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Climate change impacts on renewable energy

The Estimated Co-Benefits of Adopting a Net Zero Scenario Design

Environment, mobility and carbon emissions: the role of compactness for Italian urban centers

Local public transport and air pollution: assessing avoided emissions through a natural experiment

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Executive summary

This policy brief presents four research contributions related to the socio-economic and bio-physical impacts of climate change.

The first research line explores the impact of climate change on renewable energy generation and stability across Europe. Reliance on variable renewable energy sources like wind, solar, and hydropower presents new challenges due to weather variability and long-term climate changes. To address these, the study developed a comprehensive, open-source dataset of historical and projected meteorological data. The data show significant spatial and temporal fluctuations in renewable energy potential, driven by shifting climate patterns. This calls for adaptive power systems that include flexible energy policies, investment in energy storage, grid interconnectivity, and enhanced demand-side management. Policy recommendations include diversifying renewable energy sources by region, adopting energy efficiency standards, and investing in robust, climate-resilient infrastructure. These steps are essential in securing Europe's energy future and achieving decarbonization goals.

The second research line examines whether the climate policies that seek to ensure that temperature overshoot is avoided can generate co-benefits resulting from mitigated air pollution. It starts by providing background information with respect to the emergence of air pollution as a phenomenon jeopardizing public health and economics. It discusses the methodology that has been utilized and presents the results that have been obtained in terms of health and economic co-benefits: the adoption of the net zero scenario design would result in the consistent obtainment of health and economic co-benefits in all countries in 2030. China and India would emerge as the countries that would avoid the greatest amount of damages.

The third research line how urban compactness impacts carbon emissions from transportation in Italian cities, providing insights for environmental policy and urban planning. As global urban populations grow, research into the spatial organization of cities is crucial for understanding emissions from transport networks influenced by distances, traffic, and public transport accessibility. Using data on Italian urban centers—including variables such as population, GDP, climate, and specific indicators of urban form (compactness, range, and sprawl)—the study establishes a negative correlation between compact city structures and per capita emissions. This correlation aligns with findings from international studies, suggesting that compact urban environments support lower emissions due to shorter travel distances and higher population density. Policy implications emphasize the benefits of compact city planning, including enhanced energy efficiency and reduced GHG emissions, while also highlighting the need for policies that address potential downsides of compactness, such as air pollution and overcrowding.

The fourth research line investigates the role of local public transport (LPT), specifically rail services, in reducing air pollution, focusing on a natural experiment following a train accident in Florence, Italy, in April 2023. The accident disrupted rail services for four days, compelling commuters to switch to private vehicles and resulting in measurable increases in NOx levels. Using a difference-in-differences analysis, the research compared air quality data from 38 monitoring stations in Tuscany, with 12 stations in affected areas (treatment group) and 26 in unaffected areas (control group). Findings show a significant short-term rise in pollution in areas impacted by rail disruptions, with NO2 and NO levels rising by 36% and 47% respectively, particularly during peak commuting hours. The study highlights LPT's role in mitigating pollution and emphasizes the need for policies that encourage a shift from private vehicles to public transport to meet EU air quality and emissions goals.

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1. Presentation and description of the research activity undertaken

1.1 Climate change impacts on renewable energy

Achieving net-zero carbon emissions by mid-century requires a significant transition to low-carbon energy sources, particularly renewable sources such as wind and solar, alongside the electrification of end-use sectors like heating and transportation. However, these transformations increase the complexity of managing power systems, particularly since they become more exposed to weather variability and the long-term impacts of climate change. Weather fluctuations occur on temporal scales ranging from sub-hourly to yearly, while climate changes manifest over decades, potentially altering renewable energy availability and demand patterns. In this study, we examine the complex interactions between weather, climate, and power systems to understand how climate change will affect renewable energy generation and system reliability. We develop a comprehensive database of time series data for wind and solar power generation, hydropower inflows, and heating and cooling demand across European countries using a consistent modelling framework. This dataset, which spans both historical and projected meteorological data, allows us to evaluate the potential impacts of climate change on renewable energy generation under various carbon emissions scenarios. Our results reveal significant spatial and temporal variability in renewable energy potential and suggest guidance for energy planning, policy design, and infrastructure resilience.

1.2 The Estimated Co-Benefits of Adopting a Net Zero Scenario Design

This policy brief presents the article entitled *'Beyond the Limit: The Estimated Air Pollution Damages of Overshooting the Temperature Target'* that has been drafted by Clàudia Rodées-Bachs, Laurent Drouet, Peter Rafaj, Massimo Tavoni and Lara Aleluia Reis.

Outdoor air pollution triggers the development of serious diseases and leads countries to suffer from economic damage (Bu et al., 2021; Rafaj et l., 2021; Burnett et al., 2022; Sampedro et al, 2023; Pandey et al., 2021; Lanzi et al., 2018). Notably, the latter consequences can be alleviated by implementing policies tackling climate change (Vandyck et al., 2018; Rao et al., 2017; Aleluia Reis et al., 2022). The positive impact of the reduction of emissions on public health and the economy are known as co-benefits (Robert, 2009; Hamilton, 2017). When making estimations of climate scenarios with a focus on the latter effects, scientists usually do not explicitly consider air pollution. To address this gap, we examined whether the climate policies that seek to ensure that temperature overshoot is avoided can generate co-benefits resulting from mitigated air pollution in a consistent manner.

1.3 Environment, mobility and carbon emissions: the role of compactness for Italian urban centers

The share of the global population living in urban centers has vastly increased in recent decades and is predicted to further expand in the future. In this context, research on the environmental impact of different urban environments, in terms of both their form and built-up structure, is particularly important to understand whether smart urban design can help reduce harmful GHG emissions and contribute to fighting climate change. The spatial organization of cities can have an impact on mobility through the organization of public transport networks, distances and the amount of time spent on traffic, and all of this in turn affects the emissions of the transport sector. Our research focuses on Italy and builds a database describing its urban centers, including information on their carbon emissions from on-road transport, built-up surface, urban form (through indicators including the compactness, range and sprawl index) and related variables, such as total population, GDP, average temperature and precipitations.

