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Estimating storage needs for renewables in Europe: The correlation between renewable energy sources and heating and cooling demand

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ABSTRACT

The inexhaustible availability of solar irradiance and wind speed makes these natural resources major contributors to a CO_2 neutral energy system. Since these natural resources interact with temperatures, this paper aims at determining their correlation with temperature derived heating and cooling degree-hours (HDH and CDH) historically and based on climate projections towards 2100. The case study investigates demand and supply balancing requirements in three European climate regions Spain, Austria and northern Europe. Two approaches are used to analyse the hourly correlation on different time scales and the relationship of daily and weekly totals assuming storage. Understanding these interrelations provides a basis for appropriate planning and forecasting in smart energy systems. While solar irradiance does correlate strongly with CDH on hourly basis, achieving 0.80 in Spanish locations and 0.60 in Austria, the relation between wind speed and heating demand is more complex only reaching moderate (0.40−0.59) correlation with monthly storage in all regions. The relationship between solar irradiance and heating needs, by contrast, seems promising in central and southern Europe by applying daily storage to reach moderate to strong (0.40−0.79) results. While HDH will lose importance mostly in Madrid, but also in Vienna and Stockholm, CDH will increase. The implications for final energy demand, however, require consideration of additional parameters, such as energy efficiency measures on building insulation. Smart energy systems, therefore, should embrace the positive correlation between solar irradiance and CDH, and account for at least monthly storage of potential wind power to use VRE for heating and cooling efficiently.

1. Introduction

EU climate goals strive for a CO_2 neutral energy system until 2050. With the capability of PV and wind power plants to generate renewable energy on a large-scale, the decarbonisation of the power sector is a primary goal. The continuous cost reduction of these two renewable power technologies [1,2] is even expected to make them undercut nuclear power cost for energy, capacity and flexibility. Additionally, carbon capture and storage (CCS), despite many hopes on an uptake of the technology [2], can only remain an option to mitigate or rather clear already occurred CO_2 emissions [3]. To achieve climate goals and the decarbonisation of all end-consumption sectors, the efficient use of these large-scale, variable renewable energy sources (VRE) will be of great importance, although the management of their electricity feed-in imposes new challenges to the energy system. If vast curtailment and lost potential shall be avoided, VRE power generation, therefore, needs to be balanced by storage or demand side management or made available to other end-consumption sectors such as transport, industry and residential heating and cooling. For this purpose, either the direct electrification of these processes or the application of transformation technologies (e.g., power to gas) is required, to provide electricity as other forms of energy. This requires a new level of integration and a paradigm shift away from considering individual energy sectors (gas, electricity and heat), storage and demand towards a fully integrated supply system, as intended in smart energy systems [4]. To understand these storage or transformation needs, however, the patterns of and interrelation

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between natural resources and energy demand need to be understood.

The VRE availability varies widely with the considered climate region. While the world's northern regions have long been known for their successful use of wind energy and the rougher northern climates cause substantial heating demand, southern countries build on vast availability of solar irradiance, which is expected to correlate often with substantial cooling needs during the day [1]. The relationships between weather variables and temperature, and their role as renewable energy sources, imply the potential of using solar and wind power to cover heating and cooling needs, for which different technologies would be applicable. As an estimation of the temperature derived heating and cooling needs, cooling and heating degree hours (CDH, HDH) represent the gap between the outside and a desired indoor temperature. This paper aims at proving the hypothesis that there is a positive correlation between the patterns of solar irradiance and CDH and between wind speed and HDH, and at estimating the time discrepancy between wind speed or solar irradiance and a consequent temperature change, which causes storage requirements. Nevertheless, also the relationship between solar irradiance, which is available with a repetitive daily pattern throughout the year, and HDH could be of interest and will be analysed.

