Supplementary Materials

Understanding the drivers of regional greenhouse gas emissions: a case study of Tatarstan

Irina Demianenko[1], Yong Geng[2]

[1]School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
[2]School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai 200030, China.

Correspondence to: Prof. Yong Geng, School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai 200030, China. E-mail: ygeng@sjtu.edu.cn

ORCID: Yong Geng (0000-0002-2284-1375)

This document presents detailed supplementary materials for the paper " Understanding the Drivers of Regional Greenhouse Gas Emissions: A Case Study of Tatarstan", including tables, figures, and formulas that support and extend the analyses discussed in the main text.

S1. Reconstruction of Sectoral Energy Consumption Series (2005–2016)

To reconstruct the sectoral energy consumption time series prior to 2020, a modified RAS method (biproportional scaling) has been employed, adapted for unidimensional constraints. While the classic RAS algorithm iteratively balances a matrix against known row and column totals, this approach utilizes a unidirectional calibration step. This adaptation is required because, for the historical period, strict physical constraints exist for specific fuel totals, whereas the aggregate sectoral consumption is the unknown variable to be estimated.

First, estimation of the base matrix has been employed. The energy intensity for each economic sector and fuel type is calculated as shown in Eq. (S1)

$$EI_{i,j}^{2017} = \frac{E_{i,j}^{2017}}{G_i^{2017}} \quad \text{(S1)}$$

where $EI_{i,j}^{2017}$ represents the energy intensity for each economic sector *i* and fuel type *j*; $E_{i,j}^{2017}$ represents the consumption of fuel *j* in sector *i*; G_i^{2017} represents the Gross Regional Product (GRP) of the sector *i*.

Second, using the base-year intensity coefficients, a preliminary sector–fuel consumption matrix was generated for each year *t* over the period 2005-2017. This step corresponds to the row-adjustment mechanism in the RAS framework, whereby the base structure is projected according to sectoral economic activity and efficiency trends, described in Eq. (S2)

$$\tilde{E}_{i,j,t} = G_{i,t} * EI_{i,j}^{2017} * \tau_{i,c,t} \quad \text{(S2)}$$

where $G_{i,t}$ denotes sectoral GRP in year *t*, and $\tau_{i,c,t}$ is an exogenously specified trend index for sector *i* and fuel category *c* (gas, oil, solid fuel), normalized to unity in 2017. The trend index captures long-term technological progress and changes in energy efficiency in Russian Federation derived from Rosstat.

Third, to ensure consistency with official regional energy balance statistics, the preliminary matrix was calibrated to match the reported total consumption of each fuel. This adjustment corresponds to the column-scaling component of the RAS procedure. For each fuel *j* and year *t*, a scaling factor $\lambda_{j,t}$ was calculated as in Eq.(S3)

$$\lambda_{j,t} = \frac{C_{j,t}}{\sum_i \tilde{E}_{i,j,t}} \quad \text{(S3)}$$

where $C_{j,t}$ represents the official total consumption of fuel *j* derived from regional energy statistics.

The total reconstructed sectoral fuel consumption was obtained as in Eq. (S4)

$$E_{i,j,t} = \tilde{E}_{i,j,t} * \lambda_{j,t} \quad \text{(S4)}$$

This calibration ensures that the sum of reconstructed sectoral fuel consumption exactly matches the official fuel totals $\sum_i E_{i,j,t} = C_{j,t}$, thereby preserving physical consistency while incorporating sector-specific economic dynamics.

S2. Conversion of economic data to constant 2021 U.S. dollars

All steps of conversion of nominal Gross Regional Product and sectoral output to constant 2021 U.S. dollars are reported below. Nominal values in rubles were adjusted to 2021 prices using annual GDP deflator indices published by Russian Federal State Statistics Service (Rosstat). The conversion was performed in two stages using official Rosstat implicit GDP deflators [1] and the fixed average annual RUB/USD exchange rate for 2021 published by the Central Bank of Russia [2].

First, the nominal values are adjusted for inflation using the official price deflator as shown in Eq. (S5):

$$G_{2021,RUB,t} = \frac{G_{RUB,t}}{D_{2021,t}} \quad \text{(S5)}$$

where $G_{RUB,t}$ denote the nominal gross regional product in year *t*, expressed in current Russian rubles (RUB), $D_{2021,t}$ denote GDP deflators in year *t* with a base year 2021 = 100.

Second, the values obtained in constant rubles were converted to U.S. dollars using the average annual nominal exchange rate set by the Central Bank of the Russian Federation for 2021, as shown in Eq.(S6):

$$G_{2021,USD,t} = \frac{G_{2021,RUB,t}}{E} \quad \text{(S6)}$$

where $G_{2021,USD,t}$ denote the nominal gross regional product in year *t*, expressed in U.S. dollars (USD), E is the fixed average annual exchange rate in 2021 (RUB per USD) and is held constant across all years t (2005-2022).