The database can be used to study relevant associations between urban form urban compactness and carbon emissions from transport. The results of a preliminary correlation analysis show a negative and significant correlation between compactness and the per capita levels of emissions from transport, in line with the existing literature (Cirilli and Veneri, 2013).

1.4 Local public transport and air pollution: assessing avoided emissions through a natural experiment

The release of particulate matter (PM2.5, PM10) and nitrogen dioxide (NOx) represent one of the leading causes of death and severe chronic cardiovascular and respiratory diseases, both worldwide and in Europe (IHME, Global Burden of Disease 2024; Health and Environment Alliance 2023; Chen et al. 2024; WHO 2016. Over the past decades, the implementation of various policy measures has favored a significant reduction in air pollution from the transport sector, which represents the primary source of air pollution in Europe. Despite this achievement, 96% and 88% of European citizens are still exposed to PM2.5 and NO2 levels exceeding the WHO recommended limits, which are stricter than those adopted within the European legislation (EEA, 2024). The present research investigates the contribution of rail transport to limiting the local level of air pollution. The underlying intuition is that public and private transport are partly substitutes, the latter being more polluting than the former (Fraunhofer ISI and CE Delft 2020). This implies that, without LPT services, more people would have to use private vehicles, resulting in higher levels of air pollution. However, since avoided emissions cannot be observed, the LPT-related environmental benefits are not properly taken into account.

This research develops a natural experiment with a counterfactual approach to quantify how much LPT commuting services contribute to limiting local pollution. For this purpose, we exploit a random and exogenous adverse event which affected the railway line in the metropolitan city of Florence. We provide robust evidence of the amount of local pollution that is avoided thanks to the presence of an LPT.

2. Relationship with the existing literature

2.1 Climate change impacts on renewable energy

Weather variability, climate change and reliance on fossil fuel imports pose serious risks to a clean and secure European power system. First, intermittent low-carbon energy sources, such as wind and solar, are highly variable in space and time and not always available in quantities needed to meet electricity demand (Antonini et al., 2022 and 2024; Ruggles et al., 2024; Shaner et al., 2018). This is relevant since rising temperatures and more extreme events induced by climate change will pose new challenges to maintaining system reliability (van Vliet et al., 2012). Second, climate change is expected to impact various components of the electric power system (Craing et al., 2018) and increasing temperatures will strongly affect electricity demand and the needed investments in peak generation capacity (Auffhammer et al., 2017; van Ruijven et al., 2019). Lastly, the European reliance on fossil fuel imports has become a national security issue because of geopolitical tensions (Pedersen et al, 2022).

2.2 The Estimated Co-Benefits of Adopting a Net Zero Scenario Design

Adverse effects of air pollution on human health were detected BC. That said, scientists lacked the expertise to categorize the chemicals that polluted the air and quantify their amount for a long time and air pollution was measured for the first time in the 18th century (Fowler et al., 2020), an era that marked the advent of the industrial revolution (Mohajan, 2019; Yang et al., 2022). As the countries that first generated industrial growth were in Europe and North America, the major events that spurred the governments to combat air pollution took place in the latter regions (Igini, 2022). In this regard, in 1952, an event known as the Great London Smog occurred in London owing to the utilization of fossil fuels such as coal and diesel as a power source for buses and for the generation of energy and heat, (National Geographic, 2024) a process that releases greenhouse gases and air pollutants (United Nations, 2024). Another occurrence that brought air pollution to the forefront of environmental policy making was acid rain, which was observed for the first time in North America in the 1960s (Igini, 2022).

Given that air pollutants and GHGs often have the same drivers, (World Bank Group, 2022) the regions where the incidents occurred also had the highest GHG emissions globally (Vigna et al., 2024; Nunez, 2019). Replacing the position of the US that has maintained its position since the late 1880s as the 'world's top CO2 emitter', in 2005, China became the country emitting the highest amount of CO2 (Vigna et al., 2024). The GHG emissions that were released by the developing countries located in Asia have increased by around threefold from 1990 until 2019.

2.3 Environment, mobility and carbon emissions: the role of compactness for Italian urban centers

The urban economics literature has long studied the interactions between the spatial configurations of the urban environment and the levels of energy consumption and carbon emissions due to mobility and car use. Studies have generally found that planning for compactness as a measure against urban sprawl can reduce external costs, as compact cities have more regular shapes that minimize the distance between locations within their boundaries, and present higher population density (Makido et al., 2012; Ou et al., 2013; Gudipudi et al., 2016; Meng and Han, 2018).

In the United States, research using gridded population, land use and CO_2 emissions data finds that population density is negatively associated with on-road emissions in cities, while the relation is positive for urban sprawl (Gudipudi et al., 2016). In Japan, a study using a cross-section of 50 cities finds evidence in favor of a negative association between compactness and CO_2 emissions (Makido et al., 2012). Finally, in Italy Cirilli and Veneri (2013) look at indicators of urban form and structure (including compactness) of Italian Local Labour Systems (SLLs) to find that more compact SLLs present lower levels of CO_2 emissions due to commuting.

In general, research on the role of urban structure and its consequences for climate change is hindered by the lack of comparable city-level data especially on carbon emissions. In our research, we draw on consistent, high-resolution gridded data and focus exclusively on Italy to provide a broader description of the characteristics of its urban centers.