Engeland et al. [2] emphasized that renewable electricity supply and demand largely depend on the variability of climate aspects such as temperature, wind speed, solar irradiance and others. A broad set of literatures studied the patterns and behaviour of these weather variables and renewable energy sources. While Emeis [3] provided meteorological insight into wind speed characteristics, solar irradiance is known to have a strong daily pattern related to sunrise and sunset [4]. Influencing factors on the level of solar irradiance include cloudiness or other characteristics of the atmosphere, such as air pollution. Its short term variability has been investigated globally [5] and for different geographical regions, among others for Chile [6] and northern Europe [7]. According to Kiviluoma et al. [8], wind speed depends on turbulent eddies in the short term and pressure changes with weather patterns in the long term. Dai and Deser [9] found a strong diurnal (daily) wind speed cycle over land areas which peaks at dawn, while in nearby oceanic regions it peaks in the early evenings [10]. Wooten [11] found that wind speed and pressure both rely on temperature differences. The complementarity between wind speed and solar irradiance has been proven on a global scale [12], for Sweden [13], Britain [14] and the Iberian Peninsula [15], with an aim to define an optimal mix for energy generation.

The relationship between solar irradiance or wind speed and temperature, however, seems to be very complex specifically in the case of wind speed. A study on circulation types and British weather revealed that the direction of airflows determines the temperature consequences [16,17]. On the British Isles, winds from west or south lead to mild winters, whereas airflows from east and north result in cold periods. In summer, air from the north and east creates warm and from the west and north cold temperatures. Despite the obvious interaction between solar irradiance and temperature, there is a lack of research in the energy economics field.

A broad set of literature studied the historic interaction between temperature and electricity consumption in Europe. Most investigations have a geographical focus, since weather data differs across the globe. Pardo et al. [18] developed a model to forecast daily electricity demand from heating- and cooling degree days (HDD and CDD), and further research confirms the impact of weather patterns – specifically temperature – and seasonality on demand [19] for the UK [20], the US [21,22], Hong Kong [23,24], Saudi Arabia [25], Bangkok [26] and Serbia [27]. Other investigations detect a significant impact of mean daily air temperatures on the energy demand in office buildings [28] or households [29,30]. These conclusions could optimize energy system planning and avoid electricity system breakdowns.

The aspect of covering electricity demand, which also covers aspects of heating and cooling needs, with renewable energy has mainly been studied considering wind speed. Bell [31] investigated the correlation between wind speed and electricity load for Australia without storage and find that both increase during the morning and evening hours, which is confirmed by further research [32–34]. After an analysis of wind power variability in the Nordic countries [35], Holttinen et al. [36] analysed the impact of wind power variability on the electricity load along different integration levels using historic data from 2009 to 2011. While Leahy and Foley [37] focused on cold periods in Ireland, which often coincide with low winds and a lack of potential wind energy supply, wind speed and overall electricity demand in New Zealand correlate on monthly time scale [38]. Ueckerdt et al. [39] described the impact of wind and solar variability on the residual load and came to the conclusion that high shares of PV power over-production are a challenge, while the impacts of increasing wind energy shares are less severe.

Techno-economic research on the correlation between renewable energy sources and their known impact on temperatures in the context of heating and cooling needs, however, is scarce. Coker et al. [40] analysed the variability of wind, solar and tidal resources while, however, the analysis on their relationship with demand lacks implications on future energy system requirements. The authors' main conclusion in this respect is that solar irradiance shows the most direct correlation with electricity demand, diminished by its unavailability overnight and an even greater monthly variability than wind speed.

Recently, climate change effects are increasingly being investigated, specifically on the supply side for solar irradiance and wind speed [41–45]. While in China a decreasing trend in sunshine hours between 1960 and 2009 can be explained by the air pollution index [46] the same trend on the Canadian Prairie is caused by a climate change related increase in cloudiness [47]. Western Europe shows an increase in solar irradiance in winter and the Iberian Peninsula is characterised by negative trends in summer and positive trends in March [48,49]. A proven phenomenon, however, is a global decadal variability of stronger and weaker solar irradiance, which is referred to as dimming and brightening [47,50–52]. For the use of solar power it is, furthermore, important to note that higher temperatures may also affect solar panel efficiency [53,54]. Several literatures found a decreasing trend in wind speed [55,56] accounting for −0.014 m/s globally [57], apart from coastal sites, which experience increases. Tobin et al. [43], however, observed an increase in wind power potential for most of Europe, apart from Mediterranean areas and northern Europe. Wind power potential in northern Europe, however, could benefit from decreased icing frequency and sea ice due to the global warming [58].

