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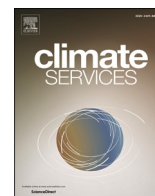
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Original research article



Temporal fragmentation of the energy demand in Europe: Impact of climate change on the maneuverability of energy system

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ABSTRACT

The energy demand in Europe is projected to be affected by climate change in the future. The heating needs are expected to decrease while the cooling needs are expected to increase. The study investigates the impact of climate change on the temporal fragmentation of heating and to a lesser extent cooling needs and its implication on the energy power system. Ten bias-corrected and downscaled simulations from CMIP6 at $25 \times 25 \text{ km}^2$ horizontal resolution over Europe have been used to estimate change in heating and cooling energy needs under four anthropogenic scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), using heating degree days (HDD) and cooling degree days (CDD) as proxies. Consistent with already published literature, here updated using the last CMIP6 simulation ensemble, the results show a large decrease of HDD over Europe and an increase of CDD under all scenarios. However, the study goes one step further by showing a fragmentation of the periods of heating needs during winter in the future which can potentially lead to a fragmentation of heating energy demand. In the worst-case scenario, periods of heating needs could be separated by up to 7 days, 9 times per winter. The cooling needs in summer are expected to be more frequent and last longer compared to the present climate. The fragmentation of temperature-sensitive energy needs for heating and to a lesser extent for cooling are expected to have an operational and economical impact on the balancing of the energy system.

Practical implications

Projected climate change is expected to impact energy demand in Europe. Downscaled CMIP6 multi-model ensemble simulations at a horizontal resolution of $25 \times 25 \text{ km}^2$ over Europe under four anthropogenic scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) show a large decrease of heating degree days (HDD) down to -60% at the end of the 21st century and an increase of cooling degree days (CDD) by up to $+30$ days per year which are used as proxies of the heating and cooling energy needs. Such results are consistent with previous published ones obtained from older CMIP projects.

For the first time, the evolution of HDD and CDD is not only quantified in terms of trend, it is also looked at in terms of fragmentation in time of heating and cooling energy needs, and quantified in terms of duration and frequency. Indeed, during

winter heating energy demand needs are projected to be less frequent and shorter, while in summer cooling energy demand needs are expected to be more frequent and longer compared to the present climate. Such fragmented energy demand needs may add variability to an electric mix increasing its share in variable renewable energies and may lead to additional flexibility challenges. The energy demand fragmentation occurs at time scale of few days, exceeding the intra-day time scale when flexibility brought by dispatchable energy sources is needed to meet the energy peak load. The type of flexibility addressed in this study is referred as maneuverability. It is shown that, in the future, the fragmentation of heating needs may exceed the margin of maneuverability and modulation of electricity production units.

1. Introduction

The last few decades have seen a significant increase in temperatures across Europe according to the 6th IPCC assessment report (AR6) (IPCC, 2023). Temperatures are expected to continue to increase in Europe in

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the future with a warming rate exceeding the average global warming. The warming rate in Europe is twice as much as the global average since the 1980s and it was approximately 2.3 °C above the pre-industrial average (1850–1900) in 2022. Average sea surface temperatures in the North Atlantic area have been the warmest on record and large parts of the region's seas have been affected by extreme marine heatwave (Lorenz et al., 2019; IPCC, 2023; Bednar-Friedl et al., 2022). The frequency and intensity of temperature extremes have increased over the past decades and are projected to continue to increase under the different greenhouse gas emission scenario (Lorenz et al., 2019; Yan et al., 2002; Bednar-Friedl et al., 2022). Cold spell frequency and freezing days are also expected to decrease under all greenhouse gas emission scenarios and over all time horizons. All these changes in the future climate may have an important impact on the energy sector (Santamouris et al., 2015; Li et al., 2012). Electricity demand is one of the most impacted component of the energy system by climate change (Bloomfield et al., 2021; Jankovic et al., 2019). For instance, the energy demand related to heating represents a large part of the total demand in most European countries (18 countries out of 28 countries) and it exceeds the demand for cooling for all of those countries, even those with relatively warm climates such as Spain, Italy, Croatia, Greece, Malta and Cyprus (Pardo et al., 2012; Zangheri et al., 2014; Connolly, 2017). For instance, in 2020, the residential sector, represented 27.4% of final energy consumption with the space heating as a main use of energy (62.8%) (Eurostat, YYYY). Thus any change in heating needs in the future may lead to a significant variation in total electric demand.

Understanding how the energy demand will potentially be affected by climate change in the coming decades is one of the most important challenges today for the energy sector. In the current context of the European ambition to achieve carbon neutrality, the electrification of uses such as heating represents an essential and accessible lever for carbon neutrality (Rogelj et al., 2019; Keramidas et al., 2020). As Rogelj et al. (2019) explain in the Policy report, achieving ambitious long-term stabilization goals (2 °C and below) requires a robust decarbonization of the power sector and a general improvement in overall efficiency. This will likely demand, on average, a faster integration of electricity usage across the economy over the next three decades. Anticipating future changes in energy demand could be essential for the sizing and the management of the future electric park (van Ruijven et al., 2019). Indeed, the limited possibilities for storing electricity require adjusting the balance between electricity production and consumption in the short, medium, and long term. Therefore, information on the potential impacts of climate change on electricity demand is valuable for the adaptation of the energy sector.

Several studies have evaluated the potential impact of future climate changes on energy demand. Globally in Europe, increasing temperatures lead to overall decrease in heating demand and an increase in cooling demand (Larse et al., 2020; Pili-Sihvola et al., 2010). Damm et al. (2017) find that global warming by 2 °C is expected to reduce electricity demand in most countries because of the decrease in heating needs, the reduced heating electricity demand over-weighing the increase in cooling demand. Other studies have focused only on the residential sector to study the impact of climate change on energy demand (Mutschler et al., 2021; Ciancio et al., 2020; Jankovic et al., 2019) and have found similar results that confirm an increase in cooling demand in summer and a decrease of heating demand over the next decades in most European countries as a result of future warming. However, locally there can be different conclusions, especially in South-Eastern Europe. For instance, the change in energy demand could be different between Northern or Southern Europe, the most significant decrease of energy demand is observed in Western and Northern Europe, while Mediterranean and Eastern European countries show a comparatively lower degree of change, and in general the total energy demand increases in South-Eastern Europe as a consequence of climate change (Zachariadis, 2010; Zachariadis and Hadjinicolaou, 2014; van Ruijven et al., 2019; Larse et al., 2020). A seasonal split shows for 31 European countries that

every 1 °C temperature drop in winter causes a rise in electricity demand by 8 kWh/yr/capita via the change in heating degree day, while it amounts to 2 kWh/yr/capita for every 1 °C temperature rise in summer (Eskeland and Mideksa, 2009).