2.4 Local public transport and air pollution: assessing avoided emissions through a natural experiment

Several studies exploit the occurrence of exogenous shock to bring evidence on the positive contribution of transport services in limiting local air pollution: Giaccherini et al. (2021) adopt a diff-in-diff design to show that local public transport strikes in Rome cause an increase in PM10 concentrations and a rise in hospitalizations (diff-in-diff). Jia et al. (2021) assess through spatial difference-in-differences design that the development of high-speed rail in China caused a significant decrease in greenhouse gas emissions. Sun et al. (2019) adopt an Instrumental Variables Method to demonstrate that the improvement in the urban public transport promoted a significant reduction of air pollution in 63 Chinese cities from 2004 to 2015. Li et al. (2019) document a positive impact of subway expansion on air quality in various major Chinese cities. Basagaña et al. (2018) show that a temporary interruption of public transportation services in Barcelona caused an increase in various air pollutants.

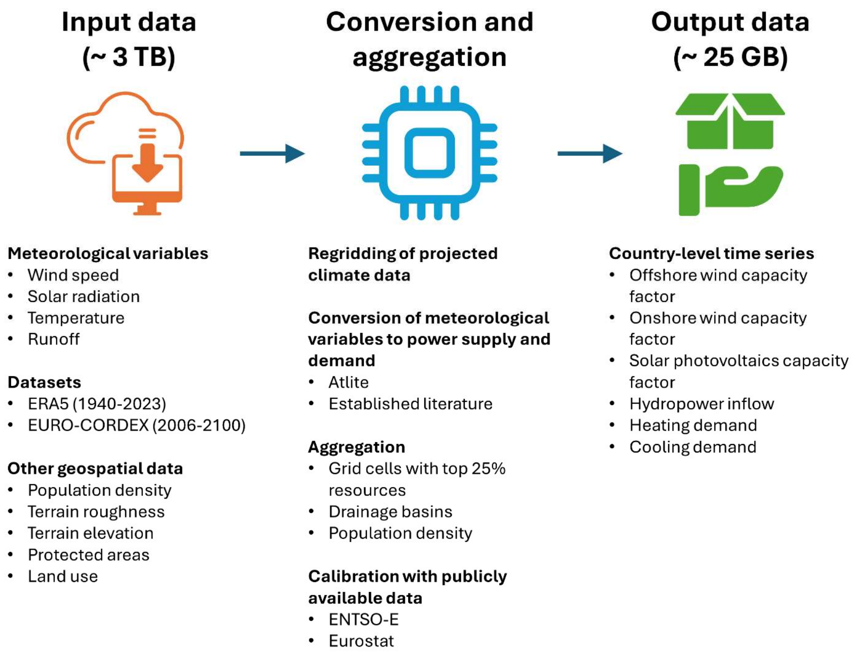
3. Research output

3.1 Climate change impacts on renewable energy

We developed a database of time series of wind and solar power generation, hydropower inflow, heating demand, and cooling demand developed using an internally consistent modeling framework that uses both historical and projected meteorological variables (Fig. 1). Unlike previous studies, our dataset includes a time series of European countries for any period between 1940 and 2100 and allows us to capture the main impacts of weather and climate on the energy systems both on the supply and demand sides. The framework is open-source and applicable to any country of the world, with the meteorological database of choice, and where appropriate energy infrastructure data are available. Here, we use both historical meteorological data from the ERA5 reanalysis and projected meteorological variables from three climate models of the EURO-CORDEX and three representative concentration pathways (RCP, trajectories of GHG concentration). On the one hand, the use of historical meteorological data allows the resulting time series to be used for analysis where actual climatic conditions are important such as assessing the potential of renewable energy or resource adequacy. On the other hand, the use of multiple projected meteorological variables from different models allows the resulting time series to be used for analysis in case of deep uncertainties in climate, policy and technological progress.

We gather other geospatial data, namely, protected areas from the World Database on Protected Areas (WDPA), land use from the Coordination of Information on the Environment (CORINE) dataset, terrain roughness and elevation from the ERA5 dataset, and population density produced by the European Commission's Joint Research Center (JRC). Lastly, we perform a calibration of the time series of the power supply against generation data retrieved from the European Network of Transmission System Operators (ENTSO-E).

In Fig. 2, we show the change per decade in power supply for all the countries considered in the analysis. Results indicate that onshore wind does not change significantly for many countries either with historical data or most climate projections. A few positive significant changes are present in the Balkans with historical data whereas negative values are present across Europe for RCP 8.5 climate projections.



Input data (~ 3 TB)

Meteorological variables
- Wind speed
- Solar radiation
- Temperature
- Runoff

Datasets
- ERA5 (1940-2023)
- EURO-CORDEX (2006-2100)

Other geospatial data
- Population density
- Terrain roughness
- Terrain elevation
- Protected areas
- Land use

Conversion and aggregation

Regridding of projected climate data

Conversion of meteorological variables to power supply and demand
- Atlite
- Established literature

Aggregation
- Grid cells with top 25% resources
- Drainage basins
- Population density

Calibration with publicly available data
- ENTSO-E
- Eurostat

Output data (~ 25 GB)

Country-level time series
- Offshore wind capacity factor
- Onshore wind capacity factor
- Solar photovoltaics capacity factor
- Hydropower inflow
- Heating demand
- Cooling demand

Figure 1. Workflow to estimate country-level time series of wind capacity factor, solar capacity factor, hydropower inflow, heating demand, and cooling demand. Meteorological variables such as wind speed, solar radiation, temperature, and runoff are retrieved from ERA5 reanalysis and EURO-CORDEX projections. Together with other geospatial data such as population density, terrain roughness and elevation, protected areas, and land use, we perform a conversion from meteorological to power variables using Atlite and methods from established literature. Lastly, we perform an aggregation to obtain country-level time series of offshore and onshore wind capacity factors, solar photovoltaics capacity factors, hydropower inflows, and heating and cooling demands.

Results for offshore wind show a broader decrease in capacity factor for most of the countries as the future climate force increases. Solar photovoltaic capacity factors show a general increase for RCP2.6 forcing and a tendency to reduced values as the forcing increases. For hydropower, there is a general decrease in inflow for most of the countries with historical meteorological data. Overall, our results show the large heterogeneity and spatial differences in the change of these resources, suggesting that more detailed studies should be conducted at least on a country level, consistently with previous studies (Gernaat et al, 2021), (Liu et al, 2023).

