Supplementary information

Cooling access and energy requirements for adaptation to heat stress in megacities

Content

1. Input data and projections

1.1. Megacities

We report in Table s1 the set of megacities included in this study. Cities are mapped to the six Global South regions used in the global energy-economy integrated assessment model MESSAGEix (Huppmann et al. 2019): sub-Saharan Africa (AFR), South Asia (SAS), Middle East and North Africa (MEA), Other Pacific Asia (PAS), Centrally planned Asia and China (CPA), and Latin America and the Caribbean (LAM).

Table s1 Set of megacities included in this study.

City	Country	Region[1]	Climate[2]	Latitude	Longitude
Luanda	Angola	AFR	Arid	-8.84	13.29
Kinshasa	Congo DRC	AFR	Tropical	-4.30	15.30
Lagos	Nigeria	AFR	Tropical	6.45	3.40
Dar es Salaam	Tanzania	AFR	Tropical	-6.79	39.21
Dhaka	Bangladesh	SAS	Tropical	23.72	90.41
Karachi	Pakistan	SAS	Arid	24.91	67.08
Lahore	Pakistan	SAS	Arid	31.55	74.34
Hyderabad	India	SAS	Tropical	17.38	78.47
Bangalore	India	SAS	Tropical	12.98	77.58
Chennai	India	SAS	Tropical	13.08	80.28
Kolkata	India	SAS	Tropical	22.57	88.37
Delhi	India	SAS	Temperate	28.60	77.20
Mumbai	India	SAS	Tropical	19.10	72.90
Baghdad	Iraq	MEA	Arid	33.32	44.37
Cairo	Egypt	MEA	Arid	30.04	31.27
Manila	Philippines	PAS	Tropical	14.63	121.02
Jakarta	Indonesia	PAS	Tropical	-6.23	106.84
Beijing	China	CPA	Cold	39.93	116.39
Shanghai	China	CPA	Temperate	29.33	121.06
Buenos Aires	Argentina	LAM	Temperate	-34.60	-58.38
Rio De Janeiro	Brazil	LAM	Tropical	-22.89	-43.20
Sao Paulo	Brazil	LAM	Temperate	-23.55	-46.63

Notes:

[1] Regions in the global energy-economy integrated assessment model MESSAGEix. Further details available at the webpage: https://iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html

[2] Main climate group according to the Köppen–Geiger climate classification (Peel et al. 2007).

1.2. Climatic data

We calculate cooling degree days based on the spatial dataset described in the main text (section 2.4) of this paper for each of the megacities at their coordinates (Table s1). We report in Table s2 the standard cooling degree days (base 18°C) used to calculate the access to air-conditioning (AC) and in Table s3 the variable degree days (base 26°C) used to assess cooling gaps and energy requirements.

Table s2 Standard cooling degree days (base 18°C) for the set of selected megacities under different climates.

City	**Country**	**Climate**			
		Current	**1.5°C**	**2°C**	**3°C**
Kinshasa	Congo DRC	2577	2887	3028	3498
Lagos	Nigeria	3371	3608	3773	4221
Luanda	Angola	2572	2720	3090	3388
Dar es Salaam	Tanzania	2840	3050	3233	3412
Karachi	Pakistan	3004	3372	3548	3855
Dhaka	Bangladesh	2780	2968	3249	3562
Lahore	Pakistan	2484	3115	2901	3250
Hyderabad	India	3222	3396	3524	4117
Bangalore	India	2610	2875	2942	3362
Chennai	India	3937	4086	4292	4628
Kolkata	India	3227	3379	3638	4012
Delhi	India	2660	3161	2985	3520
Mumbai	India	3371	3589	3756	4126
Baghdad	Iraq	1353	1826	1926	1848
Cairo	Egypt	1578	2021	2207	2268
Manila	Philippines	2706	3059	3171	3437
Jakarta	Indonesia	3542	3608	3760	4038
Shanghai	China	927	1049	1059	1276
Beijing	China	967	1088	1136	1060
Buenos Aires	Argentina	678	776	786	827
Rio De Janeiro	Brazil	1863	2053	2322	2610
Sao Paulo	Brazil	851	1063	1198	1478

Table s3 Variable cooling degree days (base 26°C) for the set of selected megacities under different climates.

City	**Country**	**Climate**			
		Current	**1.5°C**	**2.0°C**	**3.0°C**
Kinshasa	Congo DRC	336	510	599	1059
Lagos	Nigeria	987	1217	1382	1828
Luanda	Angola	594	648	848	1110
Dar es Salaam	Tanzania	590	755	908	1080
Karachi	Pakistan	1241	1450	1595	1827
Dhaka	Bangladesh	869	1027	1187	1427
Lahore	Pakistan	1175	1664	1500	1754
Hyderabad	India	1097	1276	1350	1848
Bangalore	India	558	714	776	1107
Chennai	India	1627	1774	1977	2312
Kolkata	India	1201	1372	1510	1813
Delhi	India	1187	1616	1446	1867
Mumbai	India	1196	1411	1566	1930
Baghdad	Iraq	338	640	631	669
Cairo	Egypt	447	781	932	950
Manila	Philippines	401	658	766	1033
Jakarta	Indonesia	1125	1192	1344	1621
Shanghai	China	152	190	216	305
Beijing	China	214	305	317	276
Buenos Aires	Argentina	96	139	133	140
Rio De Janeiro	Brazil	215	307	425	625
São Paulo	Brazil	18	37	78	165

1.3. Demographics and socio-economics

Population data for 2010 and predictions for 2050 under SSP1-3 for the selected megacities (Table s4) are from literature (Hoornweg and Pope 2017). We use per-capita GDP projections from a spatially gridded dataset (Murakami and Yamagata 2019) consistent with the SSP framework (Table s5) and select data at the coordinates of the selected megacities. Figure s1 shows a comparison of GDP projections for the set of megacities from the spatially gridded data and urban per-capita GDP projections at national level (Dellink et al. 2017; Riahi et al. 2017).

Table s4 Population projections for the selected megacities based on (Hoornweg and Pope 2017).

City	**Country**	**Population** (million)			
		2010	**2050 SSP1**	**2050 SSP2**	**2050 SSP3**
Kinshasa	Congo DRC	9.1	34.4	33.3	26.3
Lagos	Nigeria	10.6	34.3	36.3	37.5
Luanda	Angola	4.8	17.0	19.0	22.4
Dar es Salaam	Tanzania	3.3	19.0	19.1	16.5
Karachi	Pakistan	13.1	39.3	37.0	32.0
Dhaka	Bangladesh	14.8	43.9	37.5	31.8
Lahore	Pakistan	7.1	21.4	20.1	17.4
Hyderabad	India	6.8	18.3	16.0	12.6
Bangalore	India	7.2	19.6	17.1	13.4
Chennai	India	7.6	20.4	17.9	14.1
Kolkata	India	15.6	42.1	36.8	29.0
Delhi	India	17.0	46.0	40.2	31.6
Mumbai	India	20.1	54.3	47.4	37.3
Baghdad	Iraq	5.9	14.1	15.3	15.4
Cairo	Egypt	12.5	28.9	27.9	23.1
Manila	Philippines	11.7	25.8	25.3	25.4
Jakarta	Indonesia	9.7	19.2	18.0	15.6
Shanghai	China	15.8	24.1	22.0	19.7
Beijing	China	19.6	29.9	27.3	24.4
Buenos Aires	Argentina	13.1	16.4	18.1	20.9
Rio de Janeiro	Brazil	12.2	14.5	15.7	17.9
Sao Paulo	Brazil	19.6	23.3	25.3	28.7

Table s5 GDP projections for the selected megacities from spatially gridded urban GDP data (Murakami and Yamagata 2019).

