

SUPPLEMENTARY MATERIAL

Quantifying Sectoral Carbon Footprints in Türkiye's Largest Metropolitan Cities: A Monte Carlo Simulation Approach

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S1. ABBREVIATIONS USED in SUPPLEMENTARY MATERIAL

Agr. Irr. : Agricultural irrigation

CDD: Cooling degree days

Civil Avi.: Civil Aviation

Com./Ins. Build.: Commercial/institutional buildings

EFs: Emission factors

Energy Ind.: Energy industry

FC: Fuel consumed

GHG: Greenhouse gas

HDD: Heating degree days

LPG: Liquefied petroleum gas

LTO: Landing/take-off cycles

Man. Ind. & Const.: Manufacturing industry and construction

MCS: Monte Carlo Simulation

Water-borne Nav.: Water-borne navigation

S2. SYMBOLS USED in SUPPLEMENTARY MATERIAL

°C: Celsius degree

CH₄: Methane

CO₂: Carbon dioxide

GDP/capita: Gross domestic product per capita

gGHG/kg waste: gram of greenhouse gas per kilogram of waste

g MJ⁻¹: gram per megajoule

kg LTO⁻¹: kilogram per landing/take-off cycles

kg_{LTO} GHG⁻¹: kilogram of landing/take-off cycles per greenhouse gas

kg t⁻¹ of fuel: kilogram per ton of fuel

kg TJ⁻¹: kilogram per terajoule

ktCO₂e yr⁻¹: kilotonnes carbon dioxide equivalent per year

L 100km⁻¹: Liter per 100 kilometer

N₂O: Nitrous oxide

T: Temperature

tCO₂e/capita: ton carbon dioxide equivalent per capita

S3. GREENHOUSE GAS EMISSIONS FROM STATIONARY COMBUSTION

Table S1. Energy industry, man. ind. & const. CH₄ and N₂O EFs (kg TJ⁻¹) [113].

GHG Type	Gasoline (Engine, Aviation and Jet)	Diesel	Fuel Oil	Natural Gas
CH ₄	3	3	3	1
N ₂ O	0,6	0,6	0,6	0,1

Table S2. CH₄ and N₂O EFs of commercial/institutional buildings, residential and agricultural/forestry/fishing activities (kg TJ⁻¹) [113].

GHG Type	Fuel Oil	Anthracite	Natural Gas
CH ₄	10	300	5
N ₂ O	0,6	1,5	0,1

S4. GREENHOUSE GAS EMISSIONS FROM MOBILE COMBUSTION

S4.1. Greenhouse gas emissions from road transport

Table S3. CH₄ and N₂O EFs of fuels used on the road (kg TJ⁻¹) [113].

GHG Type	Gasoline (Engine)	Diesel	Natural Gas	LPG
CH ₄	25	3,9	92	62
N ₂ O	8	3,9	3	0,2

Table S4. Average FC (L 100km⁻¹) and EF (g MJ⁻¹) for different vehicle and fuel types [120].

Vehicle Type	Fuel Type	Average FC (L 100km ⁻¹)	EF (CO ₂) (g MJ ⁻¹)	EF (CH ₄) (g MJ ⁻¹)	EF (N ₂ O) (g MJ ⁻¹)
Passenger Cars	Gasoline	8.5	73	0.007	0.02
	Diesel	7.3	74	0.002	0.004
	LPG	11.2	65	0.02	-
Van	Gasoline	13.6	73	0.02	0.001
	Diesel	10.9	74	0.001	0.004
Truck	Gasoline	22.5	73	0.02	0.001
	Diesel	29.9	74	0.006	0.003
Bus	Gasoline	22.5	73	0.02	0.001
	Diesel	29.9	74	0.006	0.003
Minibus	Gasoline	13.6	73	0.02	0.001

Motorcycles	Diesel	10.9	74	0.001	0.004
	Gasoline	4	73	0.1	0.002

S4.2. Greenhouse gas emissions from civil aviation

Table S5. CO₂, CH₄ and N₂O EFs for airline [113].

Fuel Type	CO ₂	CH ₄	N ₂ O
Aviation Gasoline (kg TJ ⁻¹)	70000	0,5	2
Jet Kerosene (kg TJ ⁻¹)	71500	0,5	2
Cruise (kg t ⁻¹ of fuel)	3150	0	0,1

Table S6. EFs (kg_{LTO} GHG⁻¹) and FC (kg LTO⁻¹) for different aircraft types [113].