Our time series could be used to evaluate the adequacy of the considered power systems in meeting a variable and changing electricity demand. IT could also be used for developing stochastic optimization models to optimize energy system design and operation under uncertain weather and climate conditions; to investigate robust optimization techniques that can ensure the resilience of energy system designs against a wide range of possible scenarios; to evaluate the performance of energy system designs across different possible future scenarios.

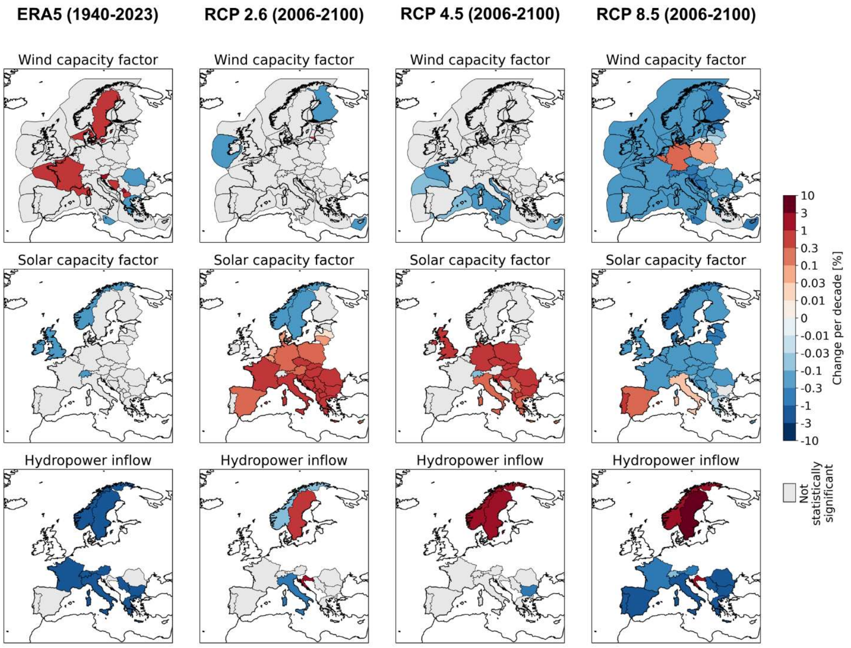


Figure 2. Change in power supply per decade. The panels show changes in onshore and offshore wind capacity factors, solar photovoltaics factors, and conventional and pumped-storage hydropower inflow. We calculated the change per decade with a linear regression of the mean annual values. The columns refer to different meteorological data sources.

3.2 The Estimated Co-Benefits of Adopting a Net Zero Scenario Design

3.2.1 Methodology

We gathered data from the ENGAGE database (Riahi et al., 2021; Bachs et al., 2024), which provides insights on scenarios involving projections of emissions originating in ten macro-regions. These scenarios are generated by six Integrated Assessment Models (IAMs')[1] that lay down various measures to achieve decarbonization depending on how power sources and land are put into use. Then, we utilized the TM5-FASST Scenario Screening Tool (Dingenen, R., 2018) to make estimations with respect to the degree to which PM2.5 and O3 are present in the air by having reduced emissions (Bachs et al., 2024). The results obtained at this stage were used to assess premature mortality linked to air pollution through the implementation of several relative risk ('RR') functions that are used for the calculation of death increases that stem from the

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[1] The six IAMs are AIM CGE, IMAGE, MESSAGEix-GLOBIOM, POLES-JRC, REMIND-MAgPIE and WITCH. See Bachs et al., 2024.

heightened level of air pollutants (Bachs et al., 2024). Lastly, economic damage due to the adverse impacts of pollution on health were estimated by using four economic functions that can either be formed based on the number of premature deaths or levels of PM2.5 and O3 (Bachs et al., 2024). In making the quantifications, we used numerous RR and economic damage functions and altered their parameters to determine the extent to which changes with the latter elements impact the outcome (Bachs et al., 2024). This allows for more robust conclusions.

3.2.2 Health Co-Benefits

We determined if the two mitigation pathways (“end of century” and “net zero”) generate statistically diverse air pollution impacts, scientists made use of the Kolmogrov-Smirnov two-sided statistical test (Gibbons and Chakraborti, 2011; Bachs et al., 2024). As shown in Figure 3.a, the introduction of the net zero pathway in China and India prevents the death of many people that would otherwise have been deceased had the end of century pathway been followed. In Figure 3.b, the use of diverse RR functions, parameters as well as counterfactual values[2] has resulted in the obtainment of diverse estimations with respect to the number of people that will die prematurely in 2030 due to air pollution. That said, as shown by the color of vertical lines that reflect the median value of the three CIs for NZ and EoC, the adoption of the net zero pathway rather than end of century pathway is estimated to trigger fewer premature deaths. In addition, as shown in Figure 3.c, the net zero pathway delivers fewer deaths across all CIs compared to the end of century CIs (Bachs et al., 2024).

3.2.3 Economic Co-Benefits

A large body of literature has studied macroeconomic impacts of climate change in the long term. (Piontek et al., 2019; Tol, 2018). These estimations, however, can change considerably depending on the methodology chosen and initial conditions. Therefore, we concluded that assessments with respect to economic effects should only be made to complement the existing studies with respect to the impacts of climate change on health.