City	**Country**	**GDP** (US$2005PPP/cap/yr)			
		2010	**2050 SSP1**	**2050 SSP2**	**2050 SSP3**
Kinshasa	Congo DRC	387	8815	4316	2420
Lagos	Nigeria	1844	14551	9916	6263
Luanda	Angola	7688	16967	10109	6738
Dar es Salaam	Tanzania	1928	16868	9686	5639
Karachi	Pakistan	3076	16432	10971	6526
Dhaka	Bangladesh	2369	20935	12009	7345
Lahore	Pakistan	3480	16325	10436	6016
Hyderabad	India	4012	29939	19137	11821
Bangalore	India	3019	22805	15416	9490
Chennai	India	3855	31877	20559	11770
Kolkata	India	4242	32781	20713	12118
Delhi	India	6785	48188	27913	15180
Mumbai	India	4212	34775	22144	12733
Baghdad	Iraq	5537	24944	17515	16447
Cairo	Egypt	8326	41145	29959	19790
Manila	Philippines	3169	15346	11087	7969
Jakarta	Indonesia	5799	46663	29217	19437
Shanghai	China	8058	62481	45487	31773
Beijing	China	12933	91664	61499	39427
Buenos Aires	Argentina	19669	64235	49836	33358
Rio de Janeiro	Brazil	18574	60431	39620	26345
Sao Paulo	Brazil	18022	56233	36611	23790

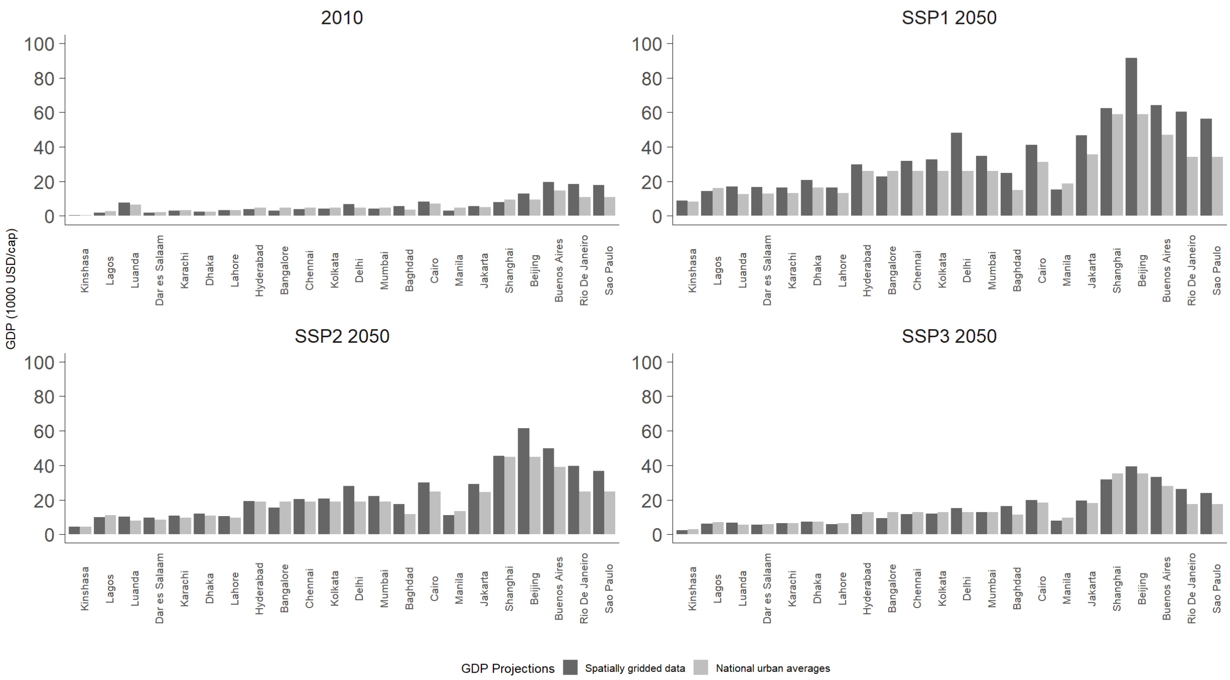

Figure s1 Comparison of GDP projections for the selected cities from spatially gridded data (Murakami and Yamagata 2019) *and national urban averages (Dellink et al. 2017; Riahi et al. 2017).*

1.4. Housing characteristics and cooling systems

We assume minimum floorspace thresholds of 10m^2 per-capita, with minimum 30 m^2 for households with up to 3 persons. These thresholds are from previous work (Rao and Min 2017; Kikstra et al. 2021) and were identified based on national guidelines for affluent, but densely populated countries. By combining household size distribution in countries (United Nations 2019) with the above per capita floorspace thresholds (Kikstra et al. 2021), we derive average per-capita floorspace values by country and attribute them to the set of megacities (Table s6).

Housing characteristics are based on the urban housing archetype identified in prior work (Mastrucci et al. 2019) and representing prevailing construction practices in the global South (Table s7). The urban housing archetype is a four-storey building with concrete framing and roofing, brick masonry, and single-glazing windows. The main building characteristics are defined based on a review of housing with durable materials in developing countries in existing literature (Mastrucci et al. 2019), to which we refer for more detailed information. Equipment for space cooling includes AC systems with 2.9 energy efficiency ratio (EER), corresponding to the current average in developing countries (IEA 2018). We consider here AC as one of the most common technologies to provide space cooling.

Table s6 Floorspace per-capita thresholds.

City	**Country**	**Floorspace** (m^2/cap)
Kinshasa	Congo DRC	10.56
Lagos	Nigeria	10.87
Luanda	Angola	10.80
Dar es Salaam	Tanzania	10.77
Karachi	Pakistan	10.17
Dhaka	Bangladesh	10.44
Lahore	Pakistan	10.17
Hyderabad	India	10.52
Bangalore	India	10.52
Chennai	India	10.52
Kolkata	India	10.52
Delhi	India	10.52
Mumbai	India	10.52
Baghdad	Iraq	10.14
Cairo	Egypt	10.71
Manila	Philippines	10.85
Jakarta	Indonesia	10.87
Shanghai	China	11.78
Beijing	China	11.78
Buenos Aires	Argentina	11.76
Rio De Janeiro	Brazil	11.46
Sao Paulo	Brazil	11.46

Table s7 Characteristics of the building envelope components in the urban archetype based on (Mastrucci et al. 2019).