Aircraft Types	EF (CO ₂)	EF (CH ₄)	EF (N ₂ O)	LTO FC
A310	4760	0.63	0.2	1510
A319	2310	0.06	0.1	730
A321	3020	0.14	0.1	960
A330-200/300	7050	0.13	0.2	2230
A340-200	5890	0.42	0.2	1860
A340-300	6380	0.39	0.2	2020
A340-500/600	10660	0.01	0.3	3370
737-100/200	2740	0.45	0.1	870
737-300/400/500	2480	0.08	0.1	780
737-600	2280	0.1	0.1	720
737-700	2460	0.09	0.1	780
737-800/900	2780	0.07	0.1	880
747-100	10140	4.84	0.3	3210
747-200	11370	1.82	0.4	3600
747-300	11080	0.27	0.4	3510
757-200	4320	0.02	0.1	1370
757-300	4630	0.01	0.1	1460
767-200	4620	0.33	0.1	1460
767-300	5610	0.12	0.2	1780
777-200/300	8100	0.07	0.3	2560
DC-8-50/60/70	5360	0.15	0.2	1700
MD-11	7290	0.24	0.2	2310
MD-80	3180	0.19	0.1	1010
ERJ-145	990	0.06	0.03	310

S4.3. Greenhouse gas emissions from railway transport

Table S7. CH₄ and N₂O EFs for railway (kg TJ⁻¹) [113].

Fuel Type	CH ₄	N ₂ O
Diesel	4,15	28,6
Low-Bituminous Coal	2	1,5

S5. MONTE CARLO SIMULATION METHOD

Table S8. EF values taken for the MCS (kg TJ⁻¹) [113].

Sub-sector	Fuel	GHG	a	c	b
Stationary Combustion	Natural Gas	CO ₂	54300	56100	58300
		CH ₄	1.5	5	15
		N ₂ O	0.03	0.1	0.3
	Coal	CO ₂	94600	98300	101000
		CH ₄	100	300	900
		N ₂ O	0.5	1.5	5
	Fuel Oil	CO ₂	75500	77400	78800
		CH ₄	3	10	30
		N ₂ O	0.2	0.6	2
Mobile Combustion	Gasoline (Road)	CO ₂	67500	69300	73000
		CH ₄	7.5	25	86
		N ₂ O	2.6	8	24
	Diesel (Road)	CO ₂	72600	74100	74800
		CH ₄	1.6	3.9	9.5
		N ₂ O	1.3	3.9	12
	LPG (Road)	CO ₂	61600	63100	65600
		CH ₄	62	62	62
		N ₂ O	0.2	0.2	0.2
	Aviation Gasoline (Civil Aviation)	CO ₂	67500	70000	73000
		CH ₄	0.215	0.5	1
		N ₂ O	0.6	2	5
	Jet Kerosene (Civil Aviation)	CO ₂	69800	71500	74400
		CH ₄	0.215	0.5	1
		N ₂ O	0.6	2	5
	Diesel (Railway)	CO ₂	72600	74100	74800
		CH ₄	1.67	4.15	10.4
		N ₂ O	14.3	28.6	85.8
	Gasoline (Water-borne navigation)	CO ₂	67500	69300	73000
		CH ₄	3.5	7	10.5
		N ₂ O	1.2	2	4.8
	Fuel Oil (Water-borne navigation)	CO ₂	75500	77400	78800
		CH ₄	3.5	7	10.5
		N ₂ O	1.2	2	4.8
	Diesel (Water-borne navigation)	CO ₂	72600	74100	74800
		CH ₄	3.5	7	10.5
		N ₂ O	1.2	2	4.8
Composting		CH ₄ (gGHG/kg waste)	0.03	4	8
		N ₂ O (gGHG/kg waste)	0.06	0.24	0.6

S6. RESULTS

S6.1 Amount of greenhouse gas emissions from stationary combustion

Table S9. Emissions from stationary combustion in Istanbul (ktCO₂e yr⁻¹).

Years	Tier 1					Tier 2				
	Residential	Com./Ins. Build.	Man. Ind. & Const.	Energy Ind.	Agr. Irr.	Residential	Com./Ins. Build.	Man. Ind. & Const.	Energy Ind.	Agr. Irr.
2015	16790.5	12031.0	9070.7	5251.3	2.4	16736.2	12018.6	9050.2	5212.0	2.4
2016	17422.7	12429.6	8893.2	3098.0	2.5	17351.6	12420.0	8872.6	3075.4	2.5
2017	18087.3	12844.7	9514.5	3984.9	3.2	18004.6	12832.2	9489.6	3950.9	3.2
2018	17607.8	16406.0	8013.8	3407.7	4.8	17482.6	16366.9	7993.3	3357.3	4.8
2019	18961.7	17309.0	8658.3	2901.8	11.6	18562.3	17181.1	8603.1	2776.3	11.6
2020	19701.2	15273.6	7295.5	2856.0	18.7	19614.4	15252.4	7286.5	2834.1	18.7

Table S10. Heating-cooling degree day temperatures of Istanbul province [110].