To estimate the impacts of future climate change on energy demand, both at global and regional scales, most climate change studies in the literature use two variables: the heating degree-days (HDD) (Thom, 1954; Quayle and Diaz, 1980), and the cooling degree-days (CDD) (Thom, 1959). HDD and CDD are calculated on the basis of the cumulative daily deviations of temperature below a heating setpoint in winter and above a cooling setpoint in summer respectively. Even though the use of those variables is associated with some limitations (Mc Intyre et al., 1987; Day and Karayiannis, 1999; Krese et al., 2011; Azevedo et al., 2015), it has been widely used in climate impact studies in Europe and other regions around the world (Büyükalaca et al., 2001; Matzarakis and Balafoutis, 2004; Rosa et al., 2015; Spinoni et al., 2015; Spinoni et al., 2018; Jankovic et al., 2019). All studies project a significant decrease of HDD (e.g. between 13% and 87% decrease in Switzerland, 27% decrease Belgium) and an accelerating positive trends for CDD (e.g. factor 2.4 in Belgium) at the end of the century (Jankovic et al., 2019; Christenson et al., 2006; Ramon et al., 2020). Isaac and van Vuuren (2009) find an increase of CDD for all regions over the world and a decrease of HDD by the end of the 21st century suggesting a global cooling energy demand increasing rapidly over the whole 21st century and a global heating energy demand increasing by 0.8% per year until 2030, and decreasing slowly after.

Most of the previously cited studies focus on the quantification of the average increase or decrease of energy demand related to heating and cooling needs under future climate changes over Europe. These studies are very informative for the sizing of future generation fleet park. However, none of them evaluates the impact of climate change on the temporal variability of the electricity demand such as the frequency and the duration of periods of heating and cooling. Indeed, an important challenge for the energy sector is the flexibility. This issue has been largely discussed with respect to the massive integration of renewable energies in the system (Impram et al., 2020; Meegahapola and Flynn, 2010; Londero et al., 2015; Eftekharijad et al., 2013). However, if the demand becomes more variable, this will add more constraints to the system. Today the electrical systems need flexibility for balancing consumption and production and for managing flows on the grid. The flexibility in traditional electric power systems is still limited which can represent a significant challenge in the future if the energy demand becomes more variable (Denholm and Margolis, 2007; Cruz et al., 2018),

This work produces and exploits ten bias-corrected and downscaled

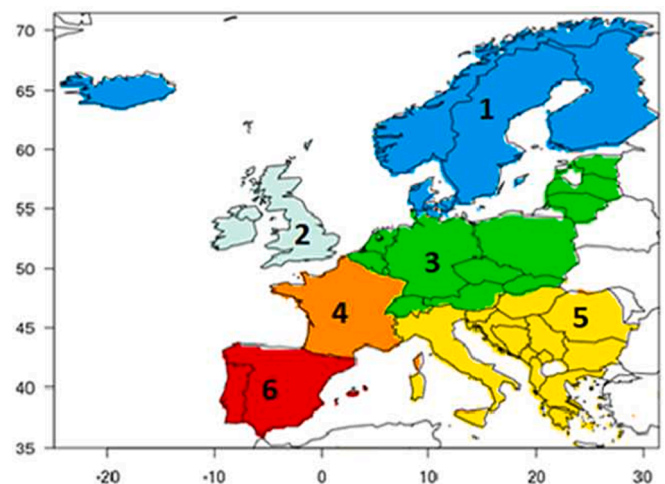


Fig. 1. Domain of interest with the 6 European sub-regions used for aggregated diagnostics in the discussion in Section 4.

simulations from the CMIP6 multi-model ensemble at a spatial resolution of $25 \times 25 \text{ km}^2$ over Europe (Fig. 1) to compute heating degree days (HDD) and cooling degree days (CDD) under four anthropogenic scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5). The spatial distribution of change in HDD and CDD in the future over Europe is analyzed and the temporal fragmentation of energy demand related to heating and cooling quantified in terms of duration and frequency.

The novelty of this work is the quantification and analysis of the evolution of HDD and CDD periods in terms of duration and frequency. Previous studies analyzed the impact of global warming on energy demand using the two indicators HDD and CDD and focused solely on the evolution of HDD and CDD intensity in the future (Büyükalaca et al., 2001; Matzarakis and Balafoutis, 2004; Rosa et al., 2015; Spinoni et al., 2015; Spinoni et al., 2018; Jankovic et al., 2019). In this study, we assess the temporal variability of these indicators under climate change in Europe, focusing on the change in duration and frequency of heating and cooling periods.

The paper is structured as follows. Section 2 describes the data, the bias-correction and downscaling technique and the method for computing HDD and CDD. Section 3 describes the spatial patterns of change in HDD and CDD and characterizes the heating and cooling periods in terms of duration and frequency. Section 4 discusses the results and their implications on the energy power system. Section 5 concludes the study.

2. Data and methods

2.1. Data

The atmospheric reanalysis of the fifth generation of the European Center for Medium Range Forecasting (ECMWF) ERA5 is used as a reference data set and as a proxy of observations covering the entire globe over the period 1950 to present. ERA5 data contains a large number of land, oceanic and atmospheric variables. The data covers the globe on a horizontal grid of $31 \text{ km} \times 31 \text{ km}$ and a vertical grid of 137 levels from the surface to a height of 80 km. For this study, we use ERA5 data retrieved from the Climate Data Store on a $25 \text{ km} \times 25 \text{ km}$ grid (Hersbach et al., 2020). The ERA5 reanalysis is used to assess the historical performances of CMIP6 models and to downscale and bias-correct the ten selected CMIP6 climate models. The ERA5 and CMIP6 data used in this study cover the entire European domain shown on the map 1 with the 5 regions.

The climate data are retrieved from the coupled model inter-comparison project phase 6 (CMIP6) database. It consists in climate simulations from more than 100 distinct climate models being produced across 49 different modeling groups (Meehl et al., 2000). CMIP6 models are running new and updated emission pathways that explore a large range of possible future outcomes. It represents a substantial improvement over CMIP5, in terms of the number of participating modeling groups, the number of future scenarios examined, and the number of different experiments performed (Meehl et al., 2000; Ségur, 2021). Specifically, a set of shared socio-economic pathways SSP (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP4-6.0, SSP3-7.0 and SSP5-8.5) provide a range of distinct climate change outcomes at the end of the century (Séгур, 2021). These updated scenarios describe in a standardized way the socio-economic characteristics influencing greenhouse gas emissions (and therefore radiative forcing), illustrating the societal trajectories linked to different levels of warming.

Four different scenarios are selected in this study: one scenario with low GHG emissions (SSP1-2.6), one scenario with intermediate GHG emissions (SSP2-4.5), and two scenarios with high and very high GHG emissions (SSP3-7.0 and SSP5-8.5). We consider for the historical simulation the 30-year period 1985–2014 with central year 2000, and for the future projections, three 30-year periods, 2015–2044 with central year 2030, 2035–2064 with central year 2050, and 2071–2100 with central year 2085.

We also implement a model selection process to choose only a subset of 10 models from the available CMIP6 database. To select a subset of CMIP6 models we first keep models with at least available daily average, maximum, and minimum near-surface temperatures for the historical simulation (1985–2014) and all four emissions scenarios (2015–2100). Applying these criteria keeps 30 models in the subset. The daily temperatures are regridded from each model's native spatial resolution to the $25 \times 25 \text{ km}^2$ ERA5 grid over Europe. To regrid the daily temperatures, bilinear interpolation is selected after comparing four methods of interpolation (bilinear, cubic, conservative, and Nearest-neighbor interpolation). The bilinear method showed to be the most suitable when comparing the root mean square error (RMSE) of temperature between the original data and the interpolated data. For the model selection process, we only consider the 2071–2100 projection period with central year 2085 and the SSP5-8.5 scenario only.