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[2] The counterfactual value is utilized to mark the minimum threshold of emissions that need to be present for making projections concerning the effects of emissions. See European Environment Agency, Assessing the Risks to Health from Air Pollution. https://eea.europa.eu/publications/assessing-the-risks-to-health/file

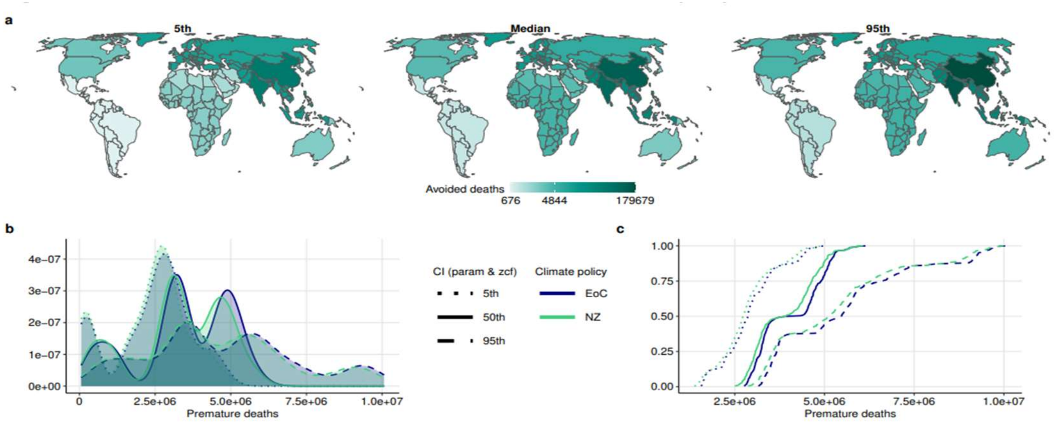

Figure 3

Within this context, when assessing economic co-benefits, we utilized four different methodologies. The methods put forward by *Dechezlepretre et al.* and *Dong et al.* make correlations between Gross Domestic Product ('GDP') and the degree to which pollutants are present in the air. The other methods, the value of statistical life (VSL) and the human capital loss (HCL), utilize data that quantify premature mortality (OECD, 2012; Zhang et al., 2023). These functions do not factor in the decreases with the costs that have previously been incurred to manage pollution. That said, costs that are generated to avoid overshooting the temperature target are covered by GDP estimations made in IAMs. Therefore, the adoption of the HCL and Dong et al. (2021) methods enable the inclusion of mitigation costs when quantifying the economic benefits that can be obtained under a net zero scenario (Bachs, et al., 2024).

Our results show that the adoption of policies geared towards the achievement of "net zero" generates more economic benefits compared to the introduction of measures that are compatible with the requirements of the "end of century" scenario. Notably, as shown in Figure 4, all countries accrue economic advantages. China obtains the greatest economic benefit by avoiding a GDP loss of 290 (273-325) billion dollars in 2030 (Figure 4.a; Bachs et al., 2024; Drouet et al., 2021).

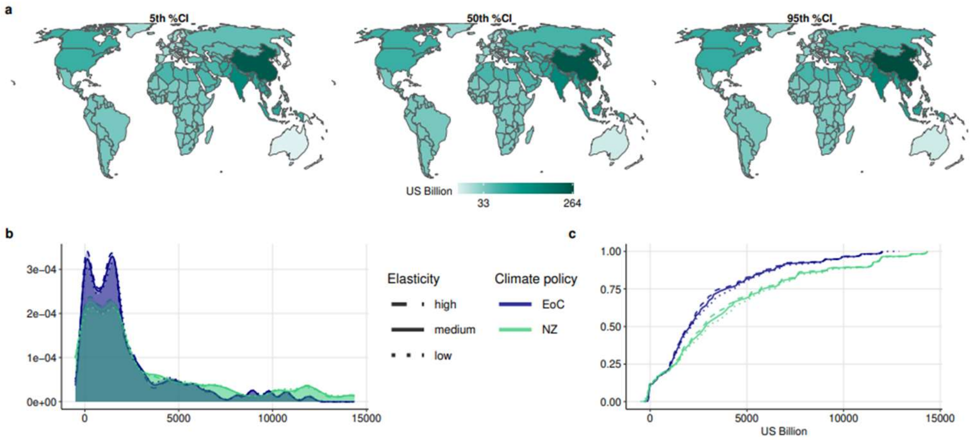

Figure 4

3.3 Environment, mobility and carbon emissions: the role of compactness for Italian urban centers

3.3.1 Data on Italian urban centers

The main goal of our research is the provision of data on the built-up surface and structure, urban form, carbon emissions for heating and cooling of buildings, and ancillary variables (population, income, temperature, precipitations) of Italian urban centers. The geo-referenced data on the boundaries of urban centers, the initial starting point of our analysis, are obtained starting from raster data on the degree of urbanization from the GHS-SMOD dataset (Pesaresi et al., 2019). To obtain polygons corresponding to "urban centers", we select only raster cells coded as such, aggregate them and transform the result into polygons representing their boundaries of each settlement. For a settlement to be classified as an "urban center", it must fall within the "Degree of Urbanization" thresholds: its population must be of at least 50,000 inhabitants, with a population density above 1,500 inhabitants per km^2 (Dijkstra et al., 2021).

We join to the data on urban centers a set of additional variables: Table 1 provides a list of the geo-referenced data sources used for the construction of the dataset, detailing information on their resolution and temporal dimension. To perform the spatial join, we overlay the polygons representing Italian urban centers and the gridded information on other variables. We assign to each urban center the values of the gridded data falling above it, weighing the sum or the average by the share of raster cell surface that is overlapping the polygon.