Envelope component	**Material**	**U-value** (W/m^{2}K)	**Envelope component area on floorspace area** (m^2/ m^2)
Walls	Fired bricks	2.10	0.985
Roof	Concrete	2.06	0.250
Windows	Single-glazing	5.79	0.125
Total envelope		2.18*	1.610

*Note: *Weighted average on building components*

2. Detailed results

2.1. Access to air conditioning

We report here below the projections of AC access (Table s8) and total population with AC access (Table s9) for the set of selected megacities, estimated for the base year 2010 and for 2050 under different SSPs and climate futures. AC access was calculated based on methods in literature (McNeil and Letschert 2008; Isaac and van Vuuren 2009).

We correct AC access values for the base year to better match existing data and literature. Empirical data on ownership of AC in cities is limited and available only for few locations and years (Table s10). Previous works have compared the results of the AC access model used in this study against measured data at national level (Mastrucci et al. 2019, 2021), showing some discrepancies for specific regions, including CPA, MEA, PAS, and SAS. We use the results of previous comparisons (Mastrucci et al. 2021) to rescale AC access values estimated by the empirical model in the base year. After rescaling, the comparison with available measured data provided satisfactory agreement, except for the cities in CPA (Shanghai and Beijing). For these cities, we apply a correction based on the measured results from literature (Hu et al. 2019) and accounting for the time difference between the base year (2010) and year of the survey (2015). While such discrepancies were found in Shanghai and Beijing for the base year, we note that projections of future AC access approach saturation levels, and therefore do not require further corrections.

Table s8 Projections of AC access for the selected megacities in different scenarios. For the base year (2010), "Estim." denotes values estimated using the AC adoption model and "Corr.." values corrected based on existing data and literature.

City	**Country**	**AC access (%)**										
		2010		**2050 SSP1**			**2050 SSP2**			**2050 SSP3**		
		Estim.	**Corr.**	**1.5°C**	**2°C**	**3°C**	**1.5°C**	**2°C**	**3°C**	**1.5°C**	**2°C**	**3°C**
Kinshasa	Congo DRC	1.7		11.2	11.2	11.3	4.2	4.2	4.2	2.7	2.7	2.7
Lagos	Nigeria	2.4		33.1	33.1	33.1	14.1	14.2	14.2	6.5	6.5	6.5
Luanda	Angola	8.8		46.5	46.6	46.7	14.6	14.7	14.7	7.2	7.2	7.2
Dar es Salaam	Tanzania	2.4		46	46	46.1	13.5	13.5	13.5	5.6	5.6	5.6
Karachi	Pakistan	3.1	9.5	43.5	43.5	43.6	17.5	17.5	17.5	6.9	6.9	6.9
Dhaka	Bangladesh	2.7		68.9	69	69.1	21.2	21.3	21.3	8.2	8.2	8.2
Lahore	Pakistan	3.4	10.4	42.9	42.8	42.9	15.7	15.7	15.7	6.1	6.1	6.1
Hyderabad	India	3.9	11.8	94.8	94.9	95	59.4	59.4	59.4	20.5	20.6	20.6
Bangalore	India	3.1	9.4	77.4	77.5	77.6	37.6	37.6	37.7	12.9	12.9	13
Chennai	India	3.8	11.4	96.7	96.7	96.8	67.2	67.2	67.3	20.4	20.4	20.4
Kolkata	India	4.1	12.5	97.2	97.3	97.3	68	68	68	21.7	21.7	21.7
Delhi	India	7.2	22.0	99.7	99.6	99.8	91.9	91.8	92	36.4	36.4	36.4
Mumbai	India	4.1	12.4	98.2	98.3	98.3	74.9	74.9	74.9	24.3	24.3	24.3
Baghdad	Iraq	5.1	36.7	82.7	83.1	82.8	48.4	48.7	48.5	42.3	42.5	42.4
Cairo	Egypt	9.7		97.5	98.1	98.3	93	93.6	93.7	61.8	62.2	62.3
Manila	Philippines	3.2	6.1	37.3	37.3	37.3	17.8	17.8	17.9	9.4	9.4	9.4
Jakarta	Indonesia	5.8	11.1	99.8	99.8	99.9	94	94	94.1	61.1	61.1	61.1
Shanghai	China	8.0	83.0	86.7	86.9	91.3	86.5	86.8	91.1	83.8	84	88.3
Beijing	China	21.3	81.0	87.6	88.7	86.9	87.6	88.7	86.9	87.1	88.2	86.4
Buenos Aires	Argentina	45.8		77.8	78.2	79.8	77.7	78.1	79.8	76	76.4	78
Rio De Janeiro	Brazil	54.6		98	98.8	99.3	97.4	98.2	98.8	87.2	87.9	88.4
Sao Paulo	Brazil	42.7		87	89.9	94	86.1	88.9	93	71	73.3	76.7

Table s9 Projections of population with AC access (million people) in different scenarios for the selected megacities.

City	Country	Population with access to AC (million)									
		2010	2050 SSP1			2050 SSP2			2050 SSP3		
			1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	3.0°C
Kinshasa	Congo DRC	0.15	3.86	3.87	3.88	1.39	1.39	1.4	0.71	0.71	0.71
Lagos	Nigeria	0.25	11.34	11.35	11.35	5.14	5.14	5.14	2.43	2.43	2.44
Luanda	Angola	0.42	7.89	7.91	7.92	2.77	2.78	2.79	1.6	1.61	1.61
Dar es Salaam	Tanzania	0.08	8.75	8.75	8.76	2.57	2.57	2.57	0.93	0.93	0.93
Karachi	Pakistan	1.25	17.12	17.12	17.13	6.45	6.46	6.46	2.2	2.2	2.2
Dhaka	Bangladesh	0.4	30.3	30.34	30.37	7.96	7.97	7.98	2.61	2.61	2.62
Lahore	Pakistan	0.74	9.16	9.14	9.16	3.15	3.15	3.15	1.06	1.06	1.06
Hyderabad	India	0.8	16.46	16.46	16.46	9.48	9.48	9.49	2.58	2.58	2.59
Bangalore	India	0.68	15.14	15.15	15.18	6.42	6.43	6.44	1.74	1.74	1.74
Chennai	India	0.87	18.64	18.64	18.64	12	12.01	12.01	2.86	2.86	2.86
Kolkata	India	1.94	38.63	38.63	38.63	25	25.02	25.03	6.29	6.29	6.3
Delhi	India	3.74	45.44	45.44	45.44	35.66	35.66	35.66	11.51	11.5	11.53
Mumbai	India	2.49	50.36	50.36	50.36	35.49	35.5	35.52	9.07	9.08	9.08
Baghdad	Iraq	2.16	11.66	11.73	11.68	7.41	7.45	7.42	6.53	6.57	6.54
Cairo	Egypt	1.21	27.66	27.66	27.66	25.12	25.12	25.12	14.25	14.35	14.37
Manila	Philippines	0.71	9.63	9.63	9.64	4.52	4.52	4.52	2.38	2.38	2.39
Jakarta	Indonesia	1.08	18.84	18.84	18.84	16.15	16.15	16.15	9.52	9.52	9.52
Shanghai	China	10.42	20.86	20.92	21.97	19	19.06	20.01	16.49	16.54	17.37
Beijing	China	14.64	26.19	26.51	25.99	23.89	24.18	23.7	21.29	21.55	21.13
Buenos Aires	Argentina	5.99	12.76	12.83	13.09	14.08	14.16	14.45	15.85	15.93	16.26
Rio De Janeiro	Brazil	6.64	14.18	14.3	14.37	14.97	14.97	14.97	15.57	15.66	15.66
Sao Paulo	Brazil	8.37	20.26	20.94	21.9	21.79	22.51	23.54	20.39	21.07	22.03

