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Performance determinants show European cities are delivering on climate mitigation

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Cities are crucial climate change actors, developing largely voluntary action plans and emission reduction targets. There is limited evidence, however, of their impact through transnational climate initiatives and little empirical support linking mitigation strategies and emissions reductions. Here, we show that 60% of more than 1,000 EU Covenant of Mayors' cities are on track to achieve their 2020 emission reduction targets. Assessments of cities' mitigation outcomes and the determinants of performance show that on-track cities tend to have less-ambitious targets and higher baseline emissions and are in countries with more-ambitious national climate policies and greater realized emissions reductions than cities that are not on track. Automated textual analysis and a regression model find city emissions reduction is influenced by plan-level, city-level and country-level characteristics. Greater emissions reductions are associated with plans targeting energy efficiency. These results of city-level achievement provide empirical support for the theorized subnational actors' contribution to global climate mitigation.

Subnational actors, which broadly include cities (for example, local jurisdictions that can include towns, urban communities, districts and counties) as well as regions (for example, subnational units that are generally broader in population and area), have become increasingly critical climate actors in recent years. These actors are adopting their own climate policies and mitigation plans[1–4], experimenting with innovative climate policy solutions that could be transferred to other local governments or scaled nationally[5,6] and building local capacity to address climate change[7]. At the international level, subnational governments often participate in transnational climate governance networks and facilitate learning and exchange between local governments and other organizations, gathering resources and knowledge that can be applied within their own national contexts[7]. The UNFCCC's Global Climate Action Portal has listed 10,614 city actors and 242 regional actors as of January 2020[8]—a number that includes 9,998 signatories from the European Union alone (www.covenantofmayors.eu/)—an increase from 7,025 cities in 2015 recording climate action[9].

While these participation trends in networks indicate a growing momentum of city government involvement in global mitigation efforts, what is less clear is their impact and performance—whether local governments are implementing largely voluntary climate actions and achieving emissions reductions. The IPCC's Chapter 12, Human Settlements, Infrastructure and Spatial Planning, in the Fifth Assessment Report concluded that there are few evaluations of urban climate action plans and their effectiveness[10], due to the lack of consistent accounting methodologies, inter-agency coordination and sparse data available on policy implementation and urban-scale GHGs to evaluate progress[11–14]. The literature further lacks evidence detailing the results of cities' climate strategies and actions and how these efforts translate into CO_2 emissions reductions[15,16]. The few analyses that do exist are mixed in their conclusions regarding whether voluntary subnational climate pledging and public reporting actually translate to achieved emission reductions. In an analysis of 25 cities that report to the Carbonn Climate Registry, no notable difference in emissions outcomes was seen between cities that reported commitments and those that did not[17]. However, participation in the C40 Climate Leadership network, which includes primarily large and wealthy megacities, was associated with increased solar photovoltaic investment among 512 cities, supporting the theory of transnational municipal climate participation's positive influence[18]. An evaluation of six cities (New York, Berlin, London, Greater Toronto, Boston and Seattle) with regularly reported GHG emissions inventories indicated that while each city was achieving reductions, the underlying drivers, whether policy or efficiency improvements, could not be distinguished[19].

To address this gap, we evaluate cities' GHG emissions mitigation performance in the transnational climate initiative EU Covenant of Mayors (EUCoM). Initiated in 2008, the EUCoM requires its members to exceed the EU's 2020 target of 20% reduction in CO_2 emissions from 1990 levels[20]. Those who signed up after 2015 commit to reduce their CO_2 emissions by at least 40% by 2030 in support of the EU's Nationally Determined Contribution to the Paris Agreement[20]. The EUCoM also requires its members to submit a Sustainable Energy and Climate Action Plan that details specific measures and policies they intend to implement to achieve their targets, focused primarily on energy consumption in the buildings and transport sectors, as well as baseline and biennial emissions monitoring reports. Because of these regular reporting requirements, the EUCoM is one of the few transnational climate initiatives that provides data adequate to determine whether local governments are achieving their goals and to shed light on the approaches adopted to address climate change mitigation. Two-thirds of the EUCoM members have a population of fewer than 10,000 inhabitants, making it a useful case study for understanding the climate mitigation impacts and contributions of smaller cities.

To evaluate the EUCoM cities' performance, we develop a statistical model (Equation (1)) that assesses cities' progress on their predominantly 2020 emissions reductions targets and the relationship to their key actions, controlling for a range of city-level and national characteristics, such as gross domestic product (GDP), population and national emissions reduction (see 54321Methods). We use natural-language-processing techniques—specifically, structural topic modelling (STM)[21]—to identify topical themes in the EUCoM cities' climate actions and incorporate these themes into our

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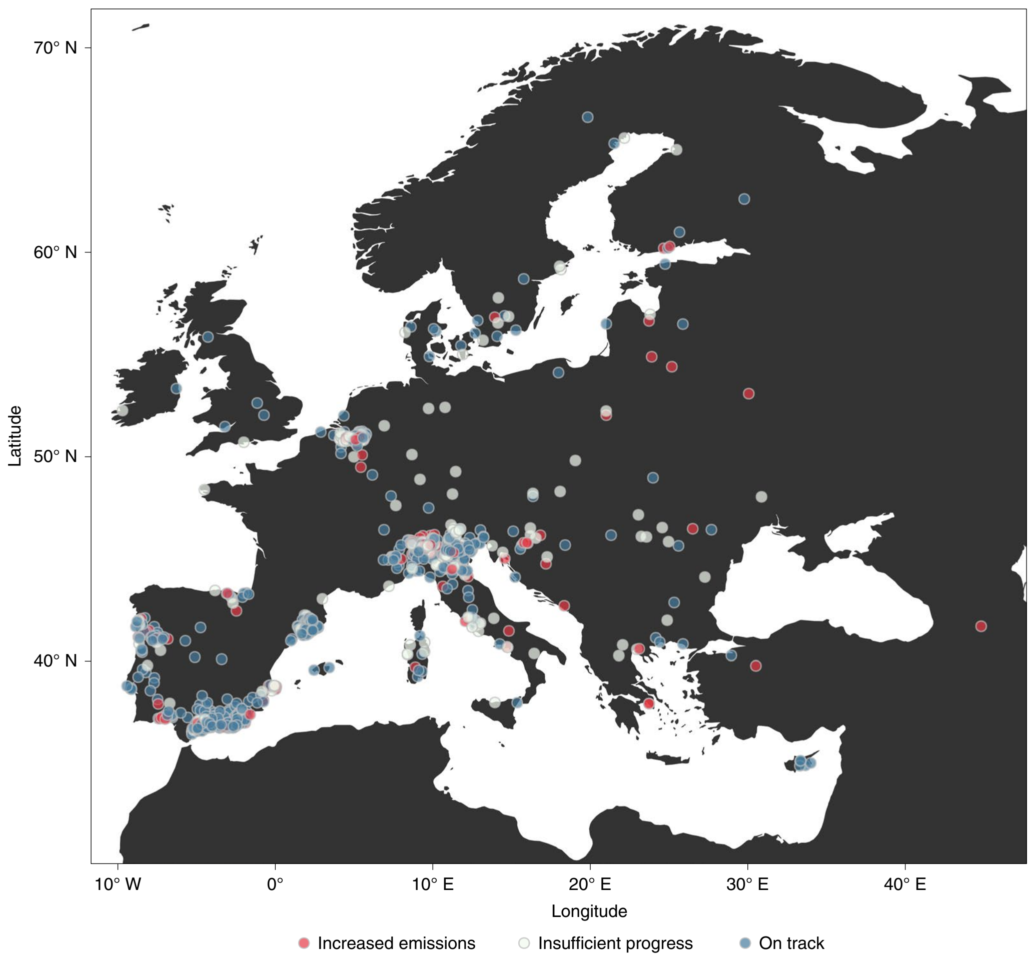