Several criteria are used in the literature to select a subset of models for regional analysis. For instance, the range of future warming or projected climate changes (McSweeney and Jones, 2016; Immerzeel et al., 2013). Other approaches consist in weighting models by performance and independence (Brunner et al., 2020). In our study, the model selection is based on two main criteria. The first criterion consists in choosing a set of models that represent a whole range of possible climate change in the future. The second criterion considers the historical performance of the models over Europe (region of interest). In order to keep a large range of climate change in the future in the selected subset, we apply an ascending hierarchical classification to group similar models based on temperature change between the projection and historical periods. Two seasons (summer and winter) are considered and the classification is performed over the whole domain. As the objective is arbitrarily to keep a maximum of 10 models in the final subset, for computing resource issues, the number of classes is set to 10, with one model only kept in each class. Finally, comparing the performances of the historical simulations from models belonging to the same class allows to exclude the models that are considered very unrealistic compared to the reference and keep only the most performing model in each class. The evaluation of the historical performances of models is performed using 4 skill scores based on the daily temperature:

- the absolute bias of the simulations from the CMIP6 models with respect to the reference data (ERA5)
- the spatial correlation between the simulations from the CMIP6 models and the reference data (ERA5)
- the root mean square error (RMSE) of the mean annual cycle of the simulations from the CMIP6 models compared to the reference data
- the spatial variability of the simulations from CMIP6 models compared to the reference data (ERA).

The subset of climate models resulting from the selection process is shown in Table 1.

2.2. Bias adjustment and downscaling technique

Generally, global circulation models (GCMs) provide realistic representations of large-scale climate processes. However, they do not describe properly the local and regional scales because of their coarse spatial resolution. Consequently, the outputs of these models cannot be used directly in impact studies that are necessarily focusing on smaller spatial scales. There are two main approaches for deriving information from the global climate models to local or regional scales; the first approach is the numerical or dynamical downscaling involving regional climate models and the second is the statistical downscaling employing statistical relationships between the large-scale and local climate fields. Different techniques of statistical downscaling are proposed in the literature such as quantile mapping technique (Q-mapping) (Cannon, 2018), analogs (Pierce et al., 2014). For this study, the CDF-t method (Cumulative Distribution Function transform) (Michelangeli et al.,

Table 1
The 10 selected CMIP6 models.

Climate Center	Model	Spatial Resolution	Climate Sensitivity	Main References
CCCma	CanESM5	2.8125° × 2.8125°	5.6°C	(Swart et al., 2019)
CMCC	CMCC-ESM2	0.9° × 1.25°	3.5°C	(Cherchi et al., 2019)
CNRM-CERFACS	CNRM-ESM2-1	1° or 140 km	4.3°C	(Séférian et al., 2019)
CSIRO	ACCESS-ESM1-5	1.875° × 1.24°	3.9°C	(Ziehn et al., 2020)
EC-Earth-Consortium	EC-Earth3-Veg	0.703° × 0.703°	4.3°C	(Döscher et al., 2021)
	INM-CM4-8	2.0° × 1.5°	1.8°C	(Volodin et al., 2018)
MOHC	UKESM1-0-LL	1.875° × 1.25°	5.4°C	(Sellar et al., 2019)
MPI-M	MPI-ESM1-2-LR	1.875° × 1.875°	3.0°C	(Mauritsen et al., 2019)
NCC	NorESM2-MM	1.25° × 0.9375°	2.5°C	(Seland et al., 2020)
IPSL	IPSL-CM6A-LR	2.5° × 1.25°	4.6°C	(Boucher et al., 2020)

2009) is applied. This method can be perceived as an extension of Q-mapping, directly dealing with and providing CDFs. It is a statistical method developed by (Michelangeli et al., 2009) to generate distribution functions for a local climate variable in future climate from distribution functions for the same variable observed or pseudo-observed in the reference climate (e.g ERA5 data) and estimated by climate simulations for the historical and future periods. This is an improvement on the Q-mapping method presented previously, by taking into account changes in the distribution function, on the simulation side, between the present and future climates. Also it is easy to set up and very performing to correct and downscale the temperature data (Flounas et al., 2013; Michelangeli et al., 2009).

The performance of the method is assessed before its use in this work. First, data are corrected based on a calibration period of 30 years, with ERA5 and we validate the method over another period of 30 years. CDFt corrects well the mean state of temperature variables and preserves their historical and future trend. This method is thus applied to downscale and correct the bias of the selected CMIP6 models over Europe, after bilinear interpolation to the ERA5 grid (25 × 25 km²). The CDF-t method is applied to daily average, maximum and minimum temperatures at each grid point over the entire European domain. The 30-year historical period (1985–2014) is used as calibration period and the CDF-t correction then applied to the three 30-year future periods (2015–2044, 2035–2064, 2071–2100). The method is applied month by month for each model and for the 4 future scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5).

2.3. Calculation of heating and cooling degree-days

To estimate the impacts of future climate change on energy demand, we use two indicators: heating degree-days (HDD) (Thom, 1954; Quayle and Diaz, 1980) and cooling degree-days (CDD) (Thom, 1959; Rosa et al., 2015). HDD is computed for winter months and CDD for the summer months. In general, these two indicators are calculated on the basis of the cumulative daily deviations below (for HDD) or above (for CDD) a given setpoint temperature. The choice of these thresholds depends on the local climate and the applications, whether for electricity production, energy balances, or others.

For such a large area as Europe, it is difficult to choose a unique and suitable threshold for all European countries as it is also difficult to calculate thresholds adapted for each country among the 28 countries studied. So, we have chosen two thresholds that are widely used in the literature in this context; 15.5 °C for the heating setpoint $T_{b,h}$ and 22 °C

for the cooling setpoint $T_{b,c}$. Larse et al. (2020) used the same thresholds to assess climate change impacts on future heating and cooling demands over Europe. The same thresholds were also used by Spinoni et al. (2015, 2018) to evaluate changes in heating and cooling degree days in Europe in the past and in the future. The same approach using the same thresholds was also adopted by the UK MET-Office (CIBSE, 2006). On the other hand, using those thresholds allows us to compare our results with the previous studies in terms of heating and cooling demand. The CDD and the HDD are computed at each grid point over the European domain using the method developed by the UK Met Office (CIBSE, 2006) and also used by Spinoni et al. (2015).

