M25	BDEFGH	*K* = 0.130	The variable D and the constant term fail the test	
M26	CDEFGH	*K* = 0.141	The variable D fails the test	
M27	BCDEF	*K* = 0.084	The variable E and the constant term fail the test	
S-M	BCDEG	*K* = 0.051	All variables and the constant term pass the test	

Notes: B: Population size; C: Per capita gross domestic product; D: Energy structure; E: Urbanization size; F: Energy utilization efficiency; G: Secondary industry structure; H: Proportion of renewable energy generation; J: Energy intensity; L: Tertiary industry structure; U: Gross domestic product per kWh.

Table S10. Variance inflation factor (VIF) values of each variable in Model S-M

Variable	VIF	Variable	VIF
ln*B*	15.094	ln*E*	1087.08
ln*C*	877.447	ln*G*	26.111
ln*D*	36.191		

Table S11. Parameters related to Model O-M

Variable	Unstandardized coefficients *B*	Standardized coefficients Beta	VIF	R^2	Adjusted R^2
Constant	−1.778	-	-		
ln*IS*	1.211	1.072	2.84	0.927	0.916
ln*J*	0.037	0.141	2.84		

Abbreviation: VIF: Variance inflation factor.

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