Supplementary Table 1. Fossil fuel classification and emission factors used in this study[3,4]

No. (t)	Energy type	Category	NCV (TJ/1000 tonnes (mln m3))	Oxidation rate (%)	CC (t CO2/TJ)	N2O (kg N2O/TJ)	CH4 (kg CH4/TJ)
1	Combustible natural gas	Gas	33.82	100	54.4	0.1	1
2	Associated petroleum gas		33.82	100	54.4	0.1	1
3	Liquefied petroleum gas (LPG)		46.01	100	63.1	0.1	1
4	Gasoline	Oil	43.67	100	70	0.6	3
5	Other petroleum products		41.91	100	73.3	0.6	3
6	Diesel		42.50	100	74.1	0.6	3
7	Fuel oil		40.15	100	77.4	0.6	3
8	Bunker fuel		41.12	100	76.0	0.6	3
9	Household boiler fuel		42.50	100	77.4	0.6	3
10	Other solid fuel*	Solid fuel	13.61	100	102	4	30
11	Peat briquettes and semi-briquettes		17.58	100	106	1.5	1
12	Coke		29.01	100	107	1.5	1
13	Coal		-	-	-	-	-
13.1	Donetsk coal		25.61	100	90.2	1.5	1

13.2	Kuznetsk coal	25.41	100	91.9	1.5	1
13.3	Bashkirsky coal	7.74	100	94.2	1.5	1
13.4	Khakassky coal	21.31	100	94.4	1.5	1
13.5	Ekibastuzsky coal	18.41	100	94.6	1.5	1
13.6	Coal from other deposits	22.51	100	94.2	1.5	1
13.7	Imported coal	22.51	100	94.2	1.5	1

* *Xiao et.al*. (2021)

Supplementary Table 2. Detailed industry classification[5]

No. (OKVED-2)	No. (j)	Socioeconomic sectors	Categories
A	**1**	**Agriculture, forestry and fishing**	
01		Crop and animal production, hunting and related service activities	
01.1, 01.2, 01.3		Crop production	Agriculture and Forestry
01.4		Animal production	
01.5		Mixed farming	
02		Forestry and logging	
03		Fisheries and aquaculture	

B	**2**	**Mining and quarrying**	
06		Extraction of crude petroleum and natural gas	
06.1		Extraction of crude petroleum and associated petroleum gas	
08		Other mining and quarrying	
08.1		Quarrying of stone, sand and clay	
09		Mining support service activities	Mining and Extraction
09.1		Support activities for petroleum and natural gas extraction	
09.10.1		Support activities for drilling services related to the production of oil, gas and gas condensate	
09.10.2		Support activities for installation, repair and dismantling of drilling rigs	
C	**3**	**Manufacturing**	
10		Manufacture of food products	
11		Manufacture of beverages	Manufacturing
13		Manufacture of textiles	
14		Manufacture of wearing apparel	

15	Manufacture of leather and related products
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
17	Manufacture of paper and paper products
18	Printing and reproduction of recorded media
19	Manufacture of coke and refined petroleum products
19.2	Manufacture of refined petroleum products
20	Manufacture of chemicals and chemical products
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
22	Manufacture of rubber and plastic products
23	Manufacture of other non-metallic mineral products
24	Manufacture of basic metals
25	Manufacture of fabricated metal products, except machinery and equipment

26		Manufacture of computer, electronic and optical products	
27		Manufacture of electrical equipment	
28		Manufacture of machinery and equipment n.e.c	
29		Manufacture of motor vehicles, trailers and semi-trailers	
30		Manufacture of other transport equipment	
31		Furniture production	
32		Other manufacturing	
33		Repair and installation of machinery and equipment	
D	**4**	**Electricity, gas, steam and air conditioning supply**	
35		Electricity, gas, steam and air conditioning supply	Electricity, gas, steam and air conditioning supply
35.1		Electric power generation, transmission and distribution	
35.11		Production of electricity	

35.2		Manufacture of gas; distribution of gaseous fuels through mains	
35.21		Gas production	
35.3		Production, transmission, distribution of steam and hot water, air conditioning supply	
35.30.1		Production of of steam and hot water	
E	**5**	**Water supply; sewerage, waste management and remediation activities**	
36		Water collection, treatment and supply	
37		Sewerage	
38		Waste collection, treatment and disposal activities; materials recovery	
39		Remediation activities and other waste management services	
F	**6**	**Construction**	Construction
42		Civil engineering	
42.1		Construction of roads and railways	
43		Specialized construction activities	
43.1		Demolition and site preparation	