Table s10 Comparison of AC access estimations with measured data for selected megacities.

City	Country	AC access (%)			Year measured value	Source measured data
		Model estimation (2010)	Corrected value (2010)	Measured value		
Delhi	India	7.2	22.0	24	2016-17	(Khosla et al. 2021)
Jakarta	Indonesia	5.8	11.1	6-89*	2012	(Surahman and Kubota 2018)
Shanghai	China	8.0	83.0	87	2015	(Hu et al. 2019)
Beijing	China	21.3	81.0	85	2015	(Hu et al. 2019)
Rio de Janeiro	Brazil	54.6	-	47**	2017	(Pavanello et al. 2021)

Note: *Range based on different housing types, from simple to luxurious. **Value for the state of Rio de Janeiro.

To further characterize uncertainty, we analysis the sensitivity of the AC access results to the main input values, Cooling Degree Days (CDD) and per-capita GDP, by varying them in the range ±10%. Figure s2 shows that varying CDD values has a limited effect on AC access results, as they define the saturation level. The effect is more significant on locations with lower level of CDD. Conversely, varying per-capita GDP inputs substantially affects AC access levels. In the base year, uncertainties are higher for the cities with higher per-capita GDP, including CPA and LAM. In 2050, uncertainties are higher for cities with medium per-capita GDP in the analyzed range, including cities in SAS and PAS, and limited to SSP1, cities in AFR.

2.1. Slums

We report in Table s11 the share of slum population for the set of megacities, based on the national values estimated according to (Mastrucci et al. 2021). The share of slum population is bounded between 0% and 100%. We analysis the uncertainty on slum projections by varying the per-capita GDP by ±10% and report results in Figure s3. The effect of varying per-capita GDP on the share of slum population is comparable across different GDP levels.

2.1. Cooling gaps

We report in this section the complete results of the cooling gap analysis for the set of selected megacities under different SSPs and climate futures, including total population affected by cooling gap (Table s12), population affected by the cooling gap living in slums (Table s13), and the cities with highest cooling gaps (Table s14).

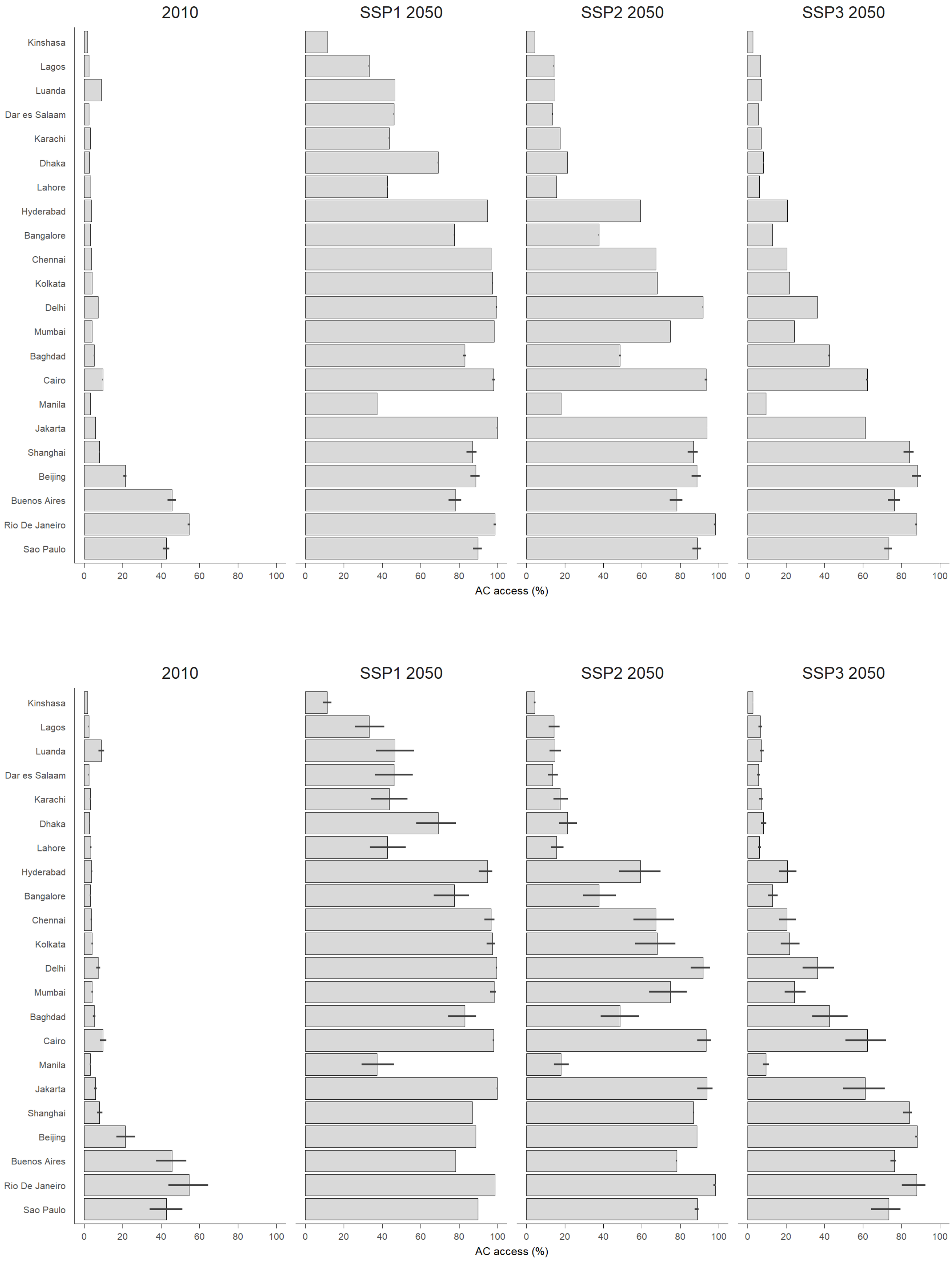

Figure s2 Results of the sensitivity analysis of AC access to the main model input drivers. Whiskers indicate the effect of varying cooling degree days (top panel) and per-capita GDP (bottom panel) by ±10%.

