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The impact of social and weather drivers on the historical electricity demand in Europe

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HIGHLIGHTS

- Very diverse country-specific daily activity profiles emerged from national electricity hourly loads.
- Temperature sensitivity was modelled to find the optimal temperature range for heating and cooling states.
- Fourier analysis of residual demand suggests long-term (seasonal and annual) storage is needed.
- Perfect interconnection between European countries could reduce storage size by up to 61 TWh/year.

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ABSTRACT

Climate change, technological innovation, as well as electrification of energy services to meet carbon targets, have a significant impact on electricity demand magnitude and patterns. Increasing generation from renewable energy sources is already changing supply variability at the hourly and seasonal timescales. Our aim is to conduct a rigorous study of European historical demand, to understand its relationship with social and weather drivers and, therefore, to gain insights into appropriate storage needs.

Daily activity profiles exhibit notable differences across European countries, with some of them reporting a consistent demand reduction, up to 25%, during school closures and Christmas festivities. In addition, temperature sensitivity differentiates demand by countries' latitude (north vs. south), and by technologies (electric heating vs. other fuel based heating). Assuming a 100% renewables scenario, European countries would display quite distinct periodicities and amplitudes of their residual electricity demands.

Annual load curves and temperature sensitivities of nations with high electric heating or cooling demand can assist in the prediction of future electricity and other fuel consumption under increased electrification and climate change scenarios. Fourier periodicity and residual demand analysis suggest that, in addition to grid storage, European countries with mutual energy needs – in terms of seasonal demand and generation surplus – might benefit from international trade to balance unmet demand. Our study of consumption variability in response to social and weather drivers constitutes a valuable resource to formulate country-specific demand scenarios, as well as to improve the design of energy system models.

1. Introduction

The analysis of the historical electricity demand for the European region (EU35) is crucial to understand the relationship between demand and its drivers at the national resolution, as well as to model the future demand of the continent. A country's energy demand is driven by many factors: population, households (i.e. one or more people living in the same dwelling), social and economic activities, wealth, culture, climate, the proportions of services met with different energy types (electricity, fossil etc.) and the technologies used. All of these factors determine both the annual electricity consumption and the hourly profiles of electricity demands.

Social behaviours in particular, which are increasingly recognised as a fundamental driver in energy models [1], can show recurring patterns in time (e.g. weekly, or summer vacation periods) and are affected by the weather, and by cultural customs, technology and policies. Diurnal patterns are predominantly determined by human activities at home, at work and elsewhere for leisure, shopping, et cetera, whereas holidays generally cause decreased activity in non-domestic sectors such as schools and factories, and increased activity in dwellings or in non-

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domestic sectors serving holidaying people, such as hotels. Since daily social activities represent the shortest cycle of those recurring patterns, energy models with various scopes (e.g. energy systems, cities or individual buildings) often include them to predict energy service demands [2], although some models may consider even longer time slices (like months or seasons). These activity patterns, or profiles, are generally expressed as a percentage of a given demand (for example, the electricity for lighting or the gas demand for hot water). Depending on the model aims, activity profiles can be estimated by different means, for example by time use surveys [3] or by metering data [4], with a time resolution ranging from hours to seconds. Moreover, energy models focussed on the Residential (or Domestic) sector can estimate social activities also by integrating the information on building occupancy [5].

Some demands are also strongly affected by environmental conditions. Most notably, space heating increases as ambient temperature decreases, and the opposite trend is shown by air conditioning. Similarly, artificial lighting increases as sunlight decreases, and hot water demand increases as water supply temperature – which varies with seasonal ground temperature – decreases.

The relationship between weather conditions and electricity consumption has been studied at the national (e.g. [7]), city (e.g. [8]), or individual households scale (e.g. [9]), as well as on specific sectors (mostly residential, e.g. [10]). The main limitation of these studies, however, is that, although analysed in detail, they focus on a limited geographic area. A few studies cover the wider European region, but at a monthly [11] or daily resolution [12]. Other studies use Heating/Cooling Degree Days (e.g. [13]), although this approach has been criticised, as the temperature threshold is arbitrary and should be adapted to each country [11].

Our study overcomes these limitations by analysing the demand temperature sensitivity of each European country at an hourly resolution, with the aim of estimating the specific heat loss coefficients for electric space heating and air conditioning. A deep understanding of how weather conditions impact electricity consumption, will make it possible to project how service demands might change in a future when electricity will provide a greater fraction of heating, or how climate changes could increase the use of air conditioning.