Several studies also consider the impact of climate change on the demand side. Totschnig et al. [59] found that cooling demand peaks are having a strong impact on residual load and suggest strong initiatives in building insulation and passive cooling solutions. This relationship has also been evaluated for Europe [60,61], the US [62], Australia [63], Brazil [64] and China [65]. Most of them detected increased cooling and decreased heating demand caused by climate warming, whereas the effects seem to be more significant in southern compared to northern Europe. Work including effects on both, the demand and the supply side is provided by Dowling [66] and Girardi [67]. Nevertheless, many aspects of the relationship between natural resources and heating and cooling needs remain untouched and require more detailed investigation.

While existing work mainly analysed the relationships either between VRE and temperatures, HDD/CDD and electricity demand or wind speed and electricity demand, a literature gap has been identified in the correlation between wind speed and solar irradiance and temperature related energy demand (HDD and CDD). There is a lack of such investigation historically, and considering climate change effects. It is, however, important in smart energy systems to understand the characteristics of natural resources and their relationship with temperature and consequent heating and cooling demand, to estimate timing discrepancies and balancing requirements.

This work, therefore, aims at providing policy recommendations for smart energy systems by analysing the correlation between its main supply sources wind speed and solar irradiance—in their purity without limiting the energy supply to a specific technology or related constraints in the electricity system—and HDH and CDH, to estimate the storage needs that are required to successfully match supply with demand. Our analysis is conducted for different climate regions in Europe (Austria, Spain and northern Europe), historically in different time resolution, and into the future. Since this work is based on weather variables only, implications for actual energy demand need consideration of additional parameters, such as energy efficiency measures on building insulation, comfort during longer periods of heat and cold, impacts of other energy demand sectors with progressive integration of the energy system.

The remains of this paper are structured as follows. Section 2 outlines the methodology including the selection of six case study locations per climate region—with an aim to cover a broad set of historic average solar irradiance and wind speed levels, location directions, inland and coastal regions—and the determination of HDH and CDH. Section 3 describes the results of the study. It presents a correlation coefficient analysis between the hourly pattern of wind speed or solar irradiance and CDH or HDH applying two different approaches. Approach 1 determines the hourly correlation for daily and weekly time-periods and the whole considered season. Approach 2 already assumes storage by analysing the correlation between daily, weekly, and monthly aggregated weather data. In Section 3.2, an assessment of climate change effects on the weather variables and the correlation results is outlined. After declaring the limitations of the study in Section 3.3, Section 4 closes with policy recommendations.

2. Methodology

The first part of this study analyses the historic characteristics of and correlation between primitive weather variables – wind speed and global horizontal irradiance – and weather variables derived from temperature on hourly basis –HDH and CDH. The study is carried out for three different European climate regions Austria, Spain and northern Europe. The correlation coefficient is analysed between the weather variables per location in each climate region, which we refer to as "self-correlation". Additionally, we look at the relationship between locations to derive a potential value of external natural energy supply via the energy grid. The correlation coefficient is analysed based on two approaches outlined in Section 2.3 and considers different time periods and data aggregation to evaluate the storage requirements. The relevant historic weather data is provided by the photovoltaic geographical information system by the European Commission on hourly resolution between 2005 and 2016 [68] and consists of the following:

- temperature at 2 m in °C,
- wind speed at 10 m in m/s
- global horizontal irradiance in W/m^2

Finally, we investigate the impact of climate change on weather variables and correlation based on daily CMIP5 weather data projected between 2020 and 2100 (see Section 2.5).

2.1. Selection of case study locations

To cover different climate regions in Europe, the case study areas have been defined as Spain, Austria and northern Europe (Sweden and Norway). For each of these regions, we selected six locations with the main objective to cover a broad range of solar irradiance and wind speed levels in each country, evaluated by the historic mean solar irradiance and wind speed between 2008 and 2017 provided by the global solar and wind atlas [69,70]. An additional requirement was to cover inland as well as coastal regions and to focus on cities with larger population. The selection was not based on covering potential power supply or specific densely populated demand locations.