Fig. 1 | Map of emissions reduction performance calculated for 1,066 cities in Europe where sufficient data are available. Cities are considered 'on track' if they have achieved a ρ value of 1 or higher; a value of $\rho=0$ indicates insufficient achievement; a negative value ($\rho<0$) describes cities that have increased emissions (see Methods for further details).

regression model to determine the relationship between actors' intended actions and emissions reductions.

Progress towards targets

We evaluated 1,066 EUCoM cities representing 47.5 million inhabitants (approximately 11% of the EU's population) that reported data adequate to monitor progress, which represents less than 10% of the total number of signatories (10,167 as of January 2020) listed on the EUCoM website. These cities' total baseline emissions of 255.6 million tons CO_2 ($MtCO_2$) represent nearly 6% of the EU-27's 2017 emissions of 4,483 Mt[22]. The cities' largest emissions sectors are transport (34.4 ± 16.6%), residential (32.5 ± 17.7%), and industry (16.01 ± 17.4%) (Supplementary Fig. 2). The average 2020 mitigation commitment for all EUCoM cities in our dataset is 23.5 ± 6.89%, which exceeds the required 20% reduction by 2020 requirement. In total, the evaluated cities have achieved 51,405,666 tCO_2 emissions reductions to date (1.08 tCO_2 per capita), equalling an average 14.87% reduction from their respective baseline emissions and an average annual per capita emissions reduction rate of 2.68 ± 4.23%.

We find that 60% of evaluated cities are on track to achieving their 2020 emission reduction goal, assuming a linear projection of emissions reductions achieved so far (pro-rated emissions target achievement (ρ) ≥ 1, see Methods for more details; Fig. 1). Comparing differences in key characteristics between cities on track and those that are not (Fig. 2), those on track have slightly higher per capita baseline emissions (5.87 ± 3.24 tCO_2 per person) than those not on track (4.56 ± 2.34 tCO2$_2$ per person), but lower inventory emissions (3.89 ± 1.84 compared with 4.57 ± 2.32 tCO_2 per person). On-track cities are also located in countries that have lowered emissions to a greater degree (3.06 ± 1.09% yr^{-1} versus 2.38 ± 1.09% yr^{-1} between baseline and inventory year), although countries exhibit substantial variation in performance (Table 1). Cities in Cyprus (6.99 ± 4.35% $person^{-1}$ yr^{-1}; $n=6$) and Turkey (9.12 ± 18.33% $person^{-1}$ yr^{-1}; $n=2$), for example, appear to have the highest annualized per capita reductions. Cities in Eastern Europe (that is, Bosnia and Herzegovina, Georgia, and Lithuania), however, underperform and have increased emissions since their baseline years. Spain has among the highest share of cities that are on track to achieving their emissions reduction target (81%; $n=413$), whereas only about 48% of the cities in Italy ($n=408$) are on track, although, on average, cities in both countries have comparable levels of emission reduction targets at around 23% reduction. On average, Belgian cities ($n=76$ cities) have achieved only about 2% reduction per annum in per capita emissions to date—only one in three cities in Belgium is on track to meet its mitigation commitment. A few countries, including Germany ($n=8$) and others in Eastern Europe—Bosnia and Herzegovina, Lithuania, Belarus, Georgia and Slovakia—have no cities on track ($\rho<1$) to meet their mitigation commitments (see Table 1).

Less than half (42%) of the evaluated cities committed to emissions reduction targets that are considered 'ambitious'—more than 21% by 2020, which represents the sample's median reduction target