Years	HDD	T≤15°C	CDD	T>22°C
2015	1686	184	238	88
2016	1590	175	286	106
2017	1812	198	199	83
2018	1560	171	279	96
2019	1516	168	187	93
2020	1552	185	223	104

Table S11. Emissions from stationary combustion in Izmir (ktCO₂e yr⁻¹).

Years	Tier 1					Tier 2				
	Residential	Com./Ins. Build.	Man. Ind. & Const.	Energy Ind.	Agr. Irr.	Residential	Com./Ins. Build.	Man. Ind. & Const.	Energy Ind.	Agr. Irr.
2015	3701.2	2430.0	10560.1	5364.2	233.7	3698.1	2429.0	10533.6	5324.1	233.7
2016	4145.2	2809.1	11209.0	4952.7	273.8	4139.6	2808.0	11183.1	4916.5	273.8
2017	4474.4	2968.2	10120.3	6050.6	271.7	4464.8	2966.8	10096.0	5998.8	271.7
2018	4922.5	3261.0	10469.9	5896.6	284.6	4914.1	3258.6	10431.6	5809.4	284.6
2019	4765.3	3979.7	12600.6	3719.8	306.6	4712.6	3972.5	12419.1	3558.9	306.6
2020	4696.7	3492.8	11466.9	2794.8	315.8	4685.9	3491.6	11435.1	2773.4	315.8

Table S12. Heating-cooling degree day temperatures of Izmir province [110].

Years	HDD	T≤15°C	CDD	T>22°C
2015	1184	150	575	128
2016	972	114	722	126
2017	985	130	687	131
2018	803	110	735	148
2019	857	124	707	137
2020	867	128	747	141

Table S13. Emissions from stationary combustion in Ankara (ktCO_{2e} yr⁻¹).

Years	Tier 1					Tier 2				
	Residential	Com./Ins. Build.	Man. Ind. & Const.	Energy Ind.	Agr. Irr.	Residential	Com./Ins. Build.	Man. Ind. & Const.	Energy Ind.	Agr. Irr.
2015	6513.1	4841.8	2791.9	2111.6	52.0	6490.8	4831.7	2786.7	2095.9	52.0
2016	7751.1	4770.3	2685.9	2037.9	93.5	7714.4	4760.0	2680.4	2023.0	93.5
2017	8179.4	5327.9	3319.5	1994.2	100.8	8140.8	5314.2	3312.4	1977.1	100.8
2018	8066.0	5633.0	4105.5	2530.9	112.5	8026.0	5612.1	4093.5	2493.5	112.5
2019	8798.2	5844.3	4781.6	1437.9	139.0	8628.2	5774.2	4736.2	1375.6	139.0
2020	9009.5	5136.2	4532.2	1310.1	149.1	8947.0	5124.6	4526.7	1300.0	149.1

Table S14. Heating-cooling degree day temperatures of Ankara province [110].

Years	HDD	T≤15°C	CDD	T>22°C
2015	2511	203	213	76
2016	2410	212	262	77
2017	2493	217	289	80
2018	1951	182	211	76
2019	2169	194	191	74
2020	2182	198	329	102

S6.2 Amount of greenhouse gas emissions from mobile combustion**Table S15:** Emissions from mobile combustion in Istanbul (ktCO_{2e} yr⁻¹).

Years	Tier 1				Tier 2	
	Road	Civil Avi.	Railway	Water-borne Nav.	Road	Civil Avi.
2015	16332.2	1444.1	203.8	870.7	13501.5	2009.4
2016	17230.9	1488.0	224.6	30.9	14253.2	2032.5
2017	17360.0	1345.6	223.3	19.3	14391.5	1945.2
2018	17236.6	1376.4	269.7	22.1	14312.9	1992.5
2019	16261.8	1560.7	317.5	57.2	13500.1	1995.1
2020	14098.0	881.9	254.3	21.4	11682.8	867.3

Table S16: Emissions from mobile combustion in Ankara (ktCO_{2e} yr⁻¹).