Table 1 – Sources used for the construction of the data

Data Sources	**Resolution**	**Years**	**Type of spatial join**	**Main Variables**
GHS-SMOD 2023 (Pesaresi et al., 2019)	1 km	1975-2020 (5 years intervals)	Master data	Urban boundaries
GHS-POP 2023 (Schiavina et al., 2023)	1 km	1975-2020 (5 years intervals)	Sum within urban boundaries	Population
GHS-BUILT 2023 (Pesaresi et al., 2023)	1 km	1975-2020 (5 years intervals)	Sum within urban boundaries	Built-up surface: total, residential, non-residential (m^2)
EDGAR v7.1 (Crippa, et al., 2018; Janssens-Maenhout, et al., 2019)	0.1 degrees (approx. 11.1x11.1 km at the equator)	1970-2021 (yearly)	Weighted sum of emissions over urban boundaries	CO_2 emissions from on-road transport (tonnes)
ISPRA, BIGBANG	1 km	1951-2021 (yearly)	Weighted mean within urban boundaries	Temperature (°C) and precipitations (mm)
Gridded data on GDP (Kummu et al., 2018)	Five arcmin (approx. 9x9 km at the equator)	1990-2015 (yearly)	Weighted sum over urban boundaries	GDP (PPP, 2011 USD)
Admininistrative data on the boundaries of Italian municipalities (ISTAT)	Geo-referenced boundaries of administrative units	2022	The name of the administrative unit with largest overlapping surface was joined	Names of admin. units (region, province, municipality)

Moreover, we construct a set of urban form indicators: the compactness index (CI), the range index (RI), and the sprawl index (SI). The CI, first introduced by Li and Yeh (2004) in a study on the evolution of land use patterns in the Chinese Pearl River Delta, compares the perimeter of an urban area to the circumference of an equivalent-area circle, indicating how close the urban form is to an optimally compact shape. The RI measures the ratio of the diameter of this equivalent circle to that of the smallest circumscribing circle, providing yet another measure of compactness (Angel et al., 2010; Harari, 2020). SI, developed by Burchfield et al. (2006) and further discussed in later research (Angel et al., 2010; 2020), uses built-up surface data to measure the extent of sprawl. It calculates the share of undeveloped space around residential units and averages this over all residential areas. Figure 5 displays the geometry behind the computation of the urban form indicators for the urban area of Rome in the dataset, for the most recent year of data availability (2020).

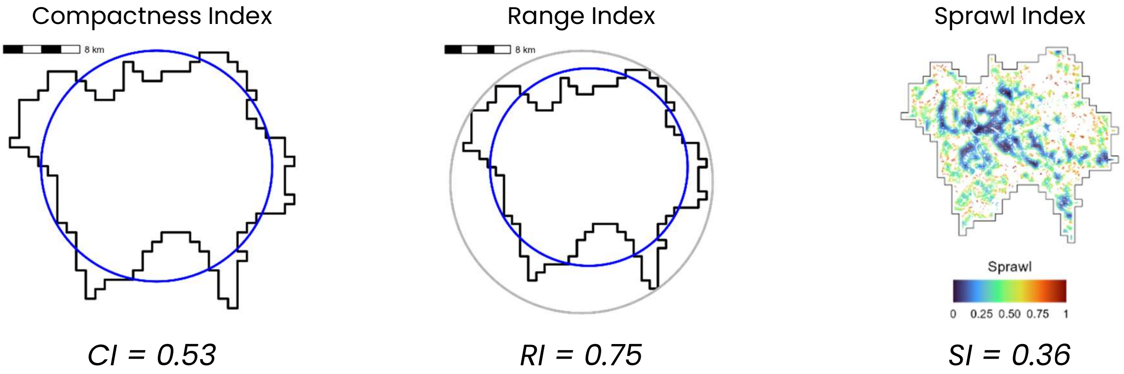

Figure 5 – Urban form indicators constructed for the data

3.3.2 Associations between urban form and emissions due to mobility

Our dataset is a resource for exploring the relation between urban planning and environmental outcomes, and how it has changed over time. Figure 6 provides an example, displaying a preliminary correlation analysis of on-road transport carbon emissions and the urban form indicators for the year 2020. CO_2 emissions per capita appear to be negatively correlated with both the compactness and range indices and positively correlated with the sprawl index, indicating that more dispersed, sprawling urban centers in Italy are normally associated with higher per capita emission levels. This preliminary result shows the potential of the data and supports the hypothesis that compact urban forms are more environmentally sustainable. Nevertheless, further research will be necessary to more clearly establish such a complex relationship.

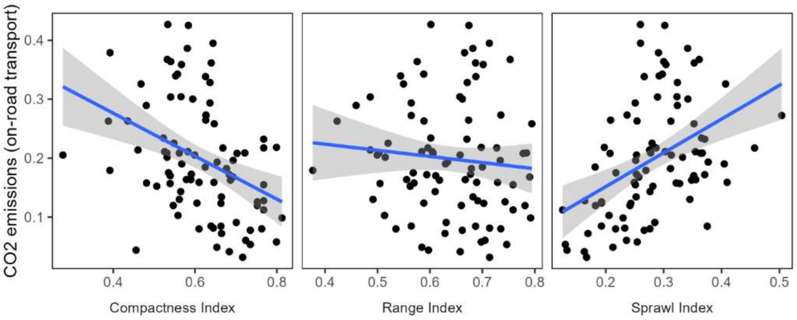

Figure 6 – Correlations between urban form indicators and per capita transport emissions, 2020

3.4 Local public transport and air pollution: assessing avoided emissions through a natural experiment

3.4.1 Identification and empirical strategy

Our research investigates the change in local levels of air pollution (NO and NO2) following a train accident that occurred April 20, 2023, around 2 a.m near the Firenze Castello station (exogenous treatment). This accident caused significant disruptions to many railway lines in Tuscany for up to four days. As several regional trains providing a daily commuting service were suddenly cancelled without any notice, commuters had to switch to a means of private vehicle transport, impacting on the local levels of air pollution.

People's commuting behaviour represents a latent variable which cannot be directly observed. Nevertheless, we do observe NO and NO2 local air pollution on an hourly basis by 38 grounded monitoring stations located in the Tuscany region: 12 stations are in the areas where the train services were temporarily suppressed (treated group). The remaining 26 stations were grouped in the control group (see Figure 7).

Our empirical strategy consists of a Two-Way Fixed Effects Difference-in-Differences (Diff-in-Diff) design: we measure the pre-post treatment variation of NO and NO2 pollutants in the treated group and compare it with the pollutants' pre-post treatment variation in the control group.[3] We control for key variables related to the

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[3] The econometric model includes monitoring station and hour's fixed effects. Unit-level fixed effects are introduced to account for differences that do not vary over time between monitoring stations, such as

meteorological conditions, which can impact the concentration of air pollutants (average wind speed, average humidity, temperature).