1. Spain

   Of the six selected Spanish locations, three are inland and three represent coastal locations (see Fig. 1). Table 1 lists the locations selected for Spain coloured in their level of solar irradiance and Table 2 shows the historic mean wind speed

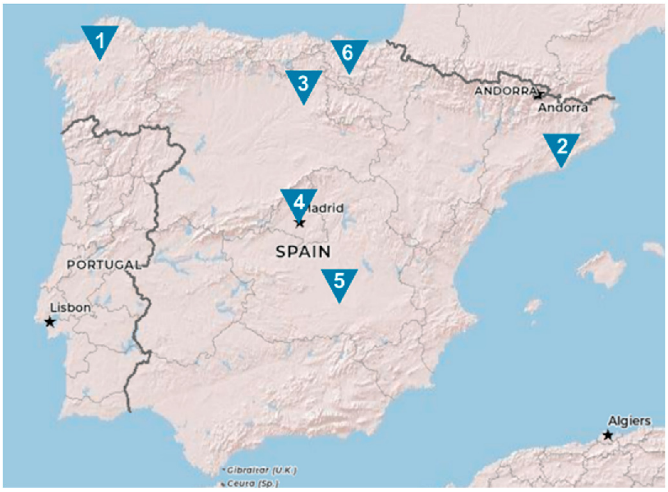


Fig. 1. Selected locations in Spain.

Table 1
Mean historic solar irradiance level of the locations in Spain (Source [70])

No	Location	Province
1	A Coruña	Galicia
2	Barcelona	Catalunya
3	Burgos	Castilla y Leon
4	Madrid	Madrid
5	Tomelloso	Castilla la mancha
6	Vitoria-Gasteiz	Pais Vasco

Table 2
Mean historic wind speed level of the locations in Spain (Source [69]).

No	Location	Province
1	A Coruña	Galicia
2	Barcelona	Catalunya
3	Burgos	Castilla y Leon
4	Madrid	Madrid
5	Tomelloso	Castilla la mancha
6	Vitoria-Gasteiz	Pais Vasco

level.

A Coruña, located at the coast in the north-west of the country, shows rather low solar irradiance and high average wind speed. Tomelloso has the highest solar irradiance, followed by Madrid in central Spain. They both experience low to very-low wind speed levels respectively. Burgos and Barcelona are characterised by medium to high solar irradiance, with very high and very low wind speed respectively.

2. Austria

The six locations selected in Austria are distributed across all directions of the country (see fig. 2). The selection aims at avoiding locations at high elevation that would not be relevant for the CDH analysis—herein manipulating the average result for Austria—and provide little potential for the use of local wind power. Table 3 lists the Austrian locations coloured in their level of solar irradiance and Table 4 shows their level of wind speed.

Austria, due to its central location, does not feature specifically high levels of solar irradiance apart from Klagenfurt in the south and Nickelsdorf in the south-west. The wind map looks more diverse, where these two locations show very low and high wind speed respectively. Bregenz, located in the far west of the country, is also characterised by low wind speed, compared to Vienna and Gmünd in the east, which show higher values.

3. Northern Europe

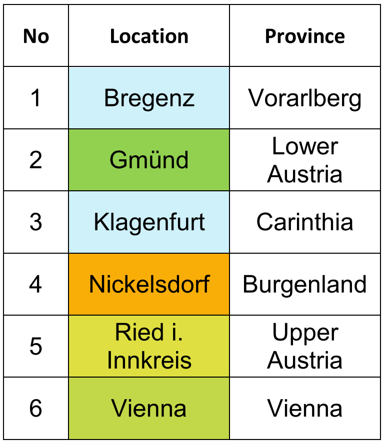
Since for northern Europe cooling demand is hardly relevant, as becomes clear from the descriptions in Section 2.3, we only consider the relationship between wind speed and solar irradiance with HDH. The six locations selected are located in Norway and Sweden (see Fig. 3). Table 5 lists the locations coloured in their level of solar irradiance and Table 6 indicates the level of wind speed. The wind speed level in Bodø is highest, followed by Gothenburg and Stockholm. Wind speed levels in Kiruna, Trondheim and Oslo are rather low.

Fig. 2. Selected locations in Austria.