Table s11 Projection of share of slum population in urban for the selected megacities based on national values (Mastrucci et al. 2021).

City	**Country**	**Slum share** (%)			
		2010	**2050 SSP1**	**2050 SSP2**	**2050 SSP3**
Kinshasa	Congo DRC	89.5	32.4	45.4	56
Lagos	Nigeria	61	23.2	30.2	38.6
Luanda	Angola	34.9	20.4	29.9	37.3
Dar es Salaam	Tanzania	60.2	20.5	30.6	40.5
Karachi	Pakistan	51.6	21	28.4	37.9
Dhaka	Bangladesh	56.4	16.5	26.7	35.7
Lahore	Pakistan	49.4	21.1	29.3	39.4
Hyderabad	India	46.8	10	18.2	27
Bangalore	India	52	15	22.1	31
Chennai	India	47.5	8.8	16.9	27.1
Kolkata	India	45.7	8.3	16.7	26.5
Delhi	India	37.1	1.3	11.3	22.4
Mumbai	India	45.9	7.2	15.5	25.6
Baghdad	Iraq	40.9	13.3	19.8	20.9
Cairo	Egypt	33.4	4.2	10	17.6
Manila	Philippines	51.1	22.2	28.2	34.2
Jakarta	Indonesia	40	1.9	10.4	17.9
Shanghai	China	34	0	2.3	8.9
Beijing	China	25.3	0	0	4.9
Buenos Aires	Argentina	17.7	0	0.7	8
Rio De Janeiro	Brazil	18.7	0	4.9	12.3
Sao Paulo	Brazil	19.3	0	6.3	14.2

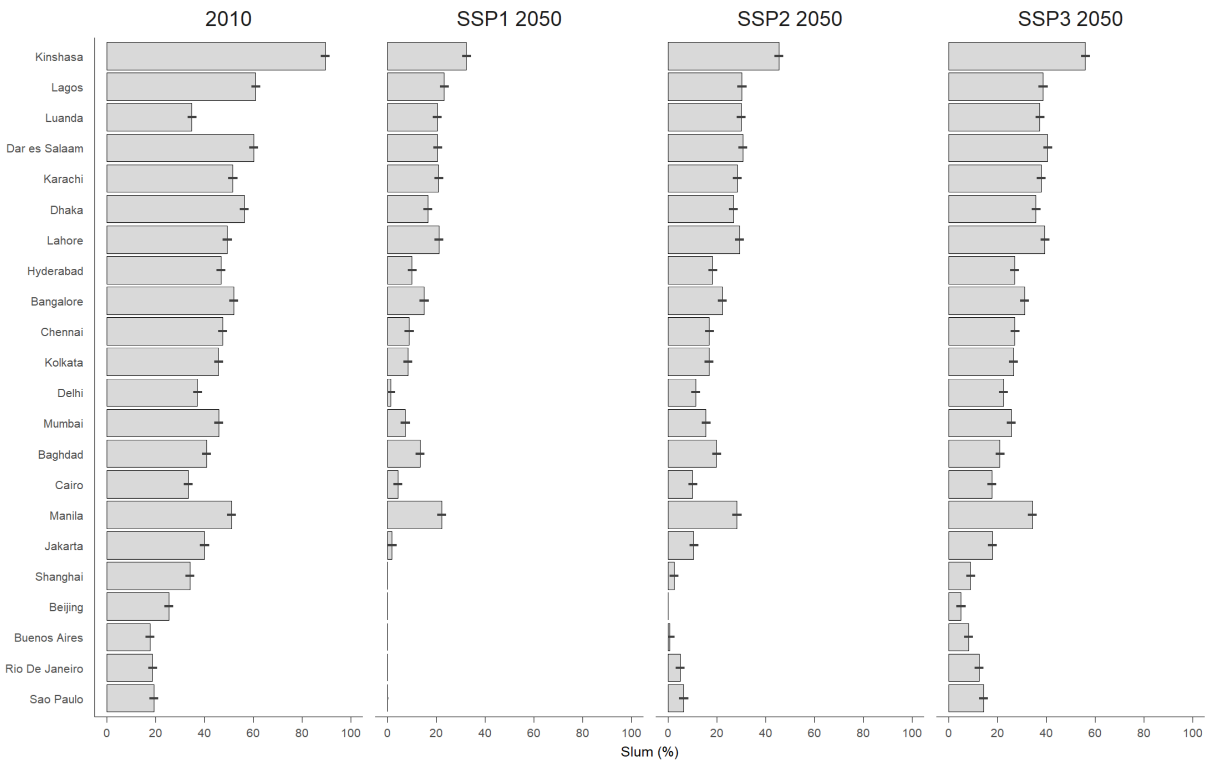

Figure s3 Results of the sensitivity analysis of slum projections to the main model input drivers. Whiskers indicate the effect of varying per-capita GDP by ±10%.

Table s12 Total cooling gap (million people) in different scenarios for the selected megacities.

City	Country	Total cooling gap (million people)									
		2010	2050 SSP1			2050 SSP2			2050 SSP3		
			1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	3.0°C
Kinshasa	Congo DRC	8.9	30.55	30.55	30.54	31.93	31.93	31.93	25.55	25.54	25.54
Lagos	Nigeria	10.32	22.96	22.95	22.95	31.18	31.18	31.18	35.11	35.11	35.1
Luanda	Angola	4.35	9.09	9.07	9.06	16.18	16.17	16.17	20.75	20.75	20.75
Dar es Salaam	Tanzania	3.24	10.27	10.26	10.25	16.51	16.51	16.51	15.54	15.54	15.54
Karachi	Pakistan	11.81	22.21	22.2	22.19	30.52	30.52	30.52	29.77	29.77	29.77
Dhaka	Bangladesh	14.4	13.65	13.6	13.57	29.51	29.49	29.49	29.21	29.2	29.2
Lahore	Pakistan	6.35	12.21	12.23	12.21	16.94	16.95	16.94	16.3	16.31	16.3
Hyderabad	India	5.96	1.83	1.83	1.83	6.49	6.48	6.48	9.99	9.99	9.98
Bangalore	India	6.55	4.41	4.4	4.37	10.65	10.65	10.63	11.71	11.7	11.7
Chennai	India	6.69	1.81	1.81	1.81	5.85	5.85	5.85	11.19	11.19	11.19
Kolkata	India	13.63	3.51	3.51	3.51	11.79	11.77	11.76	22.67	22.67	22.67
Delhi	India	13.28	0.59	0.59	0.59	4.53	4.53	4.53	20.12	20.14	20.11
Mumbai	India	17.58	3.93	3.93	3.93	11.91	11.9	11.89	28.25	28.25	28.24
Baghdad	Iraq	3.73	2.45	2.38	2.43	7.9	7.85	7.89	8.91	8.87	8.9
Cairo	Egypt	11.29	1.2	1.2	1.2	2.78	2.78	2.78	8.82	8.73	8.7
Manila	Philippines	10.95	16.19	16.19	16.18	20.82	20.81	20.81	22.98	22.97	22.97
Jakarta	Indonesia	8.63	0.36	0.36	0.36	1.88	1.88	1.88	6.06	6.06	6.05
Shanghai	China	5.37	3.21	3.15	2.1	2.95	2.9	1.94	3.19	3.14	2.31
Beijing	China	4.97	3.71	3.39	3.91	3.38	3.09	3.57	3.15	2.89	3.31
Buenos Aires	Argentina	7.1	3.65	3.58	3.32	4.04	3.96	3.67	5.01	4.93	4.6
Rio De Janeiro	Brazil	5.53	0.3	0.18	0.1	0.76	0.76	0.76	2.29	2.2	2.2
Sao Paulo	Brazil	11.21	3.03	2.35	1.4	3.53	2.8	1.77	8.35	7.67	6.7