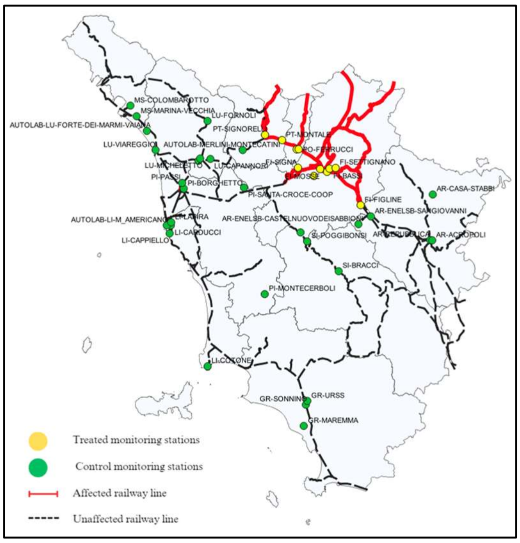

Fig 7. Tuscany regional railways affected by train derailment.

Source: Own elaboration on RFI data.

3.4.2 Results

We find that the unexpected disruption of the local railway system led to a statistically significant short-term increase in atmospheric pollution above the WHO recommended limits in those areas affected by the interruption of the regional rail services with respect to similar areas where train services were regularly in place. In particular, the day following the train accident, NO2 and NO concentrations increased on average by 4.93 $\mu g/m^3$ and 2.18 $\mu g/m^3$ (see Table 2). This corresponds, respectively, to a 36% and a 47% increase in local pollution compared to the pre-treatment average levels. This effect was particularly pronounced in the metropolitan city of Florence. The most substantial increase was registered during the first 2 days after the train accident, though it lasted up to 4 days after the event (when train services rail services were fully re-established). We also find that the increase in pollutant concentrations was significant only during the 09-12 and 17-19 time slots, suggesting that the significant increase in emissions was due to higher use of private transport vehicles and higher traffic during commuting hours (Figure 8).

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geographical location, while the second control captures temporal differences that are common across all stations. These two coefficients allow for the control of potential biases stemming from potential fixed unobserved heterogeneity.

Table 2 - Impact of train accident on NOx: Diff-in-Diff

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	no2	no	no2	no	no2	no
DID	4.934***	2.184**	3.705***	1.736*	2.640**	1.103*
	(1.497)	(0.875)	(1.173)	(0.899)	(1.121)	(0.619)
Constant	39.243	39.709	38.591	26.281	48.646**	23.003*
	(37.309)	(23.678)	(29.094)	(18.392)	(22.216)	(13.371)
Observations	4,435	4,435	5,287	5,287	6,139	6,139
Time and Fixed Effects	YES	YES	YES	YES	YES	YES
Weather Control Var.	YES	YES	YES	YES	YES	YES
R-squared	0.438	0.300	0.424	0.312	0.407	0.311
Time to treat	<=24	<=24	<=48	<=48	<=72	<=72

*** p<0.01, ** p<0.05, * p<0.1 Robust standard errors clustered in parentheses. Time to treat refers to the number of hours included in the post-treatment periods. Different columns show how the average estimated coefficient declines as the length of the considered post-treatment period increases.

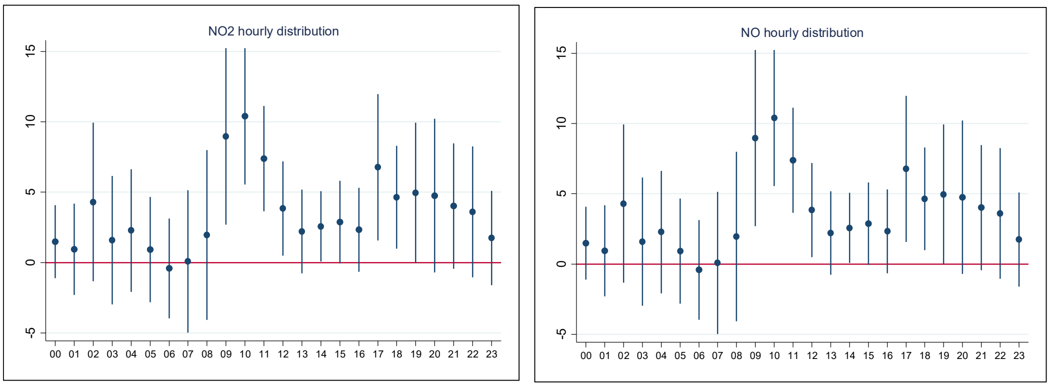

Figure 8. Impact of train accident on NOx: Heterogeneous effect across hours

4. Policy implications

4.1 Climate change impacts on renewable energy

The results of our study highlight several important policy implications regarding the resilience of future energy systems. First, the spatial and temporal variability in renewable energy potential under different climate scenarios necessitates a more flexible and adaptive energy policy framework. Renewable energy sources will be differentially impacted by climate change across various regions. This encourages the diversification of renewable energy portfolios at national and regional levels to reduce the risk of over-reliance on a single energy source.

Second, the electrification of end-use sectors and the growing demand for cooling in response to rising temperatures will place additional strain on electricity systems. Therefore, energy policy must prioritize investments in energy efficiency and demand-side management, such as the use of smart grids, energy storage solutions, and flexible demand-response mechanisms. Building codes and appliance standards should be updated to ensure that both new and existing infrastructure is optimized for energy efficiency under changing climatic conditions. Policies aimed at reducing peak demand, particularly during periods of extreme heat, will also be essential.

Third, the findings related to the potential decrease in hydropower and offshore wind capacity highlight the need for increased investment in energy storage and grid interconnectivity. Policymakers should promote research and development of advanced storage technologies as well as cross-border electricity trading through interconnected grids to mitigate regional shortages due to weather variability.