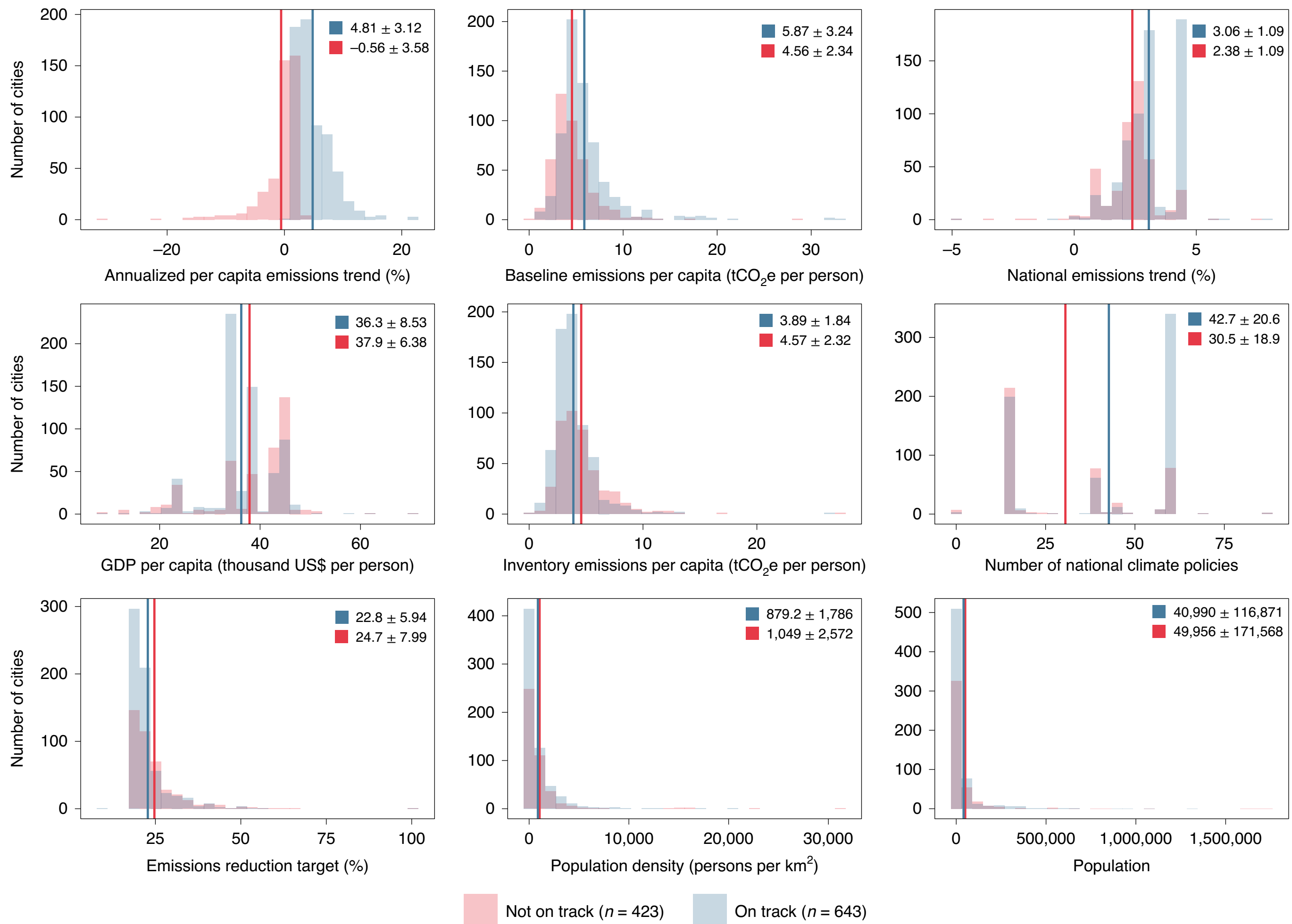

Fig. 2 | Comparison of performance metrics between cities that are on track to achieve their state emission reduction goals (ρ ≥ 1; n = 643) and those that are not (ρ < 1; n = 423). ρ is calculated as the ratio of emissions reductions achieved/reductions targeted (see Methods). Lines represent mean values for each group.

and is higher than the EUCoM required target. Forty-one percent of cities committed to exactly a 20% emissions reduction target, while those that are more ambitious tended to commit to only a marginally higher target between 21% and 25% (39% of cities). Two cities in our sample, Ringkøbing-Skjern in Denmark and Montejícar, Spain, committed to a 100% reduction in emissions by 2020 from a 2007 base year. More-ambitious targets are associated with cities that are less densely populated ($\hat{\beta}$: −0.03; SE: 0.015; $P < 0.05$), adopt earlier baseline years ($\hat{\beta}$: −0.163; SE: 0.068; $P < 0.05$) and are located in countries with more-robust national-level climate policies ($\hat{\beta}$: 0.025; SE: 0.008; $P < 0.01$) (see Supplementary Table 8).

Our regression results show that the ambition of a climate change commitment (that is, whether a city has targeted more than 21% reduction) is negatively associated with GHG emission reduction (Fig. 3 and Table 2). While cities not on track ($n = 423$) have on average committed to slightly higher 2020 emission reduction targets (24.7 ± 7.97% reduction, almost 5% higher than the EUCoM requirement) than those that are on track (22.8 ± 5.96% reduction; $n = 643$) (Fig. 2), their average achieved reductions are substantially lower (−2.4 ± 22.2% per capita compared with 30.7 ± 14.9% per capita), although the variation is wide among cities. An unambitious city with a low or moderate emission reduction target of 21% or less is likely to have an annualized per capita emissions reduction rate that is 0.535 (SE: 0.250) higher than a more-ambitious city, implying that it is likely to reduce, on average, about 0.535% more emissions per capita per year in comparison with a more-ambitious city.

Mitigation strategies

We identified six major thematic areas of climate policy strategies and actions that EUCoM cities adopt: (1) residential buildings and urban planning measures (18% prevalence across documents); (2) cross-sectoral integration (10%); (3) energy efficiency actions (10%); (4) mobility and public transport (13%); (5) buildings and public lighting (19%; and (6) municipal administration (30%). These labels were applied to the six topics on the basis of an evaluation of key words and of representative text from cities' key actions (Supplementary Table 1). We observe some country-level variation in cities' (Fig. 4) most-prevalent topic represented. For example, few cities outside of Spain ($n = 76$; 18%) have key climate actions that emphasize energy efficiency (topic 3) as the most-prevalent topic. For many cities in Italy ($n = 158$; 39%), the most-prevalent reflected topic is buildings and public lighting, while cities in Belgium ($n = 42$; 55%) and Portugal ($n = 29$; 54%) commonly emphasize cross-sectoral integration actions (topic 2).

Using topic 6 (municipal administration) as a reference topic in our model, given that the sum of all topic prevalences for a city is 1, we find that a 10% increase in the prevalence of topic 3 (energy efficiency actions) is associated with an increase of 0.22 in annualized percentage reduction in per capita emissions ($\hat{\beta}$: 2.231;

Table 1 | Summary statistics by country, including the number (*n*) of cities in our sample by country, the mean emissions reduction target, national and city emissions reductions and the proportion of cities on track according to the pro-rated reduction required by inventory year

Country	*n*	Target reduction (%)	National reduction (%)	City-level reduction (%)	On track
Spain	413	23.1 ± 6.52	3.61 ± 0.9	4.27 ± 4.76	0.81
Italy	408	23.56 ± 5.6	2.54 ± 0.49	1.47 ± 3.5	0.48
Belgium	76	20.79 ± 2.43	1.71 ± 0.69	2.01 ± 2.73	0.36
Portugal	54	22.17 ± 5.47	2.17 ± 0.89	2.28 ± 4.25	0.63
Sweden	16	38.75 ± 12.32	1.14 ± 0.37	1.57 ± 1.09	0.5
Croatia	12	24.33 ± 8.56	2.46 ± 0.77	0.63 ± 3.22	0.25
Greece	9	23 ± 5.79	4.11 ± 1.13	1.37 ± 3.34	0.33
Romania	9	22.67 ± 3.77	2.54 ± 1.23	1.93 ± 1.91	0.33
Germany	8	35.13 ± 11.64	0.77 ± 0.58	0.66 ± 0.51	0
Denmark	7	36.14 ± 30.23	3.5 ± 0.43	3.92 ± 1.83	0.71
Cyprus	6	25.67 ± 7.92	3.19 ± 0	6.99 ± 4.35	1
Finland	6	28 ± 8.12	0.95 ± 0.66	2.01 ± 4.41	0.5
United Kingdom	5	31.2 ± 5.22	2.28 ± 0.59	3.44 ± 2.11	0.8
France	4	20.5 ± 1	1.88 ± 0.61	3.08 ± 3.31	0.5
Latvia	4	23.75 ± 7.5	0.36 ± 0.3	1.09 ± 1.43	0.5
Poland	4	20 ± 0	0.65 ± 0.36	0.55 ± 0.95	0.25
Austria	3	20.67 ± 0.58	1.13 ± 1.04	1.64 ± 0.88	0.67
Bosnia and Herzegovina	3	23.33 ± 4.16	−1.12 ± 1.65	−0.44 ± 1.49	0
Bulgaria	3	25.67 ± 2.08	1.01 ± 0.83	1.42 ± 0.89	0.33
Ireland	2	20 ± 0	1.4 ± 0.44	2.87 ± 3.11	0.5
Lithuania	2	28 ± 2.83	1.34 ± 1.71	−5.09 ± 1.87	0
Slovenia	2	22 ± 1.41	1.25 ± 0.56	1.95 ± 0.11	0.5
Turkey	2	21.5 ± 2.12	−4.33 ± 0.91	9.12 ± 18.33	0.5
Ukraine	2	21.5 ± 0.71	3.07 ± 0.73	2.14 ± 0.85	0.5
Belarus	1	21	1.18	−1.42	0
Estonia	1	20	1.09	2.38	1
Georgia	1	25	−4.84	−7.57	0
Netherlands	1	25	3.06	4.99	1
Slovakia	1	21	1.86	0.83	0
Switzerland	1	25	0.58	2.19	1

The national and city emission reductions are expressed as an annualized reduction compared with cities' self-defined baselines.