Table 3
Mean historic solar irradiance level of the locations in Austria (Source [70])

No	Location	Province
1	Bregenz	Vorarlberg
2	Gmünd	Lower Austria
3	Klagenfurt	Carinthia
4	Nickelsdorf	Burgenland
5	Ried i. Innkreis	Upper Austria
6	Vienna	Vienna

Table 4
Mean historic wind speed level of the locations in Austria (Source [69]).



No	Location	Province
1	Bregenz	Vorarlberg
2	Gmünd	Lower Austria
3	Klagenfurt	Carinthia
4	Nickelsdorf	Burgenland
5	Ried i. Innkreis	Upper Austria
6	Vienna	Vienna

2.2. *Heating and cooling degree hours*

This work uses temperature based estimations of heating and cooling needs and does not consider energy technologies, carriers or cross-sectoral interdependencies. In our historical analysis, we derive heating and cooling needs from outdoor temperatures on hourly basis, referred to as HDH and CDH. The projected future data to analyse climate change is provided at daily resolution, from which HDD and CDD can be derived. HDH and CDH describe the extent of heating and cooling needs in Kelvin hours (Kh), which occur below or above a certain temperature threshold or reference temperature. They measure the difference between the outside reference temperature and a desired room temperature.

We define the reference temperatures for heating and cooling according to a general climatological approach [71] and calculate

Fig. 3. Selected locations in northern Europe.

HDH and CDH as described in Eq. (1) and Eq. (2) [71]. Heating is expected to be desired at or below 15 °C outside temperature (reference temperature) and the desired room temperature is defined as 18 °C [71].

Table 5
Mean historic solar irradiance level of the locations in northern Europe (Source [70])

No	Location	Country
1	Bodo	Norway
2	Oslo	Norway
3	Trondheim	Norway
4	Gothenburg	Sweden
5	Kiruna	Sweden
6	Stockholm	Sweden

Table 6
Mean historic wind speed level of the locations in northern Europe (Source [69]).

No	Location	Country
1	Bodo	Norway
2	Oslo	Norway
3	Trondheim	Norway
4	Gothenburg	Sweden
5	Kiruna	Sweden
6	Stockholm	Sweden

$$T^{h} = 15^{\circ}C$$

$$T_{room}^{h} = 18^{\circ}C$$

$$T_i \leq T^{h}: HDH = \left(T_{room}^{h} - T_i\right)\Big]$$

$$T_i > T^{h} : HDH = 0 \tag{1}$$

Ti … 2 m air temperature at time step i.

If, for example, the air temperature is 12 °C, the HDH index accounts for 6 Kh (18°C–12 °C). If the air temperature is 17 °C and, hence, lies above the heating threshold of 15 °C, the HDH index is 0 Kh. HDH therefore rise with decreasing temperatures.

The reference temperature for cooling is set to 24 °C outside temperature (T^{c}) and the desired room temperature to 21 °C [71].

$$T^{c} = 24^{\circ}C$$

$$T_{room}^{c} = 21^{\circ}C$$

$$Ti \geq T^{c} : CDH = \left(Ti - T_{room}^{h}\right)\Big]$$

$$Ti < T^{c} : CDH = 0 \tag{2}$$

If, for example, the current air temperature is 28 °C, the CDH index amounts to 7 Kh (28°C–21 °C). If the air temperature is 21 °C and, hence, lies below the cooling threshold of 24 °C, in that hour the CDH index is 0 Kh. CDH therefore rise with rising temperatures.

2.3. Weather variable characteristics per climate region

Fig. 4 and Fig. 5 present the historic monthly average wind speed and solar irradiance for Spain (ESP), Austria (AUT) and northern Europe (NEU) across all locations and years based on the data as described at the beginning of this Section 2 [68]. While monthly wind speed in northern Europe peaks in December and January and decreases continuously towards July, Austria and Spain both experience a minor decline in wind speed in winter between December and February. Solar irradiance shows the same pattern in all three regions, with Spain experiencing the highest level followed by Austria and finally northern Europe. It is remarkable that Austria and northern Europe achieve the same average solar irradiance in June despite the spatial difference.