Lastly, given the potential for extreme weather events to disrupt power systems, resilience and adaptation must be prioritized in energy infrastructure planning. Policies must ensure that renewable energy systems are designed to withstand climate-related risks, including heatwaves, droughts, and storms, which are projected to increase in frequency and intensity. This includes not only hardening physical infrastructure but also developing emergency response plans and regulatory frameworks that allow for rapid recovery and system restoration.

4.2 The Estimated Co-Benefits of Adopting a Net Zero Scenario Design

Despite the uncertainties stemming from RR functions and the IAM emission scenarios, we demonstrated that the adoption of the net zero scenario design would result in consistent health and economic co-benefits in all countries in 2030. Since this outcome has emerged as a result of the estimations made based on deaths related to PM 2.5 and O3, the pursuit of non-overshooting global climate policies is of crucial importance from an air pollution perspective (Bachs et al., 2024).

China and India are expected to reap the greatest health benefits and China is projected to avoid the highest amount of GDP loss. This situation demonstrates the importance of the steps taken in the latter countries to achieve decarbonization and improve air quality at the global level. To this end, China and India can seek to obtain funding from other countries by having recourse to the inter-state cooperation mechanisms that are governed in Article 6 of the Paris Agreement (Paris Agreement, 2016; Bachs. C. et al., 2024).

The results obtained can be complemented through the use of a 'Country Level Air Quality Calculator', a tool that shows the extent to which emission reductions that occur in a certain sector and country can reduce the concentration of PM 2.5 and O.3 (Renna et al., 2024). This would enable policymakers and planners to estimate the country-level and sector-level air pollution benefits.

4.3 Environment, mobility and carbon emissions: the role of compactness for Italian urban centers

The availability of a comprehensive dataset of Italian urban centers, detailing their levels of emissions for heating and cooling of buildings, describing their built-up surface and urban form and providing other ancillary variables useful for empirical analysis, offers substantial benefits for both research and policy development. For policymakers, the dataset can be an important tool for evidence-based decision-making. It allows for the identification of trends and patterns that can inform urban planning and environmental policy. By understanding how different urban forms correlate with carbon emissions, targeted interventions that promote energy efficiency and reduce greenhouse gas emissions can be designed. Additionally, the inclusion of ancillary variables such as GDP, population, temperature, and precipitation helps in crafting policies that are sensitive to local contexts and socioeconomic conditions. This approach could ensure that policies are not only environmentally effective but also economically and socially viable, paving the way for sustainable urban development.

The preliminary analysis of the dataset of Italian cities shows a negative correlation between urban compactness and on-road transport carbon emissions. Testing such a relation and finding more robust evidence also for Italy would have significant policy implications. It would encourage urban planners to prioritize compact city design and support higher-density construction, incentivizing re-development of underused areas, and discouraging urban sprawl. At the same time, potential downsides of compact city development should also be considered: the literature so far has identified issues including reduced living space, overcrowding and greater exposure to air pollution (Burton, 2000; Yao et al., 2022; Carozzi and Roth, 2023). To mitigate these issues, strategies to enhance livability should be implemented, including ensuring adequate green spaces, investing in efficient public transportation, and controlling housing costs.

4.4 Local public transport and air pollution: assessing avoided emissions through a natural experiment

Our analysis highlights the relevance of the LPT in limiting local air pollution. This finding is relevant concerning: i) the critical exposure of European citizens to local air pollutants, with negative consequences in terms of chronic diseases and premature deaths; ii) the major contribution of the transport sector to EU GHG emissions; iii) the recent European commitment to strengthen the EU air quality standards by the end of the decade to contribute to the EU's objective on zero pollution by 2050; iv) the European commitment to achieve a 90% reduction in transport-related greenhouse gas emissions by 2050.

We believe that our findings bring some relevant policy insights. First, the EU sustainable mobility plan can be strengthened and should be complemented through the design of policies aimed at supporting a progressive shift from the private road standard to the public rail alternative. This requires investments that run counter to the trends observed in Europe in recent decades, following the liberalization, privatization, and unbundling reforms of various services of general interest, including transport.

During the last decades, Italy registered a constant reduction in the net primary expenditure for the transport sector, from 40 bln € in 2007 to 30 bln in 2019-2020. Italian funds to LPT experienced a reduction from 6.1 billion in 2009, to 5.1 billion in 2023 (Pendolaria 2023) while regional train services recorded a 17% decline from 2009 to 2017 (Legambiente 2023, Isfort 2023). Given these budget constraints, Italy registered a very slow progress in the electrification of the rail grid, from 67.8% in 2001 to 72.4% in 2022, meaning that a quarter of the grid is still not electrified. Local rail services are also characterized by severe regional disparities, with a marked gap between the North and the South of the country.[4] This partly stems from the reform of this sector which, since the 2000s, has led to an increasing regionalization in the governance of the local rail transport services. As a result, the rail transport in Italy represented on average around the 10% of total transport, a relatively low value when compared to other European countries.

Considering the significant environmental benefits associated with LPT services, reversing the negative trend of investments in this sector, compared to those relating to road transport, represent a crucial strategy to achieve the EU ambitious targets in terms of both air pollution and GHG emissions' reduction. Our policy recommendations are quite aligned with the decision to address part of the NRRP funds to the renovation of the regional rail networks.

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[4] Some Northern regions recorded an increased frequency and availability of regional rail services, particularly through integrated mobility systems. There has been a gradual renewal of the rolling stock for regional trains, improving service reliability, comfort, and environmental sustainability. Conversely, southern Italy were characterized by less investment in local rail infrastructure, resulting fewer and less frequent rail connections, older infrastructure, and lower overall service quality. Particularly in rural and low-density areas, there has been a reduction or even elimination of certain rail services due to a lack of profitability, leaving some areas underserved or reliant on less efficient bus services.

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