Supplementary Information: North-South polarization of European electricity consumption under future warming

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This document contains supplementary information to Wenz, Levermann and Auffhammer (2017). Section 1 provides additional figures that complement the figures shown in the main manuscript by displaying the results for all remaining variants of daily peak load/daily electricity consumption and daily maximum/daily average temperature. Section 2 comprises four tables with detailed information on the data used in and obtained by the analysis. Specifically, Tables S2+S3 complement the two tables shown in the main manuscript by documenting computation results for daily average temperatures instead of daily maximum temperatures. Section 3 examines the robustness of the results to specific modeling assumptions.
1. Supplemental figures

Figure S1: Response of daily peak load to daily maximum temperature based on observational data for the years 2006-2012. Black dots represent the effect of replacing a day of daily maximum temperature in the omitted bin category (21°C-24°C) with a day of the relevant maximum temperature. First and last bin are chosen such that each comprises at least 2% of all data. The regression model controls for seasonality, day-of-the-week effects and large-scale economic events (Chebyshev polynomials up to degree six). Pink shaded areas denote 95%-confidence band based on Newey-West standard error. Regression functions of all countries display similar characteristics with minimal peak load values at ~22°C (71.6°F) that increase monotonically in lower and higher temperature, where data coverage is sufficient.
Figure S2: Response of daily electricity consumption to daily maximum temperature based on observational data for the years 2006-2012. Black dots represent the effect of replacing a day of daily maximum temperature in the omitted bin category (21°C-24°C) with a day of the relevant maximum temperature. First and last bin are chosen such that each comprises at least 2% of all data. The regression model controls for seasonality, day-of-the-week effects and large-scale economic events (Chebyshev polynomials up to degree six). Pink shaded areas denote 95%-confidence band based on Newey-West standard error. Regression functions of all countries display similar characteristics with minimal electricity consumption values at ~22°C (71.6°F) that increase monotonically in lower and higher temperature, where data coverage is sufficient.
Figure S3: Response of daily peak load to daily average temperature based on observational data for the years 2006-2012. Black dots represent the effect of replacing a day of daily average temperature in the omitted bin category (15°C-18°C) with a day of the relevant average temperature. First and last bin are chosen such that each comprises at least 2% of all data. The regression model controls for seasonality, day-of-the-week effects and large-scale economic events (Chebyshev polynomials up to degree six). Pink shaded areas denote 95%-confidence band based on Newey-West standard error. Regression functions of all countries display similar characteristics with minimal peak load values at ~16°C (60.8°F) that increase monotonically in lower and higher temperature, where data coverage is sufficient.
Figure S4: Response of daily electricity consumption to daily average temperature based on observational data for the years 2006-2012. Black dots represent the effect of replacing a day of daily average temperature in the omitted bin category (15°C-18°C) with a day of the relevant average temperature. First and last bin are chosen such that each comprises at least 2% of all data. The regression model controls for seasonality, day-of-the-week effects and large-scale economic events (Chebyshev polynomials up degree six). Pink shaded areas denote 95%-confidence band based on Newey-West standard error. Regression functions of all countries display similar characteristics with minimal electricity consumption values at ~16°C (60.8°F) that increase monotonically in lower and higher temperature, where data coverage is sufficient.
Figure S5: Common response function. (A) Daily electricity consumption and daily average temperature. Observational daily electricity consumption and daily average temperature data (2006-2012) of all countries are combined taking national population size into account (gray dots). Load values have been adjusted based on the country-level regression coefficients to remove the influence of non-temperature confounders and the resulting residual load data have been normalized to allow for comparison across countries ($L_{cd}^{\text{norm}}$, see Methods for detail). We obtain the response function by linking the medians of 1°C-bins (thick blue line). The first and last bin each comprises at least 20,000 data points; we linearly extend the median function for temperatures beyond these bins (dashed blue lines). (B) Daily electricity consumption and daily maximum temperature. As in A but with observational daily maximum instead of daily average temperature. (C) Daily peak load and daily average temperature. As in A but with daily peak load instead of daily electricity consumption. (D) Daily maximum temperature and normalized load data for different European regions. As in B but with daily peak load instead of daily electricity consumption (see also Fig. 2). Data points are colored according to the geographical region a country belongs to (the assignment of countries to geographical regions can be found in Table S1).
Figure S6: Estimated daily electricity demand for projected daily maximum temperatures in 2013-2099 under three different warming scenarios. Estimated daily electricity demand values for the years 2013-2099 under three different Representative Concentration Pathways (RCPs; blue, yellow, and red dots) lie well within the range of observational data ($L_{v,d}$, gray dots). Blue shaded areas denote the uncertainty range (see Methods for detail).
Figure S7: Estimated daily peak load values for projected daily average temperatures in 2013-2099 under three different warming scenarios. Estimated daily peak load values for the years 2013-2099 under three different RCPs (blue, yellow, and red dots) lie well within the range of observational data (gray dots). Blue shaded areas denote the uncertainty range (see Methods for detail).
Figure S8: Estimated daily electricity demand for projected daily average temperatures in 2013-2099 under three different warming scenarios. Estimated daily electricity demand values for the years 2013-2099 under three different RCPs (blue, yellow, and red dots) lie well within the range of observational data ($\hat{L}_{c,d}$, gray dots). Blue shaded areas denote the uncertainty range (see Methods for detail).
Figure S9: Percentage change in average daily peak load from 2006-2012 to 2080-2099 for projected daily average temperatures under mitigated (A) and unmitigated (B) climate change. While daily peak load decreases in Northern European countries, it increases in Southern and Western Europe countries. This trend is most pronounced for a scenario of unabated climate change (RCP-8.5, B) but still holds for a scenario of mitigated climate change (RCP-4.5, A). Table S2 provides data on all countries and the three RCPs, as well as on different planning horizons until 2100.
Figure S10: Percentage change in daily electricity demand (5-y average) compared with 2015-2019 average for projected daily average temperatures under different scenarios of climate change mitigation. Five-year average electricity demand values are denoted by the year in the middle of the respective time interval on the x axis. **(A)** Under a scenario of unabated climate change (RCP-8.5), daily electricity demand decreases in Northern European countries and increases in countries in Southern and Western Europe. Total European electricity demand increases in the last two decades of the century relative to 2015-2019. **(B)** For a scenario of mitigated climate change (RCP-4.5) the trend observed in A is present but less pronounced. **(C)** For a scenario of very ambitious climate change mitigation that keeps global temperature increase below 2°C (RCP-2.6), there is no clear trend. Table S3 provides data on all countries, RCPs and 5-y periods until 2100.
**Supplemental tables**