The average CDD and HDD for one location per region are presented in Fig. 6. The most southern region analysed in this study, Spain, shows a comparatively high number of CDD between May and September, with a peak in July and August at around 2.5 °C. Since the country still tends to have cold winters, also heating demand and the amount of HDD are significant from October to May with a peak between December and February. Located in central Europe, Austria shows a small amount of CDH between May and September, with a peak in July of 1.5 °C. The colder winters lead to frequent and high heating needs. The HDD are significant from September to May, peaking from December to February with almost 18 °C.

Table 7 additionally provides an overview of the historical average, maximum and minimum yearly amount of heating and cooling degree hours. The northern European countries only experience an insignificant amount of CDH between June and August. This leads us to the conclusion that an analysis of its correlation with solar irradiance can be neglected. The cold climate, however, results in substantial HDH which occur all the year through, reaching a maximum between December and February with almost 22 °C (see Fig. 6).

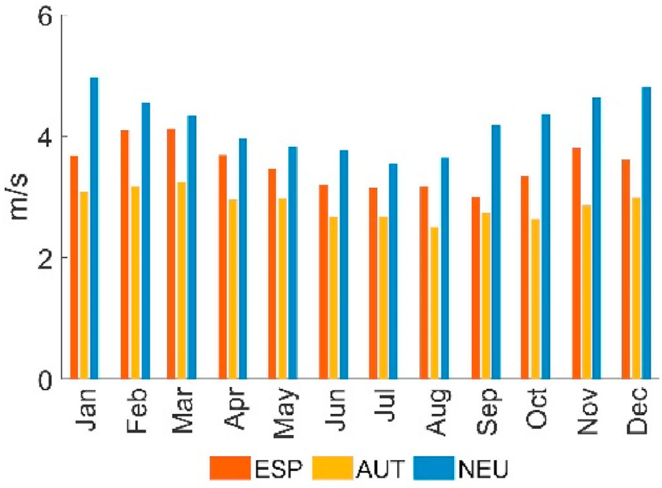


Fig. 4. Monthly average wind speed for each region

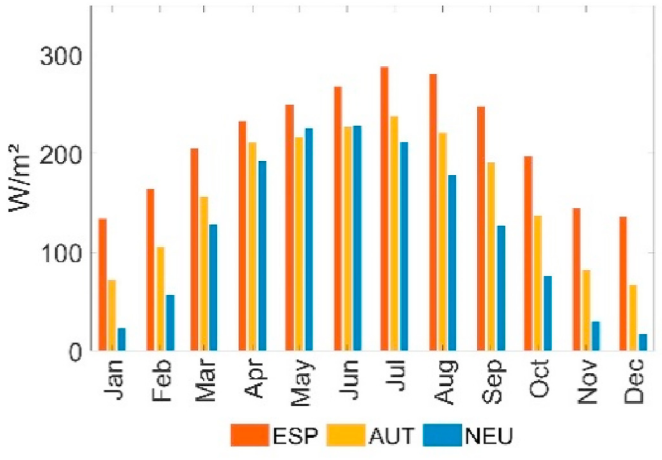


Fig. 5. Monthly average solar irradiance per area.

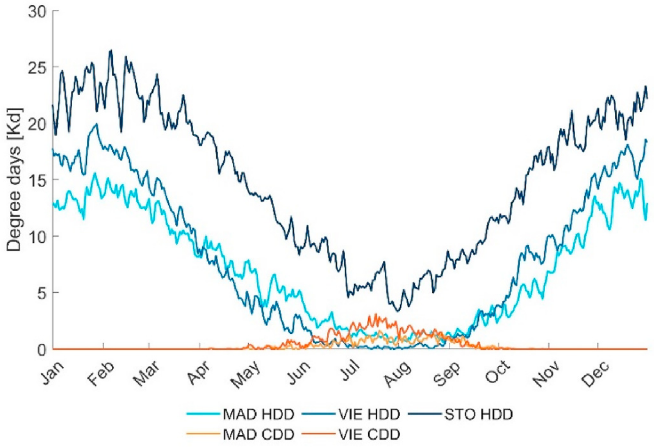


Fig. 6. Historical average HDD and CDD for Madrid, Vienna and Stockholm.