SE: 0.631; $P < 0.01$) (Fig. 3 and Table 2). Specific policy interventions within this topic target both behavioural change (such as promotion of cycling and pedestrian mobility and implementation of public awareness campaigns and training courses on energy-efficient technologies) and technological substitution (such as installation of high-efficiency glass in buildings, replacement of heating systems and use of biomass boilers instead of diesel or propane boilers) (Supplementary Table 1). We find that the expected prevalence of topic 3 in cities' key actions is higher for cities with lesser GDP per capita ($\hat{\beta}$: −0.005; SE: 0.002; $P < 0.01$) and population density ($\hat{\beta}$: −0.014; SE: 0.007; $P < 0.05$). This result suggests that less-dense and less-wealthy cities have a higher likelihood of identifying energy efficiency, relative to other topics, in their key actions.

We find that the relationship between topic prevalence and emissions reduction is influenced by city and country characteristics (Supplementary Table 10). For example, an increase in topic 1's prevalence has a more-positive association with emissions reduction in cities with lower GDP per capita, while an increase in topic 2's prevalence has a less-negative association with emissions reduction in cities with higher GDP per capita. An increase in topic 3's prevalence has a more-positive association with emissions reduction in cities located in countries that have achieved higher annualized percentage reduction in emissions.

For city-level characteristics, while we do not find a strong association of GDP, population or population density with emissions reduction, we do find that higher baseline emissions per capita is associated with higher emissions reduction ($\hat{\beta}$: 0.394; SE: 042; $P < 0.01$). For country-level characteristics, national emissions reduction is strongly associated with city-level emissions reduction ($\hat{\beta}$: 0.487; SE: 217; $P < 0.05$). The direct relationship between the number of national climate policies and city-level emissions reduction is weak, however, although national climate policies do influence subnational climate action by shaping city-level target ambition (Supplementary Table 8).

Discussion

Many cities that participate in transnational initiatives such as the EUCoM commit to ambitious climate actions and achieve emissions reductions that are contributing to national and international mitigation goals. Our analysis represents a conservative estimate of

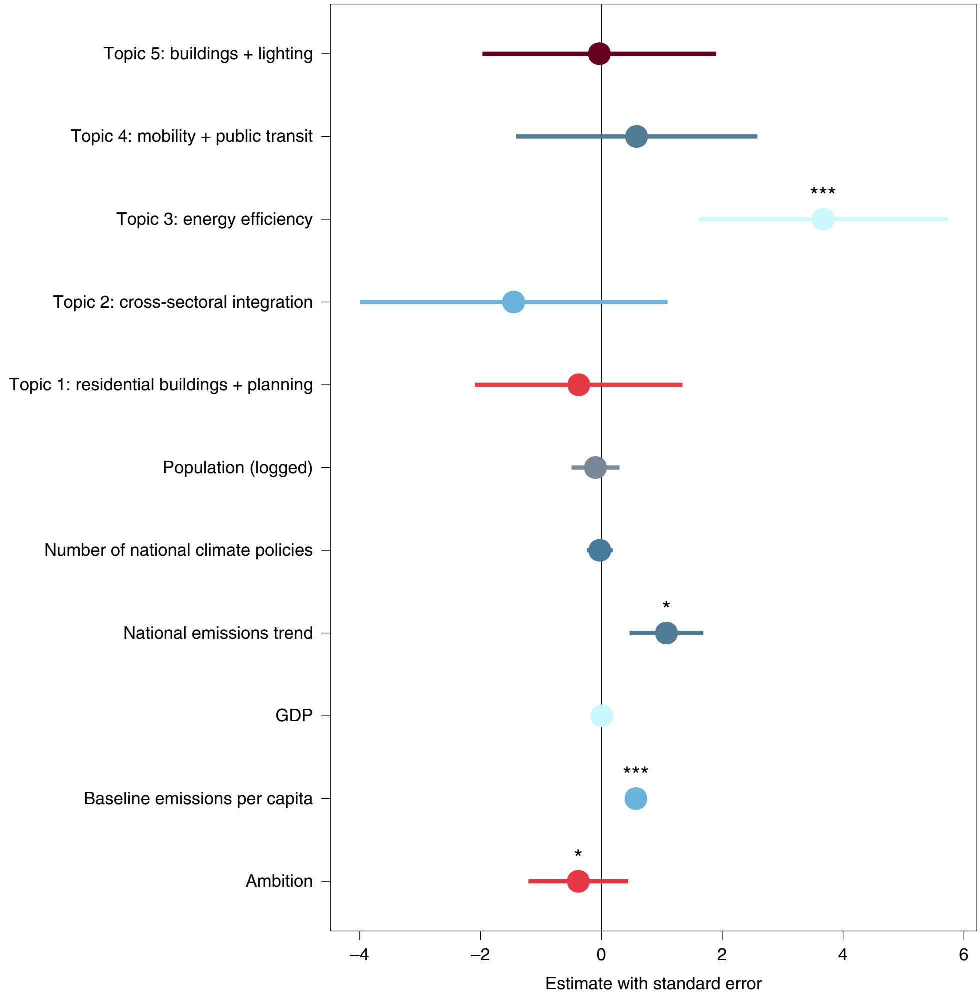

Fig. 3 | Impact of ambition and climate actions on annualized percentage reduction in per capita emissions. Because of its high prevalence (0.300) throughout the text corpus, topic 6 was used as the reference case in our model. See Table 2 for full regression results. $^{*}P<0.1$; $^{**}P<0.05$; $^{***}P<0.01$.

overall mitigation achieved through the EUCoM, given that only 15% of EUCoM cities have reported sufficient baseline, inventory emissions data and information detailing climate actions and strategies. Of the cities that are on track to achieving their 2020 emissions reduction goals, our study has shown that these cities tend to have less-ambitious targets and higher baseline emissions and to be located in countries that have a higher number of national climate policies and have achieved greater emissions reductions than countries where cities are not on track. Further, we found that city-level emissions reduction is influenced by plan-level, city-level and country-level characteristics. We discuss each of these determining characteristics in more detail and within the context of previous literature.