The Eqs. (1)–(4) represent respectively the method to compute HDD and CDD. HDD is calculated for the winter period (from October 1st to March 31st - 182 days in non-leap years) and CDD for the summer period (April 1st to September 30th - 183 days). HDD and CDD are calculated for each grid point i and for each time step t (daily sampling). The daily HDD at time t of the winter period and at grid point i ($HDD_{i,t}$) is thus given by:

$$HDD_{i,t} = \begin{cases} \frac{T_{b,h} - T_{i,t}}{2} - \frac{T_{max,i,t} - T_{b,h}}{4} & \text{if } \begin{cases} T_{b,h} \geq T_{max,i,t} \\ T_{i,t} \leq T_{b,h} < T_{max,i,t} \\ T_{min,i,t} \leq T_{b,h} < T_{i,t} \\ T_{b,h} \leq T_{min,i,t} \end{cases} \\ \frac{T_{b,h} - T_{min,i,t}}{4} & \\ 0 & \end{cases} \quad (1)$$

where $T_{i,t}$ is the daily mean temperature at day t of the winter period at grid point i . The quantities $T_{min,i,t}$ and $T_{max,i,t}$ are the daily temperature minimum and maximum, respectively and $T_{b,h}$ is the heating setpoint. The yearly HDD ($HDD_{y,i}$) is then given by summing the daily HDD ($HDD_{i,t}$) over the winter period.

$$HDD_{y,i} = \sum_{t=1}^{182} HDD_{i,t} \quad (2)$$

Similarly, the daily CDD at time t of the summer period and at grid point i ($CDD_{i,t}$) is given by:

$$CDD_{i,t} = \begin{cases} 0 & \\ \frac{T_{max,i,t} - T_{b,c}}{4} & \text{if } \begin{cases} T_{b,c} \geq T_{max,i,t} \\ T_{i,t} \leq T_{b,c} < T_{max,i,t} \\ T_{min,i,t} \leq T_{b,c} < T_{i,t} \\ T_{b,c} \leq T_{min,i,t} \end{cases} \\ \frac{T_{max,i,t} - T_{b,c}}{2} - \frac{T_{b,c} - T_{min,i,t}}{4} & \\ T_{i,t} - T_{b,c} & \end{cases} \quad (3)$$

where $T_{b,c}$ is the cooling setpoint. The yearly CDD ($CDD_{y,i}$) is then given by summing the daily CDD ($CDD_{i,t}$) over the summer period.

$$CDD_{y,i} = \sum_{t=1}^{183} CDD_{i,t} \quad (4)$$

As energy demand is much less temperature-sensitive for the tertiary and industrial sector than for the residential sector, the changes in HDD and CDD due to global warming are mainly attributable to the residential sector.

3. Results

3.1. Changes in heating and cooling degree-days

The spatial patterns of future changes in cooling and heating degree-days over Europe are displayed in Figs. 2 and 3, respectively. The mean changes on HDD and CDD are quantified for three-time horizons: the near future (2015–2044), the mid-term future (2044–2064), and the end of the century (2071–2100) compared to the recent past (1985–2014), and under four scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-5.0. Results are shown only for two scenarios SSP1-2.6 and SSP3-7.0 for

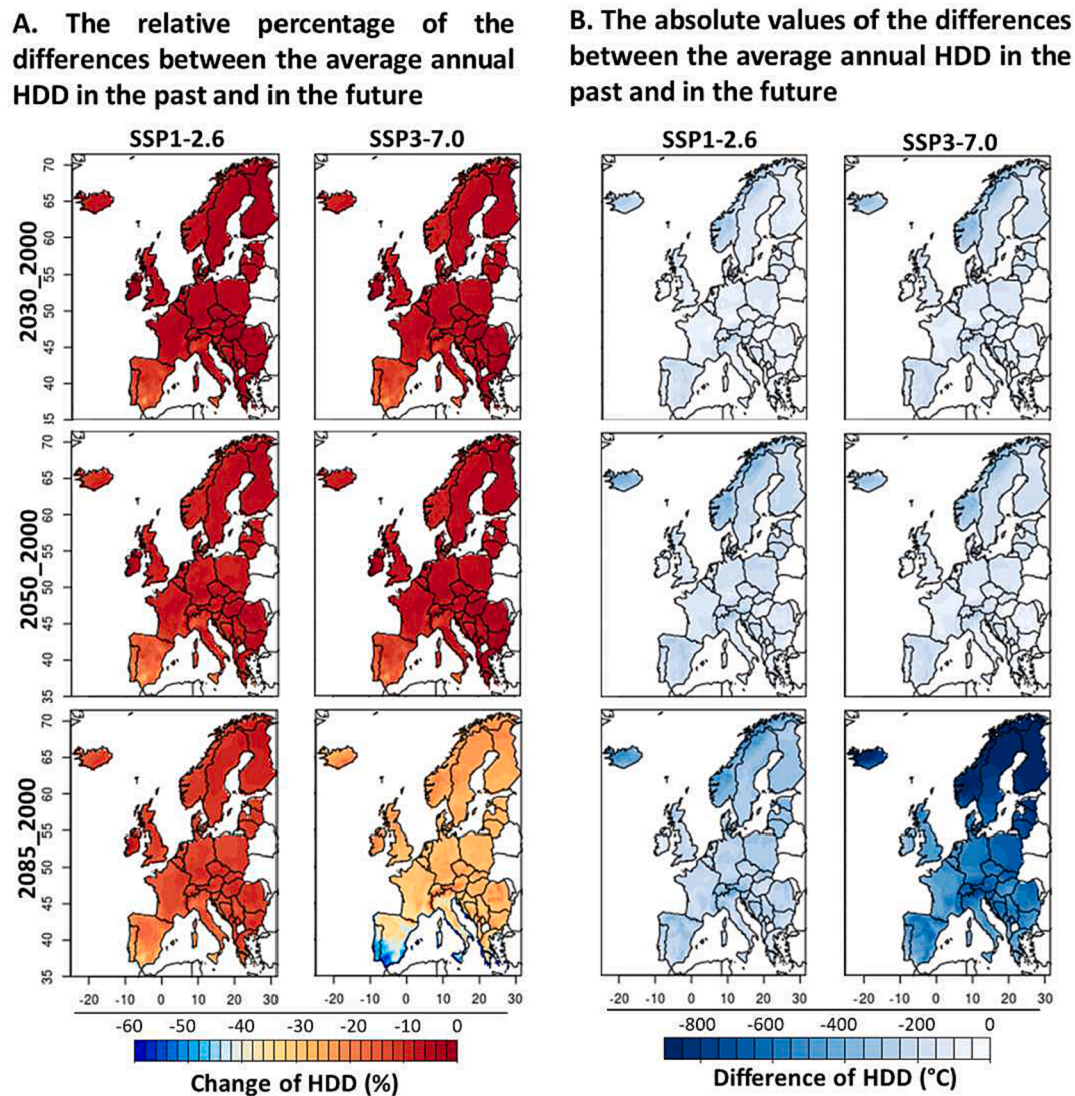


Fig. 2. (A) Relative and (B) the absolute differences in annual average of HDD between the recent past (1985–2014) (central year 2000) and respectively near future (2015–2044) (central year 2030) (upper row), mid-term future (2035–2064) (central year 2050) (middle row) and far future (2071–2100) (central year 2085) (lower row) under SSP1.2.6 (left column) and SSP3.7.0 (right column). The values represent the median of changes of the 10 selected CMIP6 models.