2.4. *Correlation coefficient: approach and interpretation*

This study analyses the correlation coefficient between solar irradiance and CDH, wind speed and HDH and solar irradiance and HDH, drawing conclusions on positive or negative correlation and flexibility needs. The correlation coefficient (ρ) is calculated between the primitive weather variables (wind speed and solar irradiance) (V_p) and the derived weather variables (V_d) CDH and HDH.

The correlation results are evaluated after Pearson [72] as described in Table 8.

This paper differentiates between the relevant seasons with respect to heating and cooling demand to achieve a most comprehensive view of the correlations. The seasons are defined based on a standard for the northern hemisphere, as described in Table 9.

Usually, the impact of the primitive variable - solar irradiance or wind speed — on the temperature and consequently the derived variable - CDH and HDH - takes some time. The main analysis in this paper already accounts for this time discrepancy between the primitive and derived variable and therefore assumes an amount of storage to that extent.

There is, for example, a time lag between the increase of solar irradiance and its impact on temperature — and consequently CDH. A similar phenomenon can be observed between solar irradiance or wind speed and HDH to a different extent. The variable x describes the amount of hours that the derived variable (Vd), for example CDH, lags behind the primitive variable (Vp) solar irradiance in any point in time (t) (see Fig. 7). In other words, Vp needs to be moved backwards by x hours from t to match Vd. We search for the best estimate of the time lag by defining x in a way to maximize the overall correlation coefficient (ρ), representing the best possible

Table 7
Historic average, maximum and minimum yearly heating and cooling degree hours per region.

	CDH/a			HDH/a		
	Average	Max	Min	Average	Max	Min
SPAIN	10.272	21.225	661	63.132	74.05	50.31
AUSTRIA	5.691	7.699	2.905	70.241	79.121	65.296
NORTHERN EUROPE	182	620	3	91.309	99.433	84.324

overlay of the primitive and derived weather variables. Our analysis hereby considers a time lag up to 24 h.

Our work applies two different approaches, of which both focus on hourly data adjusted by the time lag between the supply source and the temperature change. While approach 1 determines the hourly correlation for different time-periods, approach 2 investigates the correlation assuming daily, weekly, and monthly storage by aggregating the data. The two approaches provide valuable insights not only with respect to the hourly fit of the supply and demand pattern, but also shows how the aggregated amounts of supply coincide with demand.

Approach 1 (A1) determines the hourly correlation adjusted by the lag for hourly, daily and weekly time-periods in a season (Eq. (3)). For example, if the hourly correlation is calculated per day for the summer season (2208 h), 90 correlation results are received (2208/24). Then the average for the season is created across this amount of time intervals, e.g. the number of days or weeks *(i)*. If most daily correlations are weak according to Pearson described in Table 8 (<0.4), this average result will be weak too. If the daily correlations are moderate (0.40–0.59) or vary significantly, the average result for the daily time-period will be moderate. A strong average correlation (>0.6) for the daily time-periods implies continuously high daily correlation results. This approach describes the hourly fit of the supply and demand pattern and analyses if storage is required to achieve a better match. A negative correlation would imply, for example, high solar irradiance at times of low cooling needs. The potential solar energy would therefore need higher storage amounts to match demand.

$$\rho_{Vp,\ Vd} = \frac{1}{i}\sum_{t=1}^{n}\frac{cov(Vp_{t+x}\ Vd_t)}{\sigma_{Vp_{t+x}}\sigma_{Vd_t}} \tag{3}$$

ρ correlation coefficient

σ Standard deviation.

Vd derived variable (CDH, HDH) [Kh].

Vp primitive variable (wind speed [m/s], solar irradiance [W/m^2])

i number of time intervals (number of days, weeks, months).

x time lag.

Approach 2 (A2) investigates the value of storage based on daily or weekly aggregated weather data (Vpa2, Vda2) in a specific season or the monthly aggregated data across the whole year, as described in (Eqs. (4) and (5)). We thus compare the total amount of the primitive and derived variables for the number of hours of a day, week or month (*h*) in the respective season to see if higher heating or cooling demands coincide with higher natural resource availability (Eq. (6)). If the correlation is strong (>0.6), storage for the considered time-period is of value.

$$Vpa2 = \sum_{h=1}^{n} Vp_{t+x} \tag{4}$$

Table 8
Assessment of the correlation coefficient "ρ" after Pearson [72].