Table S1 contains an alphabetical list of all 35 European countries analyzed in this study (columns 1-2). Column 3 denotes the geographical region a country is assigned to in Figures 5, S5d and S10. Column 4 documents whether hourly load data are provided by the Entso-e database (1) for the entire 2006-2012-period or for smaller sub-periods only. The percentage of missing data points within both the 2006-2012-period and the potentially smaller country-specific coverage period is given in columns 5-6. Cyprus is excluded from the second part of the analysis because of load data scarcity.

Table S2 displays the percentage change in average daily peak load by country relative to 2006-2012 for projections of average temperature under three different scenarios of climate change mitigation.

Table S3 shows the percentage change in average daily electricity consumption by country relative to 2015-2019 for projections of daily average temperature under three different scenarios of climate change mitigation.

Table S4 documents for each country in which season annual peak load is found to occur most often at present time (2006-2012) and by the end of the century (2080-2099) under a scenario of unabated climate change (RCP-8.5). In the Netherlands and in Poland annual peak load occurs equally often in two different seasons. The last two columns indicate whether annual peak load is shifted from one season to another in general and specifically from winter to summer under future climate change. The total number of countries with a change in seasonal peak load is given in the last row.
Table S1: List of countries and temporal load data coverage

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Table S2: Percentage change in average daily peak load by country relative to 2006-2012 for daily average temperatures under RCP-2.6, RCP-4.5 and RCP-8.5.
### Table S3: Percentage change in average daily electricity consumption by country relative to 2015-2019 for daily average temperatures under RCP-2.6, RCP-4.5 and RCP-8.5

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Table S4: Seasonal peak load at present time (2006-2012) and under future climate change (2080-2099; RCP-8.5)

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<th>Country</th>
<th>Season in which annual peak load occurs most often</th>
<th>2006-2012</th>
<th>2080-2099 (RCP-8.5)</th>
<th>Current winter peak</th>
<th>Future winter peak</th>
<th>Current summer peak</th>
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<th>Winter to summer</th>
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Number of countries: 30, 12, 2, 21, 22, 19
2. Robustness of results to specific modeling assumptions

Figure S11: Robustness of results to different specification of first and last bin (3% of all data): Response of daily peak load to daily maximum temperature based on observational data for the years 2006-2012. Black dots represent the effect of replacing a day of daily maximum temperature in the omitted bin category (21°C-24°C) with a day of the relevant maximum temperature. First and last bin are chosen such that each comprises at least 3% of all data. The regression model controls for seasonality, day-of-the-week effects and large-scale economic events (Chebyshev polynomials up to degree six). Pink shaded areas denote 95%-confidence band based on Newey-West standard error.
Figure S12: Robustness of results to degree of Chebyshev polynomials (up to third degree): Response of daily peak load to daily maximum temperature based on observational data for the years 2006-2012. Black dots represent the effect of replacing a day of daily maximum temperature in the omitted bin category (21°C-24°C) with a day of the relevant maximum temperature. First and last bin are chosen such that each comprises at least 2% of all data. The regression model controls for seasonality, day-of-the-week effects and large-scale economic events (Chebyshev polynomials up to degree three). Pink shaded areas denote 95%-confidence band based on Newey-West standard error.
Figure S13: Robustness of results to degree of Chebyshev polynomials (up to tenth degree): Response of daily peak load to daily maximum temperature based on observational data for the years 2006-2012. Black dots represent the effect of replacing a day of daily maximum temperature in the omitted bin category (21°C-24°C) with a day of the relevant maximum temperature. First and last bin are chosen such that each comprises at least 2% of all data. The regression model controls for seasonality, day-of-the-week effects and large-scale economic events (Chebyshev polynomials up to degree ten). Pink shaded areas denote 95%-confidence band based on Newey-West standard error.
Figure S14: Robustness of result to bin-width (3°C-width): Common response function. Observational daily peak load and daily maximum temperature data (2006-2012) of all countries are combined taking national population size into account (gray dots). Load values have been adjusted based on the country-level regression coefficients to remove the influence of non-temperature confounders and the resulting residual load data have been normalized to allow for comparison across countries ($\hat{L}_{C,d}^{\text{norm}}$, see Methods for detail). We obtain the response function by linking the medians of 3°C-bins (thick blue line). The first and last bin each comprises at least 20,000 data points; we linearly extend the median function for temperatures beyond these bins (dashed blue lines).
References