Regarding the future energy system at the European scale, these demands might be met by increasing renewable sources. Assuming a 100% renewable generation scenario by extrapolating historical data, we could calculate the residual demand, and therefore, gain insights into the future storage and transmission requirements in Europe. Very few studies considered the synergy between storage and interconnection within a 100% renewable scenario, focussed either on the EUMENA region (Europe, Middle East and North Africa) [14], or on the United Kingdom [15,16]. The only work regarding Europe [17] estimated the renewable backup energy demand starting from a range of storage choices and grid capacities, rather than calculating them.

Our aim was to find the theoretical boundaries of the storage size required at the European scale between two extreme cases (non-existent and perfect interconnection) to quantify the reduction of storage that can be achieved by transmission. Moreover, calculating the frequencies of the residual demand would provide a measure of the periods when storage would be necessary, and of the appropriate storage size in each period [18,19].

2. Methods

2.1. Data sources

Data on energy consumption were collected from international databases freely available for academics. In particular, the electricity hourly demand and monthly generation of the EU35 countries (see Appendix) from 2010 to 2015 was taken from the European Network of Transmission System Operators for Electricity (ENTSO-E) [20], whereas the annual energy consumption from 1990 to 2014 for the same subset of countries was extracted from the "World energy balances" database by the International Energy Agency (IEA) [21]. The final consumption by end use was taken from the Odyssee database [22], which includes values for the EU28 countries, Norway, and Switzerland from 1990 to 2015. Data on hourly temperature, net downward solar irradiation at the surface, and wind speed by approximately 0.5 degree latitude/longitude was taken from the NASA MERRA re-analysis database [23] as detailed below:

- Temperature (K): MERRA T2M variable at 2 m above the displacement height was used as an estimate of ambient temperature;
- Solar irradiation (W/m^2): Hourly net downward solar irradiation at the surface;
- Wind speed (m/s): Hourly wind speed values at 2 m, 10 m and 50 m above the displacement height.

2.2. Data processing for energy consumption

The hourly electricity demand data time zone was converted from Central European Time/Central European Summer Time (CET/CEST) to Coordinated Universal Time (UTC). The values for Northern Ireland, reported separately by ENTSO-E until 2015 inclusive, were added to the hourly electricity demand of the United Kingdom. The hourly loads were calculated by the national Transmission System Operators (TSO) as "gross consumption" (including export, imports, distributed autogeneration, and transmission losses, but excluding plant auxiliaries, plant losses, and pumped storage); however, they seem to exclude transmission losses, despite what is stated in the ENTSO-E documentation, as the annual sums of the national loads are very similar to the final consumption of electricity in the IEA and Odyssee database. Data from the IEA database was extracted for coal and peat products (indicated as "Sol"), primary and secondary oils ("Liq"), natural Gas ("Gas"), heat ("Hea"), electricity ("Ele"), as well as biofuels and waste ("Ren"); in particular, to get an overview of the historical energy demand and fuels used in Europe the following flows were used: "Total final consumption", "Industry", "Transport", "Residential", and "Commercial and public services" (as "Services"). National energy consumption was also grouped by end use (i.e. service demand) and carrier from Odyssee.

2.3. Activity profiles from hourly national electricity load

To estimate the national social activity of a given time period, hourly electricity demand from ENTSO-E were averaged for each hour and each day of the week, to obtain the hourly demand for an average week. Then, these hourly values were divided by their sum to get the fraction of the weekly demand, and normalised by the hourly mean of the selected period to obtain an activity profile $a_{h,d}$ for each hour and day of the week:

$$a_{h,d} = \frac{\frac{x_{h,d}}{\sum_{h=0}^{23}\sum_{d=1}^{7} x_{h,d}}}{\bar{x}_{h,d}} \tag{1}$$

where $x_{h,d}$ is the electricity demand at hour h and on day d.

2.4. Population weighting of weather time series

Population weighting a gridded weather dataset is a way to get a single value for each time step that represents the weather experienced by a subset of people, for example in a country. To population weight NASA MERRA data by country, gridded population data from *The Global Rural-Urban Mapping Project (GRUMP) version 4* were used, whereas the MERRA grid was recreated in a GIS by creating Voronoi polygons around each grid point. Each grid cell's population geographically belonging to a given country was multiplied by the weather