Cities have been "in a healthy competition to be at the forefront of emission reduction efforts" for decades[23], yet more-ambitious climate commitments do not necessarily translate into steeper emissions reductions when controlling for factors such as the time frame of the commitment, GDP per capita and number of national-level climate policies. This finding is consistent with previous studies that have found more-ambitious climate commitments or voluntary self-reported long-term goals do not necessarily translate into steeper emissions reductions[17]. Cities' emission reduction targets are often set as "political statements or aspirational goals" without consideration of abatement potential[24], which may explain why cities failing to meet their reduction targets set goals inconsistent with their capacities or take actions that have only incremental reduction, such as distribution of efficient lighting, or require longer time frames, such as large-scale infrastructural changes or urban planning measures. This gap between stated ambition and realized outcomes is a key reason why scholars have called for a better scientific foundation to underpin cities' climate policy efforts[25,26].

Determining an empirical link between cities' climate actions and emissions reductions remains a challenging task[16,19,27]. We find a significant ($p<0.01$) positive relationship between energy efficiency actions and city-level mitigation performance, suggesting that cities that have identified key actions specifically in energy efficiency are associated with higher GHG emission reductions. These actions emphasize a range of measures, including technological substitutions in heating systems with energy-efficient boilers, roof insulation, heat pumps and solar water heaters; policy measures such as a commitment to purchase 100% green energy supply; and public awareness campaigns and training courses about energy-efficient technologies. As previous studies have noted[16,19], however, it is difficult to disentangle at the city scale which measures lead to overall emission reductions without detailed, disaggregated data, and our study does not attribute emission reductions to specific interventions within topics. The key actions cities articulate also demonstrate a high degree of crossover and co-benefits, making it challenging to tie actions to sector-wide reductions, especially without more granular data on emissions inventories. Capacity-building measures on energy efficiency, for example, can lead to reductions in multiple sectors, from residential buildings to personal mobility.

Table 2 | Main regression results with topic 6 as the reference case

	Reduction (%)
Ambition	−0.535**
	(0.250)
Topic 1	−0.008
	(0.522)
Topic 2	−1.076
	(0.767)
Topic 3	2.231***
	(0.631)
Topic 4	0.754
	(0.608)
Topic 5	−0.156
	(0.593)
Recent baseline	−0.903
	(0.727)
Long-term target	0.808
	(2.169)
Time since baseline: spline 1	−1.323
	(2.522)
Time since baseline: spline 2	−2.724
	(2.553)
Time since baseline: spline 3	−3.056
	(2.210)
GDP	0.019
	(0.030)
Ln (population)	0.090
	(0.120)
EPC	0.394***
	(0.042)
Ln (population density)	−0.144
	(0.117)
National reduction	0.487**
	(0.217)
Policy	0.026
	(0.064)
Observations	1,066
R^2	0.259
Adjusted R^2	0.226

Standard errors are in parentheses. The regressions include country fixed effects. *$P<0.1$; **$P<0.05$; ***$P<0.01$.

Identifying which technological and policy measures most successfully produce emissions reductions in cities is critical to facilitate knowledge sharing and learning to realize the full potential of transnational climate initiatives' contributions to the polycentric climate system[28,29]. While this study focused mainly on European cities, especially less-populous municipalities (fewer than 50,000 inhabitants), our results have potential applicability to other cities and evaluation of transnational climate initiatives outside of the region. Identifying which factors (for example, ambition-level, sectoral policy focus) are associated with emissions reductions can help cities in other parts of the world with similar characteristics (for example, population, density or baseline emission levels) identify counterparts for good practices and policy learning[30–37]. Cities outside of Europe, for example, may have distinct transportation infrastructure, yet buildings may be similar enough to warrant these cities' consideration of policy or technological interventions implemented by the on-track EUCoM cities.

Cities with higher baseline emissions per capita (EPC) demonstrate higher emission reductions; a 1-ton-per capita increase in baseline emissions is associated with almost 0.4% reduction per year in per capita emissions ($P<0.01$). This finding is consistent with other studies that found EUCoM's cities' planned emissions reductions were driven primarily by baseline emissions, particularly in high-emitting sectors such as buildings and transport[16]. One explanation for the relatively lower reduction in low-baseline cities may be that blanket directives for emission reduction target setting such as the EUCoM have a tendency to 'punish' municipalities with lower levels of starting emissions, making it more difficult for these cities to demonstrate as impressive reductions as those with higher levels of baseline emissions[26]. Adopting a longer-term emissions target (for example, 2050) may help these municipalities identify more-realistic short- to medium-term targets, although few (18% of signatories as of January 2020) of the EUCoM cities to date have set 2030 targets.

We found no significant relationship between the number of national climate policies and emission reduction achievement ($\hat{\beta}$: 0.026; SE: 0.064), although more-ambitious emissions reduction targets are positively associated with the number of national climate policies. These findings indicate that while national-level policy directives may play a role in determining the ambition or level of target setting for emissions reduction, they may play less of a role in subnational climate mitigation performance—especially after controlling for the national emissions reduction trend—than suggested by previous studies[17]. Only four EU countries (the United Kingdom, Denmark, France and Slovakia) require local climate action plans from municipalities[3]. Of these countries, only the United Kingdom (80% on track; $n=5$) and Denmark (60% on track; $n=5$) have a majority of cities on track to achieve their emission reduction targets.

In the absence of national policy directives for local climate mitigation plans, transnational initiatives such as the EUCoM play an important role in 'orchestrating'[38] small and medium-sized cities' climate change management, assisting in the development of climate action plans, emissions monitoring and reporting. In Italy, where national capacity for environmental policy implementation is low, local authorities find value in the EUCoM capacity-building functions and are able to deliver on their EUCoM commitments more than cities in the United Kingdom, for example, where mayoral powers are weaker and EUCoM is considered redundant with other climate-related efforts[39]. The role of territorial coordinators or orchestrators, usually regional or provincial authorities, that provide technical support to EUCoM signatories and assist with development of Sustainable Energy Action Plans (SEAPs) and inventories[40] could explain why Spanish cities' key actions have the highest average prevalence for energy efficiency (Supplementary Table 2): 98% of Spanish cities (mean population 22,658 inhabitants) participate with the support of territorial coordinators, who have particular expertise in the field of energy, production and distribution systems[40]. These actors' achievements demonstrate the ability of small municipalities to contribute to global climate mitigation and underscore the effectiveness of transnational climate initiatives in building technical capacity and strategies for smaller actors with fewer financial resources to follow through on voluntary climate actions.