Table s13 Population living in slums (million people) in different scenarios for the selected megacities.

City	**Country**	**Population living in slums (million)**									
		2010	**2050 SSP1**			**2050 SSP2**			**2050 SSP3**		
			1.5°C	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Kinshasa	Congo DRC	8.11	11.14	11.14	11.14	15.14	15.14	15.14	14.71	14.71	14.71
Lagos	Nigeria	6.45	7.95	7.95	7.95	10.97	10.97	10.97	14.5	14.5	14.5
Luanda	Angola	1.66	3.46	3.46	3.46	5.66	5.66	5.66	8.33	8.33	8.33
Dar es Salaam	Tanzania	2	3.89	3.89	3.89	5.85	5.85	5.85	6.67	6.67	6.67
Karachi	Pakistan	6.74	8.24	8.24	8.24	10.48	10.48	10.48	12.1	12.1	12.1
Dhaka	Bangladesh	8.35	7.26	7.26	7.26	10	10	10	11.36	11.36	11.36
Lahore	Pakistan	3.5	4.51	4.51	4.51	5.88	5.88	5.88	6.83	6.83	6.83
Hyderabad	India	3.16	1.83	1.83	1.83	2.9	2.9	2.9	3.39	3.39	3.39
Bangalore	India	3.76	2.93	2.93	2.93	3.78	3.78	3.78	4.17	4.17	4.17
Chennai	India	3.59	1.81	1.81	1.81	3.01	3.01	3.01	3.8	3.8	3.8
Kolkata	India	7.13	3.51	3.51	3.51	6.15	6.15	6.15	7.69	7.69	7.69
Delhi	India	6.32	0.59	0.59	0.59	4.53	4.53	4.53	7.09	7.09	7.09
Mumbai	India	9.21	3.93	3.93	3.93	7.35	7.35	7.35	9.57	9.57	9.57
Baghdad	Iraq	2.41	1.88	1.88	1.88	3.03	3.03	3.03	3.23	3.23	3.23
Cairo	Egypt	4.18	1.2	1.2	1.2	2.78	2.78	2.78	4.05	4.05	4.05
Manila	Philippines	5.96	5.74	5.74	5.74	7.13	7.13	7.13	8.67	8.67	8.67
Jakarta	Indonesia	3.88	0.36	0.36	0.36	1.88	1.88	1.88	2.79	2.79	2.79
Shanghai	China	5.37	0	0	0	0.51	0.51	0.51	1.75	1.75	1.75
Beijing	China	4.97	0	0	0	0	0	0	1.21	1.21	1.21
Buenos Aires	Argentina	2.31	0	0	0	0.12	0.12	0.12	1.67	1.67	1.67
Rio De Janeiro	Brazil	2.28	0	0	0	0.76	0.76	0.76	2.2	2.2	2.2
Sao Paulo	Brazil	3.77	0	0	0	1.6	1.6	1.6	4.08	4.08	4.08

Table s14 Cities with the highest cooling gaps in 2050 under different SSPs and 2.0°C climate.

2050 – SSP1		2050 – SSP2		2050 – SSP3	
City	**Cooling gap** (million people)	**City**	**Cooling gap** (million people)	**City**	**Cooling gap** (million people)
1. Kinshasa	30.5	1. Kinshasa	31.9	1. Lagos	35.1
2. Lagos	23.0	2. Lagos	31.1	2. Karachi	29.8
3. Karachi	22.2	3. Karachi	30.5	3. Dhaka	29.2
4. Manila	16.2	4. Dhaka	29.5	4. Mumbai	28.2
5. Dhaka	13.6	5. Manila	20.8	5. Kinshasa	25.5

2.2. Energy requirements

We report in this section the complete results of the analysis of minimum energy requirements for basic cooling comfort for the set of selected megacities under different SSPs and climate futures, including energy intensities (Table s15), total energy demand under projected AC access (Table s16), total energy requirements under universal access to cooling comfort (Table s17), and the cities with highest energy requirements under universal access to cooling comfort (Table s18).

Table s15 Energy intensity for basic space cooling for the set of selected megacities under different climates.

City	**Country**	**Energy intensity (kWh/m^2/yr)**			
		Climate			
		Current	**1.5°C**	**2.0°C**	**3.0°C**
Kinshasa	Congo DRC	7.80	9.29	10.28	12.54
Lagos	Nigeria	11.74	12.94	13.75	15.79
Luanda	Angola	8.58	9.18	10.80	12.25
Dar es Salaam	Tanzania	9.27	10.67	11.67	12.71
Karachi	Pakistan	11.30	13.03	13.68	15.17
Dhaka	Bangladesh	9.65	10.53	11.53	12.88
Lahore	Pakistan	9.75	12.42	11.49	12.87
Hyderabad	India	11.64	12.36	12.95	15.99
Bangalore	India	8.46	9.88	10.29	12.58
Chennai	India	14.93	15.71	16.69	18.13
Kolkata	India	11.47	12.23	13.29	14.93
Delhi	India	10.10	12.34	11.46	13.65
Mumbai	India	13.04	14.14	14.99	16.65
Baghdad	Iraq	4.44	6.35	6.56	6.59
Cairo	Egypt	5.88	7.71	8.55	8.80
Manila	Philippines	8.30	10.42	11.11	12.30
Jakarta	Indonesia	12.89	13.18	13.84	15.02
Shanghai	China	2.47	2.90	2.95	3.81
Beijing	China	3.13	3.73	3.81	3.56
Buenos Aires	Argentina	2.00	2.30	2.38	2.55
Rio De Janeiro	Brazil	4.90	5.81	6.71	8.24
Sao Paulo	Brazil	1.42	2.05	2.57	3.80

Table s16 Projections of total minimum energy demand for basic cooling comfort under projected AC access in different scenarios for the selected megacities.