G		Wholesale and retail trade; repair of motor vehicles and motorcycles	
45		Wholesale and retail trade and repair of motor vehicles and motorcycles	
46		Wholesale trade, except for motor vehicles and motorcycles	
46.71		Wholesale of solid, liquid and gaseous fuels and related products	
47		Retail trade, except of motor vehicles and motorcycles	
H	**7**	**Transportation and storage**	Transportation and storage
49		Land transport and transport via pipelines	
49.1		Passenger rail transport, interurban	
49.2		Freight rail transport	
49.3		Other passenger land transport	
49.4		Freight transport by road and removal services	
49.5		Transport via pipeline	
50		Water transport	
51		Air transport	

52		Warehousing and support activities for transportation	
53		Postal and courier activities	
J	**8**	**Information and communication**	Information and communication
P	**9**	**Education**	Education
Q	**10**	**Human health and social work activities**	Human health and social work activities
86		Health service activities	
S	**11**	**Other service activities**	Other service activities
C	**12**	**Other economic activities***	Other economic activities

*Other economic activities refer to activities not explicitly classified under OKVED-2 but included to ensure a comprehensive accounting of fuel and energy resource combustion.

Supplementary Table 3. Annual LMDI decomposition analysis results on GHG emissions in Tatarstan, 2005-2022 (Mt CO2eq.)

Period	ΔC_P	ΔC_G	ΔC_{IS}	ΔC_{EI}	ΔC_M	ΔC_{CC}
2005-2006	-0.05	2.70	-1.43	1.12	0.27	0.02
2006-2007	0.01	2.82	2.72	-8.16	-0.20	-0.07
2007-2008	0.03	0.99	1.49	-2.84	-0.23	-0.01
2008-2009	0.05	-1.86	6.13	-5.81	0.08	0.00
2009-2010	0.08	-0.33	-2.79	3.92	-0.03	-0.06
2010-2011	0.02	3.51	-1.17	1.42	0.14	0.02
2011-2012	0.22	0.13	1.75	-0.58	0.33	-0.10
2012-2013	0.24	0.56	-2.69	-0.69	-0.69	0.02
2013-2014	0.21	-0.33	2.86	-2.42	-0.07	0.01
2014-2015	0.21	1.20	-3.81	0.57	-0.01	0.03
2015-2016	0.18	1.85	0.80	-2.62	0.28	0.01
2016-2017	0.21	1.09	-0.86	2.71	0.19	0.10
2017-2018	0.17	1.60	-0.73	2.11	-0.09	0.05
2018-2019	0.14	1.16	-0.33	-1.05	0.20	-0.03
2019-2020	0.12	-2.68	-1.13	0.31	0.27	-0.01
2020-2021	0.01	4.40	-1.37	1.12	-0.37	-0.01
2021-2022	0.02	-0.30	-1.41	0.72	0.22	0.02

Supplementary Table 4. Annual LMDI decomposition analysis results on GHG emissions in Tatarstan in key sub-sectors, 2017-2022 (Mt CO2eq.)

Period	ΔC_P	ΔC_G	ΔC_{IS}	ΔC_{EI}	ΔC_M	ΔC_{CC}
2017-2018	0.094	1.775	0.435	0.731	-0.035	0.008
2018-2019	0.076	-0.414	0.624	-0.055	0.219	0.012
2019-2020	0.065	-0.902	-1.219	-2.029	-0.194	-0.011
2020-2021	0.006	0.290	0.913	2.210	-0.049	-0.004
2021-2022	0.011	0.246	0.170	-1.239	0.168	0.01

Supplementary Table 5. Cumulative LMDI decomposition analysis results on GHG emissions in Tatarstan by key sub-sectors and factor, 2017–2022 (Mt CO2eq.)

Sector	ΔC_P	ΔC_G	ΔC_{IS}	ΔC_{EI}	ΔC_M	ΔC_{CC}
Electric power generation, transmission and distribution	0.11	0.42	1.46	-1.66	0.01	0.00
Freight rail transport	0.00	0.00	0.00	0.00	0.00	0.00
Freight transport by road and removal services	0.00	0.00	0.05	-0.07	0.00	0.00
Other passenger land transport	0.00	0.00	-0.58	0.66	0.00	0.01
Passenger rail transport, interurban	0.00	0.00	0.00	0.00	0.00	0.00
Production of of steam and hot water	0.14	0.57	0.00	0.68	0.10	0.01
Water transport	0.00.	0.00	0.00	0.00	0.00	0.00
Total	0.25	1.00	0.92	-0.38	0.11	0.02

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