With the emissions gap between current climate policies and global goals widening[41], assessing the contributions of subnational

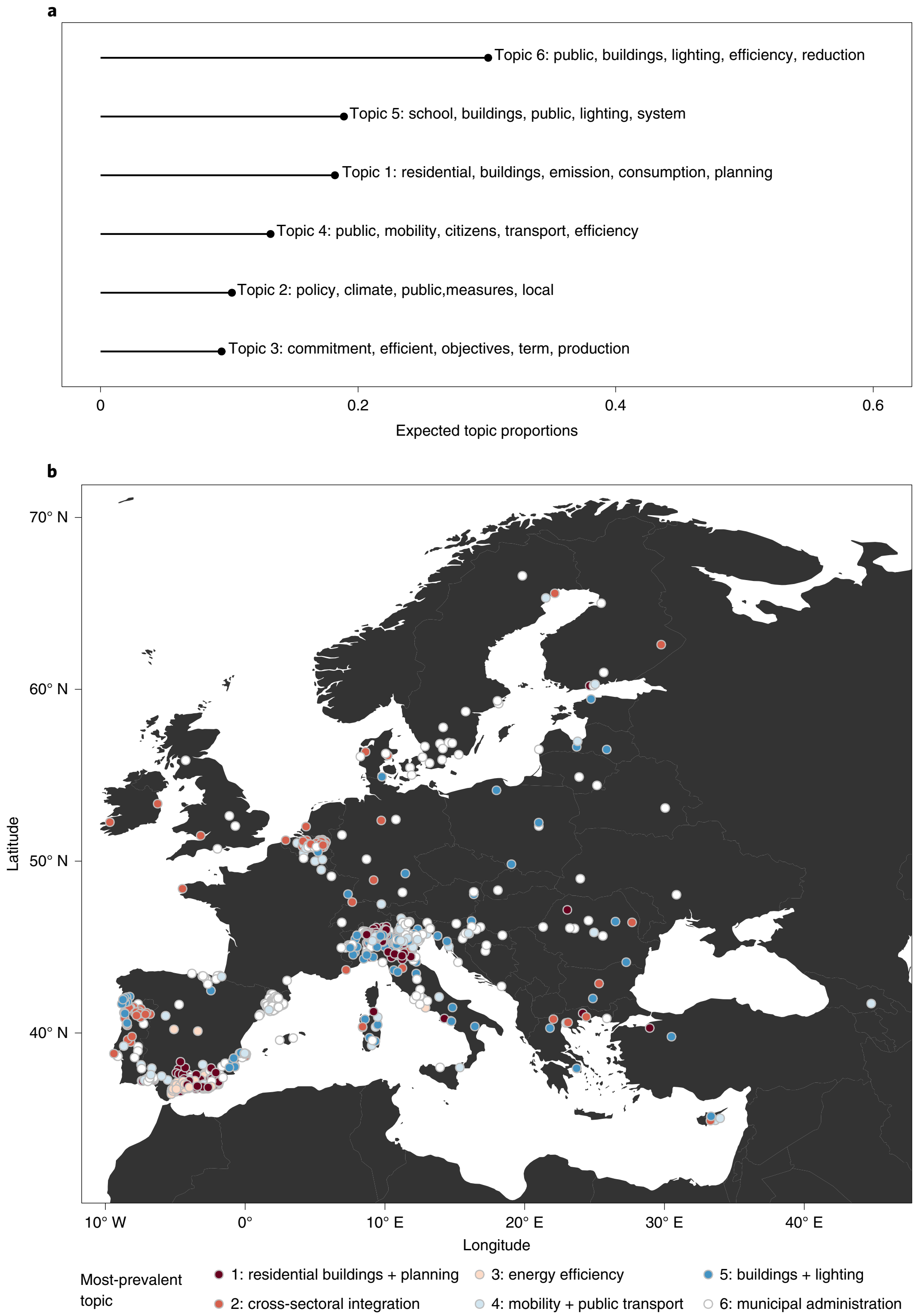

Fig. 4 | Topic prevalences and key terms in the analysis. **a**, Prevalences and key terms associated with each topic. **b**, Map of most-prevalent topics for cities in the analysis. The expected topic prevalences represent the probability certain words within a document are associated with each topic (see Methods). The topic labels in **b** are shortened due to space limitations; for a full description of the topics, see Supplementary Table 1.

governments is critical for identifying where there may be additional mitigation opportunities. This analysis has addressed three knowledge gaps with respect to cities' climate efforts: establishing the impact of largely voluntary actions through transnational climate initiatives, providing an empirical link between mitigation strategies and emissions reductions, and developing a method using automated, large-scale textual analysis that can be scaled and replicated. Future research should examine how climate performance data could be collected for subnational actors beyond Europe to further understand what determinants influence cities' abilities to achieve climate goals that contribute to national climate goals and that could even help increase their ambition. This kind of performance evaluation is critical to establish subnational actors' credibility and continued contributions to global climate action.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-020-0879-9.

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Methods

We developed a model to estimate the effect of city-level climate action on annualized percentage reduction in per capita emissions while controlling for city-level and country-level characteristics. We estimate the reduction for each city (i) in region (r) in country (c) using the following equation:

$$\begin{aligned}\text{reduction}_{i,r,c} &= \lambda + \alpha \times \text{plan\_level\_characteristics} + \beta \\ &\times \text{city\_level\_characteristics} + \delta \times \text{country\_level\_characteristics} + \gamma_c + \varepsilon_i\end{aligned} \tag{1}$$

where $\text{reduction}_{i,r,c}$ is the annualized percentage reduction in per capita emissions and λ is the y intercept.

The plan-level characteristics include the following:

- ambition_i indicates whether the city has a target greater than 21%.
- topic_{1-5} is the prevalence of each topic in each city's action plan.
- recentbaseline_i indicates whether a city's baseline emissions were recorded after 2004.
- longtermtarget_i indicates whether the target year for emissions reduction is beyond 2020.
- $\text{timesincebaseline}_i$ refers to a cubic spline of the difference between a city's inventory year and base year.

The city-level characteristics include the following:

- GDP_r is the per capita GDP in constant PPP in the region or country where the city is located.
- EPC_i is the emissions per capita of the city in its respective baseline year.
- population_i is the natural log of the city's population.
- density_i is the natural log of the city's population density.

The country-level characteristics include the following:

- $\text{nationalreduction}_c$ is the national emissions reduction trend between baseline and inventory year
  policy_c is the number of national climate policies enacted where the city is located.
- γ_c is a country d//ummy to capture unobserved, time-invariant factors common to cities within a country.

ε_i is a random error term.

Our independent variables consist of a binary variable (ambition_i) that indicates whether a city's emission reduction target is considered high ambition (1, if it constitutes a more than 21% reduction from baseline levels) or low (0, if it is below this threshold). We include five topic variables (six were identified, but due to the high prevalence (0.30) of topic 6 throughout the documents, we use it as a reference case in Equation (1)) that are derived from an STM[21] of a text corpus consisting of all 1,066 cities' climate actions reported to the EUCoM website (see the description that follows of text processing and topic modelling).