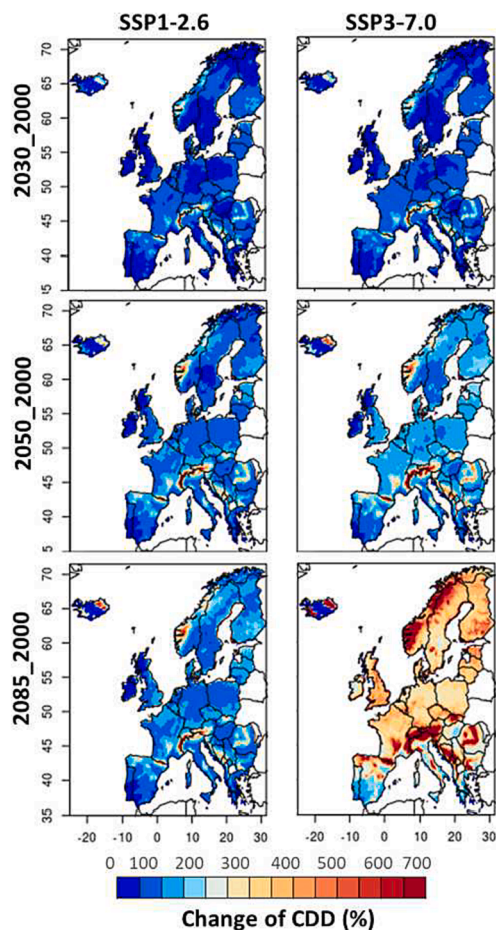
two main reasons: First, there are similar changes between SSP1-2.6 and SSP2-4.5, therefore, the sustainable scenario SSP1-2.6 is only shown. The second one is because the SSP5-8.5 scenario is considered to be implausible to unfold (Hausfather and Peters, 2020). The relative differences in HDD and CDD are shown in Figs. 2A and 3A in percentage computed as the mean difference of each model between the future and the past relative to the mean of the ten selected CMIP6 models. The absolute differences (in °C) in HDD and CDD are shown in Figs. 2B, 3B. The 10th and the 90th percentiles of the differences in HDD and CDD of this model ensemble have also been compared to evaluate the extreme changes, the results are presented in the Supplementary information (Figs. S1 and S2).

Fig. 2A shows that overall, the largest decrease in HDD for the three future time horizons relative to the recent past is observed in Southern Europe, especially over Spain and Portugal. However, in terms of absolute changes, the largest decrease is seen in Northern Europe. As expected, the decrease in HDD is stronger at the end of the century and for the most emissive climate scenarios. The decrease in HDD ranges from –35 to –60% over Southern Europe, and from –25 to –35% over Northern Europe under the scenario SSP3-7.0 and from –10 to –30% under the SSP-1.2.6 over the whole Europe for the 2085 time horizon.

For the 2050 horizon, the decrease of HDD ranges from –5 to –25% under the two scenarios all over Europe. The near future represents the smallest decrease of HDD, from –5 to –20% in both scenarios SSP1-2.6 and SSP3-7.0. Regarding the absolute differences (Fig. 2B), the largest decrease in HDD is observed over Northeastern Europe with more than –1000 °C under SSP3-7.0 and between –400 and –600 °C under SSP1-2.6. The smallest decrease in absolute value is found over Southern Europe, where the decrease in HDD is about –300 °C under SSP3-7.0. These results are consistent with Spinoni et al. (2018) using CMIP5 simulations. Spinoni et al. (2018) find a continuous decrease in HDD until the end of the 21st century under scenarios RCP8.5 (most emissive) and RCP2.6 (least emissive) with more than –800 °C for most countries, and of more than –1100 °C for Northeastern Europe. These results are similar to the values found in our study under the scenario SSP3-7.0.

Fig. 3A shows a continuous increase in CDD. The relative increase in CDD by 2085 horizon is very large over Northern Europe and over high lands compared to the recent past, reaching in some places nearly 700% under the scenario SSP3-7.0. This is mainly explained by the very low values of CDD in the past over those regions. Overall, the CDD are projected to double by 2050 horizon over Europe compared to the recent past. The increase of CDD ranges from 100% to 200% under the two

A. The relative percentage of the differences between the average annual CDD in the past and in the future



B. The absolute values of the differences between the average annual CDD in the past and in the future

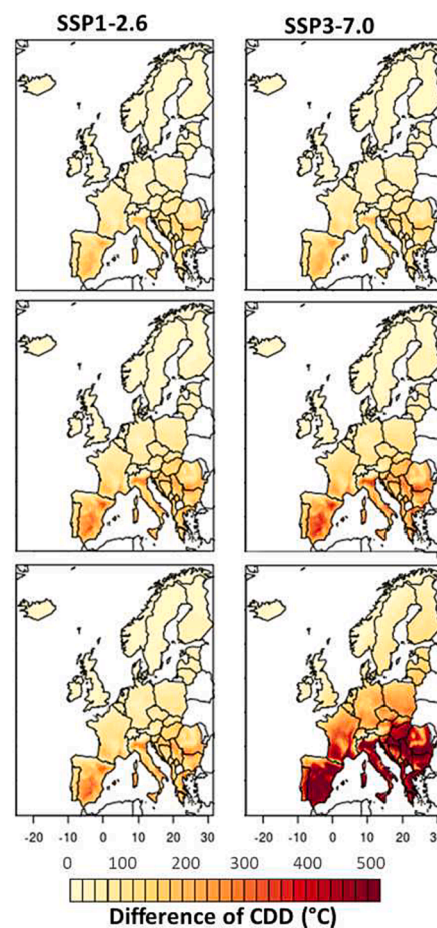


Fig. 3. (A) Relative and (B) the absolute differences in annual average of CDD between the recent past (1985–2014) (central year 2000) and respectively near future (2015–2044) (central year 2030) (upper row), mid-term future (2035–2064) (central year 2050) (middle row) and far future (2071–2100) (central year 2085) (lower row) under SSP1.2.6 (left column) and SSP3.7.0 (right column). The values represent the median of changes of the 10 selected CMIP6 models.

scenarios SSP1-2.6 and SSP3-7.0 over Europe. At the end of the century, the CDD are projected to increase by more than 300% on average over most of European countries under the SSP3-7.0 scenario. Regarding the absolute differences (Fig. 3B), the largest increase in CDD is observed over Southern Europe with more than 500 °C under SSP3-7.0 and between 200 and 300 °C under SSP1-2.6. The smallest increase in absolute value is found over Northern Europe, where the increase in CDD is less than 100 °C. These results are consistent with Spinoni et al. (2018) using CMIP5 simulations. Spinoni et al. (2018) found an increase in CDD in the future and especially at the end of the 21st century where this increase can be extreme under scenarios RCP8.5 (most emissive) and reach more than 600 °C over southern Europe. The absolute CDDs/HDDs values are presented in Supplementary material (Figs. S5 and S6).

3.2. Changes in periods of heating and cooling

To go one step further than the assessment of the average change of heating and cooling needs (via HDD and CDD proxies), which confirms previous published work based on older CMIP, the change in duration and frequency of heating and cooling periods are also quantified. Heating (respectively cooling) periods are defined here as the number of successive days where the temperature is below (respectively above) the heating (respectively cooling) setpoint, assuming that people turn on

their heating (respectively cooling) device. In practice, those periods are calculated as the number of successive days where the value of HDD or CDD exceeds 1 °C, with a minimum of two successive days. We choose 1 °C to distinguish unambiguously between periods of heating/air conditioning use and periods of disruption when HDD/CDD values are almost zero. Taking into account the inertia of buildings, the decrease in temperature and a positive HDD during a single day is not necessarily sufficient to switch on the heating, hence the choice of a period with at least two successive days with an HDD higher than 1 °C to define a heating or cooling period was made.