City	Country	Energy demand for basic cooling comfort (PJ/yr)									
		2010	2050 SSP1			2050 SSP2			2050 SSP3		
			1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	3.0°C
Kinshasa	Congo DRC	0.05	1.36	1.51	1.85	0.49	0.54	0.66	0.25	0.28	0.34
Lagos	Nigeria	0.12	5.74	6.1	7.01	2.6	2.77	3.18	1.23	1.31	1.51
Luanda	Angola	0.14	2.82	3.32	3.77	0.99	1.17	1.33	0.57	0.67	0.77
Dar es Salaam	Tanzania	0.03	3.62	3.96	4.32	1.06	1.16	1.27	0.38	0.42	0.46
Karachi	Pakistan	0.52	8.17	8.58	9.52	3.08	3.23	3.59	1.05	1.1	1.22
Dhaka	Bangladesh	0.14	11.98	13.14	14.7	3.15	3.45	3.86	1.03	1.13	1.27
Lahore	Pakistan	0.26	4.16	3.85	4.32	1.43	1.32	1.49	0.48	0.45	0.5
Hyderabad	India	0.35	7.7	8.07	9.97	4.44	4.65	5.75	1.21	1.27	1.57
Bangalore	India	0.22	5.67	5.9	7.23	2.4	2.5	3.07	0.65	0.68	0.83
Chennai	India	0.49	11.09	11.78	12.8	7.14	7.59	8.24	1.7	1.81	1.97
Kolkata	India	0.84	17.9	19.44	21.84	11.58	12.59	14.15	2.91	3.17	3.56
Delhi	India	1.43	21.24	19.72	23.5	16.66	15.48	18.44	5.38	4.99	5.96
Mumbai	India	1.23	26.97	28.6	31.75	19	20.16	22.39	4.86	5.15	5.72
Baghdad	Iraq	0.35	2.7	2.81	2.81	1.72	1.78	1.79	1.51	1.57	1.57
Cairo	Egypt	0.27	8.23	9.12	9.38	7.47	8.28	8.52	4.24	4.73	4.88
Manila	Philippines	0.23	3.92	4.18	4.63	1.84	1.96	2.17	0.97	1.03	1.15
Jakarta	Indonesia	0.54	9.72	10.2	11.07	8.33	8.74	9.49	4.91	5.15	5.6
Shanghai	China	1.09	2.57	2.62	3.55	2.34	2.39	3.23	2.03	2.07	2.81
Beijing	China	1.94	4.15	4.28	3.92	3.78	3.91	3.58	3.37	3.48	3.19
Buenos Aires	Argentina	0.51	1.24	1.29	1.41	1.37	1.43	1.56	1.55	1.61	1.76
Rio De Janeiro	Brazil	1.34	3.4	3.96	4.89	3.59	4.14	5.09	3.73	4.34	5.32
Sao Paulo	Brazil	0.49	1.71	2.22	3.43	1.84	2.39	3.69	1.72	2.23	3.45

Table s17 Minimum energy requirements for universal access to basic cooling comfort in different scenarios for the selected megacities.

City	Country	Energy requirements for universal access to basic comfort (PJ/yr)									
		2010	2050 SSP1			2050 SSP2			2050 SSP3		
			1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	3.0°C
Kinshasa	Congo DRC	2.68	12.15	13.45	16.4	11.77	13.03	15.88	9.27	10.26	12.51
Lagos	Nigeria	4.85	17.36	18.46	21.2	18.39	19.54	22.44	19.01	20.2	23.2
Luanda	Angola	1.59	6.06	7.13	8.09	6.76	7.96	9.02	7.97	9.38	10.64
Dar es Salaam	Tanzania	1.19	7.87	8.6	9.37	7.9	8.63	9.4	6.81	7.45	8.11
Karachi	Pakistan	5.4	18.76	19.7	21.85	17.64	18.52	20.54	15.25	16.01	17.76
Dhaka	Bangladesh	5.36	17.38	19.04	21.27	14.82	16.23	18.13	12.58	13.78	15.4
Lahore	Pakistan	2.53	9.71	8.99	10.07	9.13	8.45	9.47	7.89	7.3	8.18
Hyderabad	India	2.98	8.56	8.97	11.07	7.47	7.83	9.67	5.88	6.16	7.61
Bangalore	India	2.32	7.32	7.62	9.31	6.39	6.65	8.13	5.03	5.24	6.4
Chennai	India	4.27	12.17	12.92	14.04	10.62	11.28	12.26	8.36	8.88	9.65
Kolkata	India	6.77	19.52	21.2	23.82	17.04	18.51	20.8	13.42	14.57	16.37
Delhi	India	6.51	21.51	19.98	23.8	18.78	17.44	20.78	14.79	13.73	16.36
Mumbai	India	9.91	29.07	30.83	34.23	25.38	26.92	29.88	19.98	21.19	23.53
Baghdad	Iraq	0.95	3.27	3.38	3.4	3.55	3.66	3.68	3.58	3.7	3.71
Cairo	Egypt	2.84	8.58	9.51	9.79	8.3	9.19	9.47	6.86	7.6	7.83
Manila	Philippines	3.78	10.51	11.2	12.4	10.31	10.99	12.17	10.32	11	12.18
Jakarta	Indonesia	4.89	9.9	10.39	11.28	9.3	9.76	10.59	8.03	8.43	9.15
Shanghai	China	1.65	2.96	3.02	3.89	2.7	2.75	3.55	2.42	2.47	3.18
Beijing	China	2.6	4.74	4.83	4.51	4.32	4.41	4.12	3.87	3.95	3.69
Buenos Aires	Argentina	1.11	1.6	1.66	1.77	1.77	1.83	1.96	2.03	2.1	2.25
Rio De Janeiro	Brazil	2.46	3.47	4.01	4.92	3.77	4.36	5.35	4.28	4.94	6.07
Sao Paulo	Brazil	1.15	1.97	2.47	3.65	2.14	2.68	3.97	2.43	3.05	4.5

Table s18 Cities with the highest minimum energy requirements for universal access to cooling in 2050 under different SSPs and 2.0°C climate.