Years	Tier 1			Tier 2	
	Road	Civil Avi.	Railway	Road	Civil Avi.
2015	7588.1	324.4	92.0	6006.2	323.2
2016	8256.3	1021.4	95.5	6558.1	1018.6
2017	8932.4	819.7	104.1	7134.9	816.1
2018	9046.6	812.3	115.1	7237.7	808.8
2019	8806.3	791.0	127.3	7044.3	788.7
2020	8126.6	449.5	107.6	6521.3	447.5

Table S17: Emissions from mobile combustion in Izmir (ktCO_{2e} yr⁻¹).

Years	Road	Tier 1			Tier 2	
		Civil Avi.	Railway	Water-borne Nav.	Road	Civil Avi.
2015	5367.9	373.5	61.1	10.5	4288.0	373.3
2016	5812.8	426.0	67.8	55.4	4684.9	425.8
2017	6101.9	430.9	65.7	46.5	4951.7	431.7
2018	6208.5	425.6	74.4	37.5	5026.2	426.6
2019	5729.4	325.7	82.4	30.4	4456.8	326.6
2020	5392.4	199.3	63.7	54.7	4327.4	199.6

S6.3 Amount of greenhouse gas emissions from enteric fermentation**Table S18:** Emissions from enteric fermentation (ktCO_{2e} yr⁻¹).

Years	Ankara	Istanbul	Izmir
2015	747.2	156.9	1077.6
2016	795.5	155.3	1100.9
2017	1018.7	185.8	1304.4
2018	1166.0	191.1	1434.6
2019	1207.3	205.4	1457.8
2020	1308.5	213.8	1492.0

S6.4 Amount of greenhouse gas emissions from waste sector**Table S19:** Emissions from solid waste landfills (ktCO_{2e} yr⁻¹).

Years	Ankara	Istanbul	Izmir
2015	395.5	3033.9	378.3
2016	533.1	3229.1	383.3
2017	513.7	3466.3	387.4
2018	506.1	3159.2	453.5
2019	524.6	2990.1	450.6
2020	429.4	2973.6	470.2

S6.5 City-based comparisons**Table S20:** Total emission amount from Ankara, Istanbul, and Izmir (ktCO_{2e} yr⁻¹).

Years	Ankara	Istanbul	Izmir
2015	23683.4	63577.8	28126.4
2016	26684.6	62551.0	30175.4
2017	29157.3	65373.0	31155.5
2018	30948.0	66009.7	32407.5
2019	31409.9	67362.3	32217.3
2020	29851.6	62472.5	29334.7

Table S21: Per capita GHG emissions versus per capita GDP for all cities.

Years	Ankara (GDP/capita)	Ankara (tCO _{2e} /capita)	Istanbul (GDP/capita)	Istanbul (tCO _{2e} /capita)	Izmir (GDP/capita)	Izmir (tCO _{2e} /capita)
2015	2768.2	4.49	3441.9	4.34	2388.52	6.75
2016	2728.9	4.99	3407.8	4.23	2357.34	7.14
2017	2679.5	5.35	3356.8	4.35	2326.42	7.28
2018	3116.1	5.62	3986.9	4.38	2810.49	7.50

2019	3649.2	5.57	4447.9	4.34	3131.94	7.38
2020	4431.1	5.27	5102.7	4.04	3629.17	6.68

S6.6 Monte Carlo Simulation Results

Table S22: MCS results from 2015-2020 (ktCO_{2e} yr⁻¹).

	City	2015	2016	2017	2018	2019	2020	Total
Mean	Ankara	24049.3	27476.7	29728.7	31335.2	31812.4	29887	174289.3
	İstanbul	65003.5	63891.3	66772.3	67429.8	69198.1	63521.8	395816.8
	İzmir	28628.8	30685.1	31680.0	32748.6	32725.3	29700.4	186168.3
%2,5	Ankara	21831.6	25080.6	27118.4	28589.2	29037.8	27248.1	158905.7
	İstanbul	59665.0	58717.4	61333.2	61951.2	63570.9	58295.1	363532.8
	İzmir	25970.1	27908.5	28792.0	29780.6	29749.4	26987.6	169188.1
%97,5	Ankara	26267.0	29872.8	32339.1	34081.2	34587	32525.9	189673.0
	İstanbul	70342.0	69065.1	72211.3	72908.5	74825.3	68748.6	428100.7
	İzmir	31287.6	33461.8	34568.0	35716.6	35701.2	32413.2	203148.4
Standard Deviation	Ankara	1131.5	1222.5	1331.8	1401.0	1415.6	1346.4	7848.8
	İstanbul	2723.7	2639.7	2775.0	2795.2	2871.0	2666.7	16471.4
	İzmir	1356.5	1416.7	1473.5	1514.3	1518.3	1384.1	8663.3