Fig. 4 illustrates the evolution of the average duration (panel A) and frequency (panel B) of periods of heating per year. Over the historical period (1985–2014), winter is in general characterized by one to two very long heating periods (panel A) except in Southern Europe where 2 to 6 shorter periods (between 20 days and 80 days) already suggests the impact of a warmer climate. Indeed, in the future and over Central and Southern Europe, the heating periods shorten, interspersed with warmer periods where the temperature exceeds the heating setpoint. In central Europe and the United Kingdom, the number of heating periods under SSP1-2.6 change from 1 in the past to 2 or 3 periods in the future with a duration of 50 days. Under SSP3-7.0, it increases up to 3 to 6 periods lasting between 20 to 40 days for the 2085 time horizon. In Southern Europe, the number of heating periods of heating could reach 15, lasting

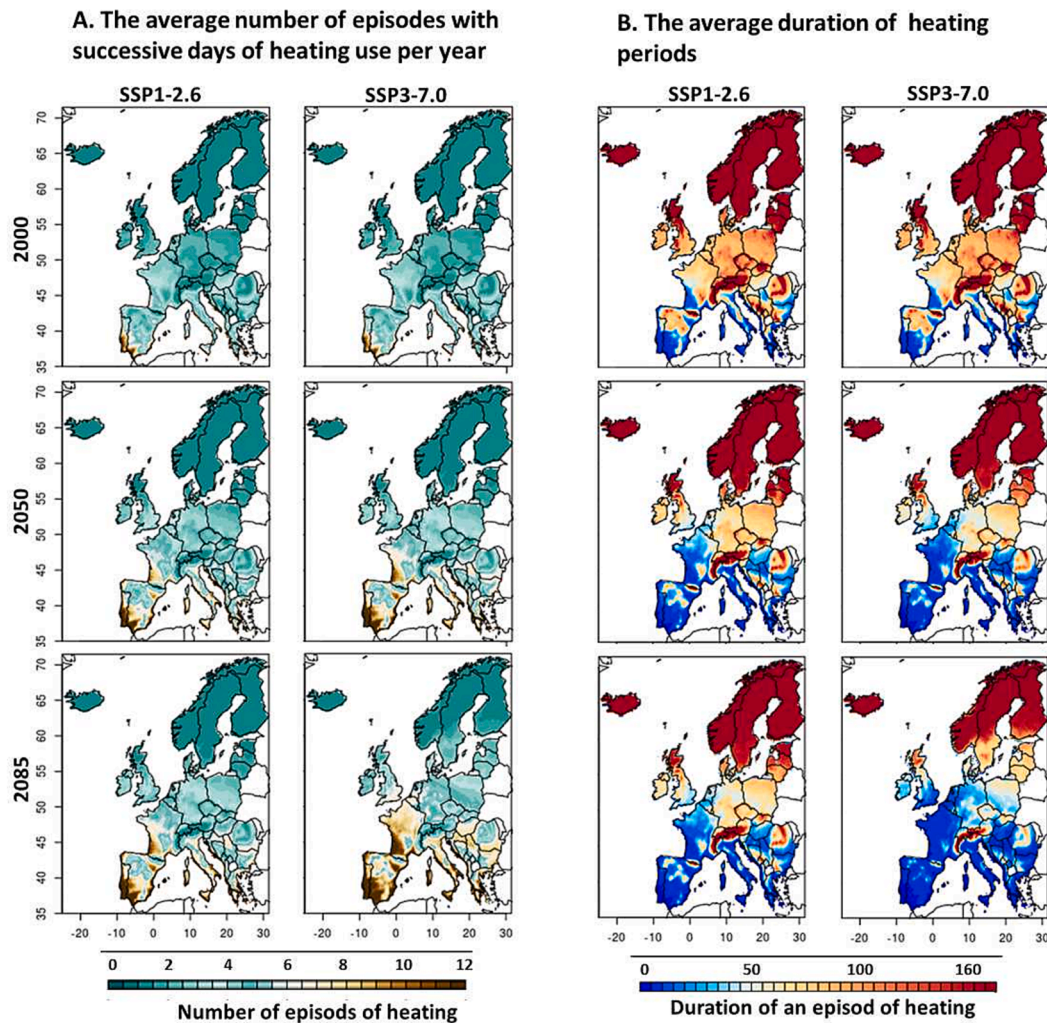


Fig. 4. (A) Number of heating periods per year and (B) average duration (over the 10 CMIP6 models) in the historical period 1985–2014 (central year 2020) (upper row) and 2 time horizons: 2035–2064 (central year 2050) (middle row) and (2071–2100) (central year 2085) (lower row) and under the two scenarios SSP2-1.6 (left column) and SSP3-7.0 (right column).

less than 10 days under SSP3-7.0 for the 2085 time horizon.

Fig. 5 is similar to Fig. 4 but for the cooling periods. The frequency as well as the duration of cooling periods are projected to increase all over Europe. In Southern Europe, cooling periods that do not exceed a maximum of 5 days in the historical period, are expected to last 4 to 7 days under SSP2-1.6 and SSP3-7.0, respectively. In Central Europe, the frequency of cooling periods should nearly double, from 7 to 10 periods over the recent past to more than 14 periods in the future and under both scenarios. In the Scandinavian region, the number of cooling periods are projected to increase from almost zero up to 6 periods for SSP1-2.6 scenario and up to 10 periods for SSP3-7.0 scenario. The results for the two other scenarios SSP2-4.5 and SSP5-8.5 concerning the evolution of the frequency and duration of periods of heating/Cooling use are presented in [Supplementary material \(Figs. S7 and S8\)](#).

4. Discussion

Climate change clearly impacts the cooling and heating needs in Europe, using HDD and CDD as a proxies. Our results are consistent with previous studies ([Spinoni et al., 2018](#); [Rosa et al., 2015](#); [Spinoni et al., 2015](#)) and represent an update with the most recent climate simulations from CMIP6. It also quantifies for the first time, the impact of climate change on the temporal variability of energy demand related to heating and cooling needs. The results show, on one hand, an increase of the

fragmentation of the periods of heating during winter with a decrease in their duration, and on the other an increase in both number and duration of cooling periods during summer. As the share of heating in the total demand of the residential sector in EU is about 62%, the fragmentation of the heating demand may have a strong impact on the future electric power system, especially for countries where the rate of electric heating is very important. For countries where the use of gas for heating is fairly substantial compared to electric heating, the variability of gas demand linked to the temporal fragmentation of heating use periods may not have an important impact, as gas can be stored to meet heating needs, unlike electricity, which requires a certain flexibility to ensure supply-demand balance.

An overview of the flexibility and maneuverability of the power system in Europe and the related costs sheds light on how changes in heating and cooling needs challenge the resilience of the electrical power system. The flexibility is generally used to show the ability of power generation systems to follow the load curve and respond to intraday consumption peaks. However, in this study we are mainly talking about a variability of demand over several days as a consequence of the fragmentation of the heating period, which is hereafter referred as the maneuverability of the production systems.