2050 – SSP1		**2050 – SSP2**		**2050 – SSP3**	
City	**Energy requirements** (PJ/yr)	**City**	**Energy requirements** (PJ/yr)	**City**	**Energy requirements** (PJ/yr)
1. Mumbai	30.8	1. Mumbai	26.9	1. Mumbai	21.1
2. Kolkata	21.2	2. Lagos	19.5	2. Lagos	20.2
3. Dehli	20.0	3. Karachi	18.5	3. Karachi	16.0
4. Karachi	19.7	4. Kolkata	18.5	4. Kolkata	14.6
5. Dhaka	19.0	5. Dhaka	17.4	5. Dhaka	13.8

Thermal comfort thresholds and cooling behavior of households are characterized by large uncertainties (Mastrucci et al. 2019; Khosla et al. 2021), that can substantially affect cooling requirements across different regions. Figure s4 shows the results of the sensitivity analysis of cooling energy intensity to main behavior-related model input drivers, including variation of indoor set point temperatures by ±2°C and doubling the number of hours of operation of cooling systems. Similar to previous studies (Mastrucci et al. 2019), the results show a high level of uncertainty related to both set point temperatures and hours of cooling operation. The effect of varying other activity-related parameter, such as per-capita floorspace and share of cooled floorspace, is similar to varying the number of hours of cooling operation, and therefore not shown.

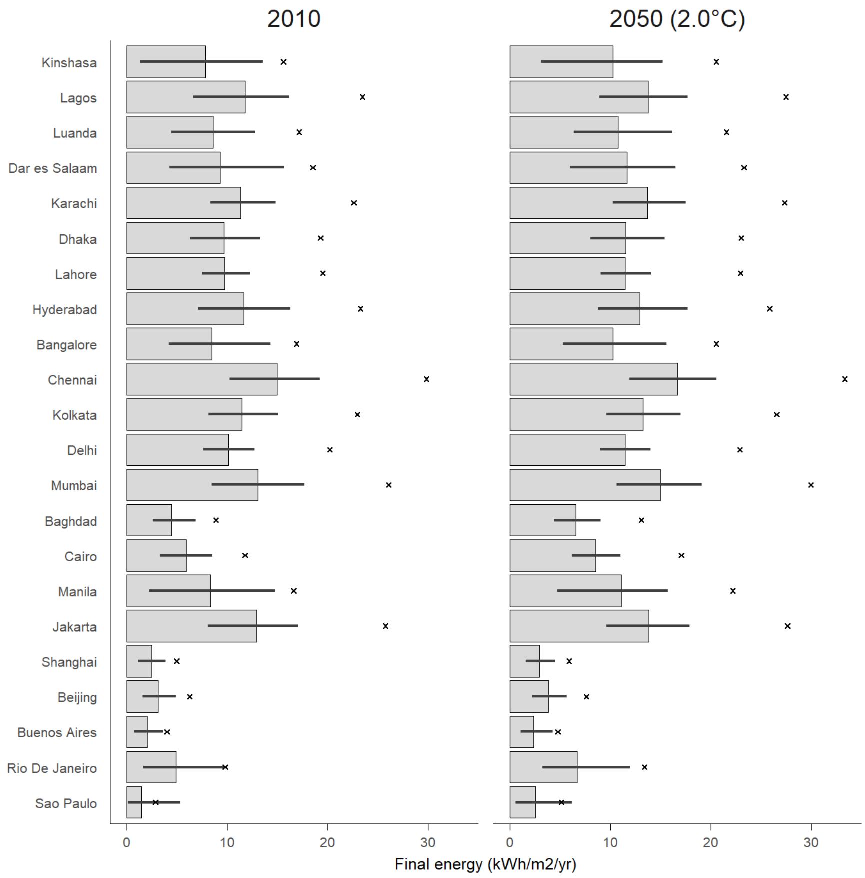

Figure s4 Results of the sensitivity analysis of energy intensity for basic cooling to the main model input drivers. Whiskers indicate the effect of varying the indoor set point temperature by ±2°C. The symbols "x" indicate energy intensities after doubling the number of hours of cooling operation.

Bibliography

Dellink R, Chateau J, Lanzi E, Magne B (2017) Long-term economic growth projections in the Shared Socioeconomic Pathways. Glob Environ Chang 42:200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

Hoornweg D, Pope K (2017) Population predictions for the world's largest cities in the 21st century. Environ Urban 29:195–216. https://doi.org/10.1177/0956247816663557

Hu S, Yan D, Qian M (2019) Using bottom-up model to analyze cooling energy consumption in China's urban residential building. Energy Build 202:. https://doi.org/10.1016/j.enbuild.2019.109352

Huppmann D, Gidden M, Fricko O, et al (2019) The MESSAGE ix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy , climate , the environment , and sustainable development. Environ Model Softw 112:143–156. https://doi.org/10.1016/j.envsoft.2018.11.012

IEA (2018) The Future of cooling. Opportunities for energy-efficient air conditioning. 90. https://doi.org/10.1016/S0181-5512(07)79285-9

Isaac M, van Vuuren DP (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37:507–521. https://doi.org/10.1016/j.enpol.2008.09.051

Khosla R, Agarwal A, Sircar N, Chatterjee D (2021) The what, why, and how of changing cooling energy consumption in India's urban households. Environ Res Lett 16:. https://doi.org/10.1088/1748-9326/abecbc

Kikstra JS, Mastrucci A, Min J, et al (2021) Decent living gaps and energy needs around the world. Environ Res Lett 16:. https://doi.org/https://doi.org/10.1088/1748-9326/ac1c27

Mastrucci A, Byers E, Pachauri S, Rao ND (2019) Improving the SDG energy poverty targets : Residential cooling needs in the Global South. Energy Build 186:405–415. https://doi.org/10.1016/j.enbuild.2019.01.015

Mastrucci A, van Ruijven B, Poblete-Cazenave M, et al (2021) Global scenarios of residential heating and cooling energy demand. Clim Change 168:. https://doi.org/https://doi.org/10.1007/s10584-021-03229-3

McNeil M a., Letschert VE (2008) Future air conditioning energy consumption in developing countries and what can be done about it: the potential of effi ciency in the residential sector

Murakami D, Yamagata Y (2019) Estimation of Gridded Population and GDP Scenarios with Spatially Explicit Statistical Downscaling. Sustainability 11:1–18. https://doi.org/10.3390/su11072106

Pavanello F, De Cian E, Davide M, et al (2021) Air-conditioning and the adaptation cooling deficit in emerging economies. Nat Commun 12:. https://doi.org/10.1038/s41467-021-26592-2

Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644. https://doi.org/10.5194/hess-11-1633-2007

Rao ND, Min J (2017) Decent Living Standards: Material Prerequisites for Human Wellbeing. Soc Indic Res 138:225–244. https://doi.org/10.1007/s11205-017-1650-0

Riahi K, Vuuren DP Van, Kriegler E, et al (2017) The Shared Socioeconomic Pathways and their energy , land use , and greenhouse gas emissions implications : An overview. 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Surahman U, Kubota T (2018) Chapter 32 Household Energy Consumption and CO2 Emissions for Residential Buildings in Jakarta and Bandung of Indonesia. In: Sustainable Houses and Living in the Hot-Humid Climates of Asia. Springer Nature Singapore Pte Ltd., pp 325–333

United Nations (2019) Household Size & Composition Last acccessed March 2022. https://www.un.org/development/desa/pd/data/household-size-and-composition