We also control for a series of city- and country-level characteristics that may influence a city's emissions reductions. At the city level, we include per capita GDP (GDP_r) as a proxy for resource availability, which may influence city climate strategies and execution[42,43]. We control for a city's population because more-populous cities are also likely to differ from less-populous cities in their energy consumption and their capacity to create cross-sectoral strategies[4,40,44], as well as their ability to benefit from agglomerative effects[45]. Due to the latter mentioned density effects, we control for a city's density, defined as population per square kilometre as greater density and more-compact urban forms are associated with lower emissions[46,47]. We include recentbaseline_i as a dummy variable that indicates whether a city's baseline emissions were recorded after 2004 as the baseline year is likely to be correlated with a city's economic structure and may influence the likelihood of emissions reductions[47]. For example, a city that transitions from a primarily industrial base with higher baseline emissions before 2004 may be at an advantage for achieving a higher emissions reduction than a city that has a primarily secondary or tertiary economic structure that is less carbon intensive.

A dummy variable (longtermtarget_i) indicates whether a city has instituted a long-term target (that is, beyond 2020) as a longer time frame for emissions reduction may affect the rate of emissions reduction in the near term. We include the variable $\text{timesincebaseline}_i$ to account for differences between cities' base and inventory years. Rather than assume a fixed relationship between emissions reduction (rate) and time since baseline, we use a cubic spline, created using the 'splines' package in R[48], to capture the possible nonlinearity between the two. We control for baseline EPC (EPC_i) as, ceteris paribus, higher per capita emissions indicate a larger scope to achieve emissions reduction. We also include a control variable for the number of climate mitigation policies that exist at the national level (policy_c), which may influence the ambition and achievement of local government. We also include a country dummy variable γ_c to account for unobserved, time-invariant characteristics that might influence a city's climate change performance but are difficult to measure such as a country's culture, language and geography[43].

To determine whether a city is on track to achieving their stated emission reduction goal, we calculated a measure, ρ, which is the ratio of actual (that is, achieved) per capita emissions reduction in the inventory year to the targeted per capita emissions reduction in the inventory year, both in comparison with the baseline year, assuming that emissions reduction between the baseline year and the target year are pro-rated linearly (that is, constant emissions reduction from one year to the next). More specifically, we define ρ through the following Equations (2–5):

$$\text{Reduction}_{\text{achieved}} = \text{EPC}_{\text{baseline}} - \text{EPC}_{\text{inventory}} \tag{2}$$

where $\text{EPC}_{\text{baseline}}$ is the EPC of the city in the baseline year and $\text{EPC}_{\text{inventory}}$ is the EPC of the city in the inventory year.

$$\text{Timelapsed} = \left(\text{Year}_{\text{inventory}} - \text{Year}_{\text{baseline}}\right) \div \left(\text{Year}_{\text{target}} - \text{Year}_{\text{baseline}}\right) \tag{3}$$

Where $\text{Year}_{\text{baseline}}$ is the year for which baseline emissions are reported, $\text{Year}_{\text{inventory}}$ is the year for which inventory emissions are reported and $\text{Year}_{\text{target}}$ is the year by which committed emissions reductions are to be achieved.

$$\text{Reduction}_{\text{required}} = \text{EPC}_{\text{baseline}} \times \text{Target} \times \text{Timelapsed} \tag{4}$$

where Target is the committed emissions reduction of the city (percentage).

$$\rho = \frac{\text{Reduction}_{\text{achieved}}}{\text{Reduction}_{\text{required}}} \tag{5}$$

Data collection and preparation. The data for European cities' carbon emissions and climate actions were collected from the EUCoM website. We scraped data from the website using the Beautiful Soup Python package[49] between April and November 2019 for each actor's overview, baseline review, action plan and progress web pages on the EUCoM website written in hypertext markup language (HTML). For the key actions, cities are asked to include details on an action's sector, implementation time frame, policy instrument, among others, as a short highlight of climate actions (see Supplementary Information for more details). All non-English text data were translated into English using the Google Cloud Translate API. While the website as of December 2019 included 10,167 signatories, only 6,146 included action-plan information, and only 2,349 reported progress information. In total, the number of cities with both baseline and inventory emissions data was around 1,162, and of these, only around 1,091 had sufficient textual data reported through key-actions pages.

According to the EUCoM reporting guidelines[50], members are required to report only energy consumption for buildings and related equipment (that is, residential, municipal and tertiary consumption), the transport sectors and local energy generation (that is, combined heat and power or renewable electricity generation) (see Supplementary Fig. 1), with industrial sources that are not already covered by the EU Emissions Trading Scheme and waste as optional sources. Reporting cities are not required to include consumption-based emissions in their inventories, but can optionally use life-cycle-based emission factors to include upstream emissions associated with fuel consumption[51]. They are required to report only CO_2 emissions, although they can optionally include other gases in CO_2-equivalent (CO_2e). For EUCoM members, the aim of emissions inventories is not meant to be 'exhaustive' but to focus primarily on emissions sources the cities have authority to control or influence[52].

To ensure quality, we perform the following sense checks on the data and include only cities that satisfy the following criteria: (1) per capita emissions greater than 0.2 tCO_2e and less than 40 tCO_2e;[53] (2) ratio of inventory emissions and baseline emissions of 10 or less; (3) compounded annual growth rate in emissions of greater than −50% and less than 50%; (4) ρ greater than −10 and less than 10. Our final sample consists of 1,066 cities after removing cities where inventory or baseline emissions data did not meet our quality checks.

While the EUCoM dataset records the population of a city for one year, to compute the per capita emissions we also require city population in the baseline and inventory emissions' year. We compute these using national population data from the World Bank[54] and estimating the ratio of the city population to the national population and applying the national population trend to the city. The OECD.Stat repository is used for collating data on GDP per capita (GDP_i)[55]. Where available, we include per capita GDP of the tier 1 subnational region as a proxy for city per capita GDP, but use national per capita GDP for cities where the regional GDP data are not available[54]. Data on historical greenhouse gas emissions for Belarus, Bosnia and Herzegovina, Georgia and Ukraine was collated from World Resources Institute[56] and for the remaining countries was collated from European Environment Agency[57]. The policy variable is derived from the number of national climate policies from the European Environment Agency that were active as of 10 July 2019[58]. These included climate change mitigation policies and measures—such as informational, regulatory, economic and research—implemented or planned for reducing GHG emissions in EU countries. While most policies and measures were announced within the past decade, several were announced in the 2000s and a few before then. We processed the data by removing any policy that was not at the government level, and removed any policy that was no longer implemented or adopted, then tallied the number of policies for each of the EU countries. We considered other control variables, such as the number of heating and cooling degree days[16] and industrial structure, but for reasons of data availability, we were unable to include them. Heating and cooling degree days are important climactic drivers of GHG emissions in cities, particularly in the buildings sector[15,59]. Although industrial-sector emissions comprised 20% of the EU's total emissions in 2017 (1.97 tCO_2 $person^{-1}$) excluding land-use and forestry sectors[60], the EUCoM does not require cities to report emissions from industry, which makes controlling for them less relevant for our study.