The massive penetration of renewable energy resources as set by European energy policies ([Strbac et al., 2021](#)), increases the needs of flexibility of the power system because of their inherent intermittency

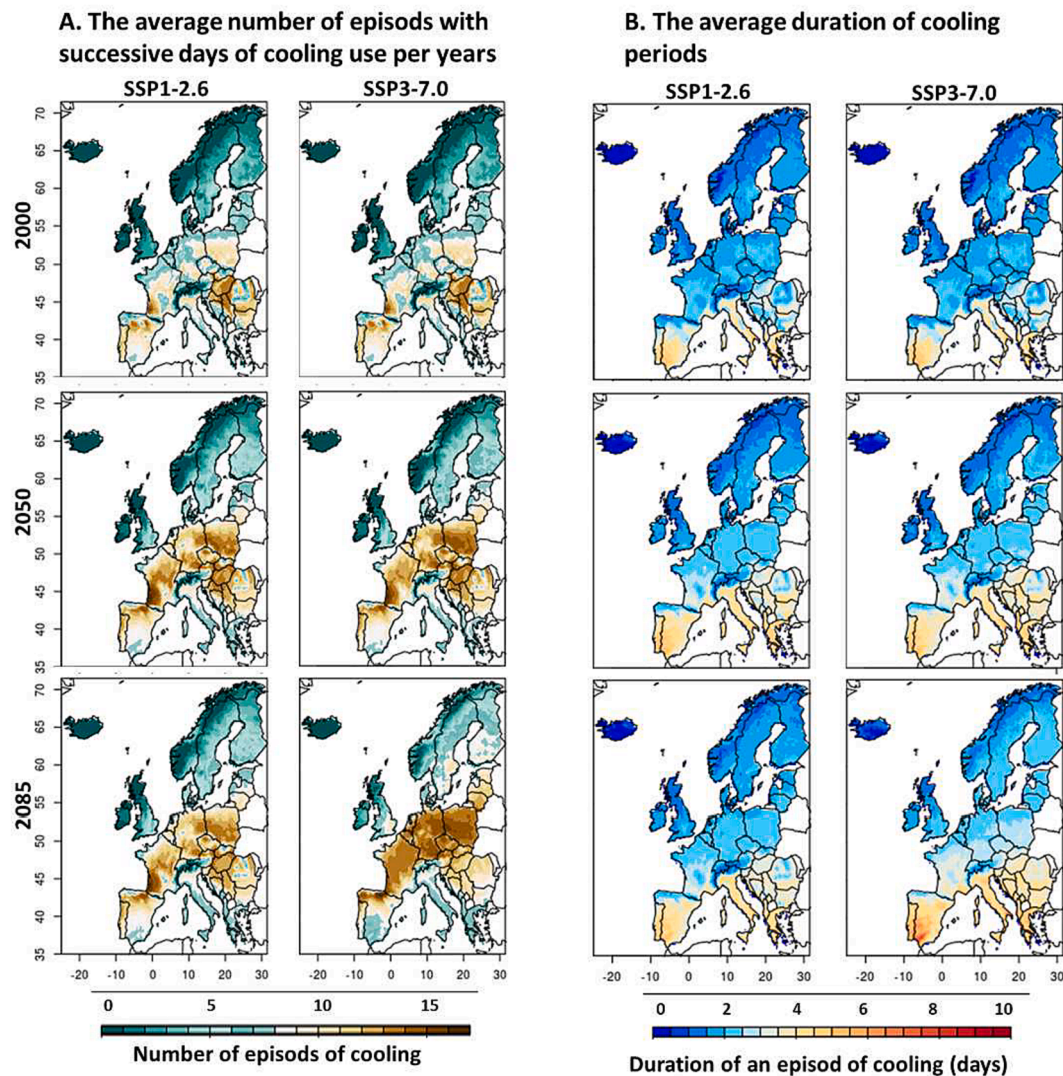


Fig. 5. (A) Number of cooling periods per year and (B) average duration (over the 10 CMIP6 models) in the historical period 1985–2014 (central year 2020) (upper row) and 2 time horizons: 2035–2064 (central year 2050) (middle row) and (2071–2100) (central year 2085) (lower row) and under the two scenarios SSP2-1.6 (left column) and SSP3-7.0 (right column).

(Impram et al., 2020) and represents a real challenge for the stability of the electric power system (Meegahapola and Flynn, 2010) due to frequent start-up of power plants. Many studies (Meegahapola and Flynn, 2010; Londero et al., 2015; Eftekharijad et al., 2013; Liu et al., 2010; Abdrahem et al., 2013) showed that wind and solar energies have a strong influence on voltage stability. The electric grid topology also impacts transmission losses and system performance against outages which affects the stability of the power system when the levels of penetration of renewable energies are very high. Therefore, even during high production periods of wind and/or solar energy, the variability and the manoeuvrability of the electric power system is limited. In the future, a more variable demand driven by the fragmentation of heating needs will potentially require an adaptation of electric power production management. For instance, in France, an increase of air temperature by 1 °C in winter decreases the electric demand by about 2,4 GW (RTE, 2020).

To evaluate the manoeuvrability of dispatchable power units, two criteria are taken into account: the starting time and the maximum power ramp (Table 2). Nuclear power plants have broadly the same manoeuvrability capacities as coal-fired power plants except the cold start duration. Although the potential of nuclear reactors is very important by their nominal power, the time required to connect the

Table 2

The flexibility and maneuverability capacities of dispatchable power plants from Cany (2017, 2021).

	Cold Starting time	Warm Startin/g time	%Pn/min max
Hydraulic	one to a few minutes	one to a few minutes	-
Diesel	15 min	5 min	25
Combined cycle gas	3 h	30 to 60 min	7
Gas combustion turbine	10 to 20 min	10 to 20 min	20
Coal	6 h	2 h	5
Nuclear	1 to 2 days	2 h	5

nuclear power plants to the electricity network after a shutdown is higher than the other types of power plants (Table 2); if a nuclear power plants takes several hours to ramp up to maximum power, a CCG takes only few minutes (Mazauric, 2021). Table 2 shows that the most flexible and modular types of electrical production in an European power systems are fossil fuels (diesel, fuel gas, etc.). However, these types of productions are carbon intensive. For hydropower, which is widely used in Europe, it can respond to grid disturbances because of its high

flexibility. During the peak consumption, it can represent an efficient energy source due to the rapid response (Table 2) (Mazauric, 2021). However, in terms of maneuverability, for hydropower as well as the other types of renewable energy, it is not possible to lower the energy produced to a given threshold. So it is either used at full power or it is shut down to respond to the variability of the demand. Also, the hydroelectric potential in Europe is already largely exploited and will be potentially impacted by climate change in the future (van Vliet et al., 2013), so it may not be enough as an efficient solution in case of an important variability of electric demand in Europe during winter.

Dispatchable energy sources are needed to bring flexibility and maneuverability in the electric power system. Regarding the nuclear power production, the maneuverability of this type of production represents many challenges. The nuclear power plants are considered as the most complex power plants (Kerker and Paulin, 2021). In general, operating a nuclear reactor requires strict compliance with safety rules. Those rules, specific to the physical properties integrated into a reactor, as well as the rules for authorization of radioactive discharges, limit the maneuverability of nuclear reactors. The nuclear power plants are designed for a number of maximum allowable power variations during the life of the reactor, a maximum power ramp, a minimum operating power, a minimum and maximum duration of operation at intermediate power, a number of stops and starts defined, associated with required duration (Cany, 2017). In certain European countries such as France and Germany, it is possible to modulate nuclear power to follow the load curve, however nuclear power plants require careful operation and maintenance because operation at partial load causes unplanned shut-downs (Cometto and Keppler, 2012).

Fig. 6 and Table 3 show that periods of non-use of heating could last more than 3 successive days in the future in several regions in Europe (see Fig. 1), and these periods could become very frequent in the future. With regard to nuclear power and renewable energy, the fragmentation of demand can represent a real challenge for these types of production especially if the decrease of demand is very significant and exceeds the margin of maneuverability and modulation of the electric production units. After more than 3 days of continuous energy demand decline due to the non-use of heating device, the production units may reduce their production to balance the demand and the electricity production, and if the decrease of electric demand reaches a critical low, it may be necessary to shut down some power plants with consequent constraints related to starting time after the shut-downs (Table 2). Thus the fragmentation of heating demand may potentially impact the management of productions units in the future, as the decrease of heating demand may exceed the margin of maneuverability of the production system.

Regarding the economic costs related to the maneuverability of the electric power system, the start-up and shutdown of power plants can be very costly (Xu et al., 2017) (see Table 4) (Xu et al., 2017). If we exclude

hydropower which is key for intra-day flexibility but not for maneuverability, the shut-down and start-up costs are typically few hundreds of US dollars per MW. A multiplication of shut-down and start-up operations of dispatchable power plants may bring additional system costs that should be taken into account for the future electric power system.

Finally, it is also important to point out one of the limitations of this study, which is considering common setpoints for all European countries to calculate HDD or CDD. A setpoint adapted to the economic, demographic and climatic context of each country would be more relevant than the two thresholds chosen. These thresholds (15.5° for heating and 22° for cooling) have been chosen in agreement with the literature (Spinoni et al., 2015; Spinoni et al., 2018; Larse et al., 2020). Nevertheless, we have analyzed the sensitivity of our results to other extreme thresholds. For that purpose, we calculated HDD considering two extreme thresholds 11.5° and 17.6°, and for CDD we considered 18° and 26°. To choose the two extremes thresholds for HDD, we took the minimum and maximum thresholds calculated by Kozarcin et al. (2019). The analysis of the evolution of heating and cooling periods shows that heating periods become more fragmented for a lower threshold, and this fragmentation can be seen also in the Nordic countries, whereas for a higher setpoint, the fragmentation of heating periods is not seen in northern Europe, but is seen in all other regions of Europe. In summer, if we consider a very low setpoint, periods of air-conditioning use become more frequent and longer than if we consider a relatively high setpoint.

5. Conclusion

We analyzed, in this study, the impact of global warming on the power system using two indicators heating degree days (HDD) and cooling degree days (CDD) and based on a subset of ten bias-corrected and downscaled climate simulations from the CMIP6 multi-model ensemble. The novelty of this work is the quantification and analysis of the temporal fragmentation of HDD and CDD in terms of duration and frequency under different scenarios SSP (the sustainable scenario SSP1-2.6, the intermediate one SSP2-4.5 and the two highest scenarios SSP3-7.0 and SSP5-8.5).

Here, we show that in winter, heating needs can be more fragmented, with potential heating periods shorter and more frequent in different regions in Europe leading to a potential fragmentation of energy demand. Conversely, in summer, cooling periods become more frequent and longer.

The fragmentation of temperature-sensitive energy needs for heating are expected to have an operational and economical impact on the balancing of the energy system. With the massive penetration of renewable energy resources as set by European energy policies, the future energy system is less controllable. Then the duration of the more

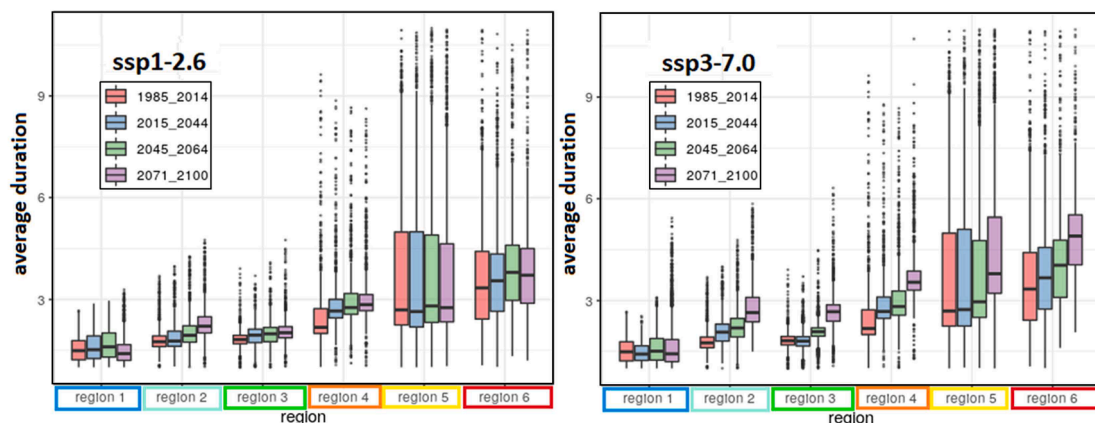


Fig. 6. The distribution of the average duration of periods of non-use of heating in the 6 regions of Europe shown in Fig. 1.

Table 3

Summary tables of the number and average duration of periods of non-use of heating in each of the 6 regions of Europe shown in Fig. 1.

Regions	Duration of periods of non use of heating					Number of periods of non use of heating				
	Historical	ssp1-2.6		ssp3-7.0		Historical	ssp1-2.6		ssp3-7.0	
	2005	2050	2085	2050	2085	2005	2050	2085	2050	2085
1	1	1	1	1	1	1	1	1	1	1
2	2	2	2	2	3	2	3	3	3	5
3	2	2	2	2	3	2	2	3	3	4
4	2	3	3	3	4	4	5	6	6	8
5	4	4	4	4	6	5	6	6	6	7
6	4	4	5	5	7	6	7	8	8	9

Table 4

Typical generator ramp rates and start-up/shut-down costs from Xu et al. (2017).

Fuel Type	Ramp rate	Start-up costs (\$/MW/start)	Shut-down costs (\$/MW/shutdown)
Coal	0.6–8	100–250	10–25
Natural Gas	0.8–30	20–150	2–15
Nuclear	0–5	1000	1000
Hydro	15–25	0–5	0–0.5
Wind		non-dispatchable	

frequent intermittent decrease in temperature-sensitive energy may potentially impact the management of productions units in the future, especially if the decrease of heating demand exceed the margin of variability and maneuverability of the production system. This impact can also induce additional financial cost in the system operation.

Finally quantifying the challenges that such fragmentation of energy demand can have on the energy system of each European country had quite a few limiting constraints. One limitation was associated with our choice of predefined set points for cooling and heating to calculate the HDD and CDD in order to facilitate intercomparison of change in energy needs at European scale and to align with other studies in this context. Studying the impact of adaptation strategies at the national level by integrating various set points, energy mixes and energy policies is left for future work.

Data availability

Data could be available if requested.

CRediT authorship contribution statement

Hajar Filahi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Hiba Omrani:** Conceptualization, Supervision, Validation, Writing – review & editing. **Sandra Claudel:** Conceptualization, Data curation, Formal analysis, Validation, Writing – review & editing. **Philippe Drobinski:** Conceptualization, Formal analysis, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.cliser.2024.100469>.

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