Text pre-processing. In compiling the corpus for text analysis, we conducted two pre-processing steps. First, we included only key actions listed on an actor's website that were 25 words or more (the average document length is 185 ± 121 words, see Supplementary Table 3). The textual data were then converted into a document-feature matrix using the STM package[21] that allows for extraction of topic prevalences for each actor that could then be used as a variable in our statistical model. Second, we removed frequently repeated words, including 'energy', 'emissions', 'sector(s)', 'municipal(ity)', "'city', 'based', 'main', 'action', 'change', 'plan', 'covenant' and 'mayor(s)'[61]. We conducted a sensitivity analysis and determined the removal of these words did not detract from the overall content and meaning of cities' key actions but allowed for the identification of more-robust and meaningful topics. We also removed stop words such as 'a', 'and', 'in', 'the', which occur commonly in the English language but provide little information about the content of the text. We then converted the document-feature matrix into 'tidy' format, which can be read by the native STM package functions in R[62].

Topic selection modelling. We used topic modelling to identify categories of key actions and measure the prevalence of each category in each city's action plan. Topic modelling relies on statistical analysis to 'discover' hidden or latent topics, meaning one cannot directly observe the topics themselves, in a document corpus on the basis of the premise that a document consists of one or more topics[63]. Specifically, we used the STM algorithm, which is a statistical model that assumes each document in a corpus contains a mix of topics that are found throughout and indicates the probability certain words within a document are associated with each topic[21]. STM identifies correlation among the discovered topics, meaning each document in the corpus has its own prior distribution over identified topics that can be used in a regression model. To determine the number of topics in the text, an input required by a topic mode, we examined metrics provided by the STM package, including exclusivity (for example, uniqueness), held-out likelihood (for example, cross-validation), semantic coherence of models (for example, whether the topics contain words that are representative of a single coherent concept) and minimizing residuals (for example, error). We evaluated topic models ranging from 5 to 20 topics on the basis of these metrics and resulting word clouds that illustrate the probability a word comes from a particular topic and representative text (Supplementary Table 1)[64]. On the basis of this analysis, we selected six topics as the optimal number of topics for our model, although we recognize that there is some degree of subjectivity associated with these labels.

Sensitivity and robustness checks. We conducted a series of robustness checks to test the sensitivity of our model. First, we tested the sensitivity of the findings to changes in variable selection (Supplementary Table 4). We found that our main findings do not change substantially even if we run a regression on a model without any covariates or include the baseline year, the target year and time since baseline year in their original form rather than as dummies and spline. Subsequently, we checked the sensitivity of the findings to different functional forms of topic prevalence (Supplementary Table 5). We found that, when the logarithm of topic prevalence is included in the model, an increase in topic 3, relative to topic 6, is still positively associated with annualized percentage reduction in per capita emissions while an increase in the prevalence of topics 2 and 5 is now negatively associated with the dependent variable. In case of the quadratic form, while the coefficients of the linear and quadratic terms of the prevalence of topics 1 and 5 are individually associated with emissions reduction, the coefficients of the prevalence of topic 3 are jointly associated with emissions reduction. This indicates that while the findings are sensitive to the functional form of topic prevalence, they are more robust in the case of topic 3 than in the other topics. In addition, we varied the reference topic to examine whether the findings are sensitive to our choice of reference (Supplementary Table 6). We found that regardless of the choice of reference topic, topic 3 is more likely than any other topic to correspond to higher emissions reduction. Finally, we examined the regression results on the basis of other measurements of emissions reduction, including percentage emissions reduction, percentage reduction in per capita emissions and ρ. We found that, regardless of choice of dependent variable, prevalence of topic 3, baseline emissions per capita and national emissions reduction trend are positively associated with emissions reduction. Further, in case of ρ, baseline emissions per capita is also positively associated with achievement.

Limitations. Our study is limited by several considerations. First, our analysis focuses only on Europe and cities that are members of the EUCoM, and only a subset of the EUCoM cities that have reported sufficient evaluation data. While there are many more cities that participate in transnational climate action networks, only a number of cities outside of Europe report adequate baseline emissions and inventory data or details of climate actions[14]. Second, we rely on data self-reported by the EUCoM cities themselves, which inherently adds a degree of uncertainty that is not reported alongside emissions inventories. As the IPCC acknowledges[10], measuring municipal GHG emissions in a comparable way across cities is challenging, given varying boundary definitions, accounting methodologies, production- versus consumption-based approaches and emissions sources, among other challenges. For countries, the IPCC has established a single standard that only requires accounting of production-based emissions[65], which allows for comparability. For urban areas, accounting is much more difficult given the existence of multiple standards and the global footprint of cities through flows of goods and services[51]. The comparability of cities' emission inventories should improve, however, as more cities develop inventories according to the Global Covenant of Mayors Common Reporting Framework[66].

Third, because the EUCoM only requires its members to report emissions from selected sources (that is, buildings, transport and energy), the reported data could be missing sources of emissions (that is, industrial sources or consumption-related emissions) that are important to a city's carbon footprint. Particularly considering consumption-based or scope 3 emissions can constitute up to 25% of a city's emissions inventory[51], failure to account for these emissions can greatly add to the incompleteness and uncertainty of a city's true emissions. Most cities do not yet fully account for consumption-based emissions because of the difficulty in quantifying them, which requires sufficient financial and technical capacity[16]. Finally, a last limitation of our analysis and more broadly of quantitative city climate mitigation studies is the question of implementation[53]. This study assumes that cities are actually implementing climate actions and achieving the reductions they report in their monitoring emissions inventory. More-detailed, sector-disaggregated monitoring emissions data would help elucidate some of these uncertainties, but this reporting is not consistent or widespread.

Software. All statistical analyses were conducted using the R statistical programming environment (version 3.6.2) and the lm package[67,68] for the regression analysis, the stm package[21] for the topic analysis and the splines package for creating a cubic spline[48]. Figures were made using the ggplot[69].

Data availability

Data used to create figures are available at www.github.com/datadrivenenvirolab and on the Harvard Dataverse Network[70] (https://doi.org/10.7910/DVN/IJ4DDI). Source data are provided with this paper.

Code availability

Code used to create figures is available at www.github.com/datadrivenenvirolab and on the Harvard Dataverse Network[70] (https://doi.org/10.7910/DVN/IJ4DDI).

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Author contributions
A.H. conceived and designed the study, collected data, conducted statistical analysis, made figures and wrote the paper. N.G. conducted background research and statistical analysis and contributed to the paper's writing. Y.M.N. helped design the statistical model and conducted statistical analysis. J.T., W.T. and RV conducted the structural topic modelling.

Competing interests
The authors declare no competing interests.

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