ρ	INTERPRETATION
<0.19	Very weak
0.20–0.39	Weak
0.40–0.59	Moderate
0.60–0.79	Strong
0.80–1.00	Very strong

Table 9
Meteorological seasons.

TIME PERIOD	SEASON
Mar 1st – May 31st	Spring
Jun 1st – Aug 31st	Summer
Sep 1st – Nov 31st	Autumn
Dec 1st – Feb 29th	Winter

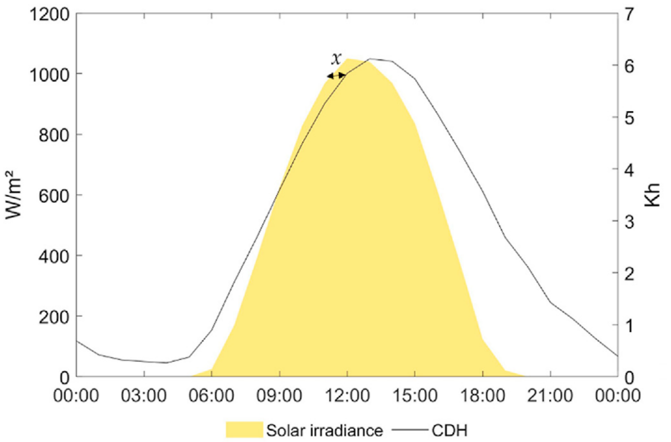


Fig. 7. Exemplary day describing the time lag (*x*) between solar irradiance and cooling degree hours.

$$Vda2 = \sum_{h=1}^{n} Vd_t \tag{5}$$

$$\rho_{Vpa2,\ Vda2} = \frac{1}{i}\sum_{h=1}^{n}\frac{cov(V_{pa2}\ Vd_{a2})}{\sigma_{Vpa2}\sigma_{Vda2}} \tag{6}$$

h number of hours across which data is aggregated.

Vda2 aggregated derived variable (CDH, HDH) [Kh].

Vpa2 aggregated primitive variable (wind speed [m/s], solar irradiance [W/m^2])

Another important investigation is the seasonality of the correlation coefficient, which is calculated hourly for monthly time-periods based on approach 1. This analysis enables conclusions on the relationship between the hourly weather variables and heating and cooling demand in each month.

2.5. Climate change effect: data and evaluation

The assessment of climate change effects on the weather variables and the consequences for future correlation coefficients is based on projected CMIP5 weather data between 2020 and 2100 [73]. The model EC-EARTH provides future projections considering the representative concentration pathways (RCP) assuming different levels of radiative forcing between 2.6 and 8.5 [74]. Our research is based on a middle path applying the RCP4.5 of the CMIP5 data at daily resolution within certain latitude and longitude boundaries for one location per climate region: Madrid, Vienna and Stockholm.

The development of weather variables is conducted comparing a 5-year trend towards 2100 with that of 2020. The relative development in percent is presented for temperatures, solar irradiance, wind speed, and CDD and HDD in Section 3.2.1. In a next step, the absolute correlation coefficients are calculated for the future based on this daily data and analysed with respect to the changes observed in the weather variables.

3. Results

This Section provides a detailed analysis of the correlation coefficients in the locations per climate region according to the approaches described in the methodology, followed by a regional comparison of the results in subsection 4. Finally, the climate change effect on the weather variables and the impact on the correlation coefficients is described.

3.1. Correlation results

The analysis for Spain and Austria starts with the relationship between solar irradiance and CDH, which is not relevant for northern Europe, followed by wind speed and HDH and solar irradiance and HDH. A detailed graph shows the results for both approaches (see Section 2.4) with the locations numbered from 1 to 6 according to the assignment in Section 2.1. Additionally, the interrelation between locations is briefly described, to consider spatial exchange and investigate the value of the energy networks.

In all three regions, the time lag between solar irradiance and CDH accounts for 2 h, which describes the time solar irradiance, requires to have an impact on the temperature. The lag between wind speed and HDH amounts to 14 h and between solar irradiance and HDH to 16 h, which leads to an overly of the noon peak of solar irradiance with the early morning HDH peaks.

3.1.1. Correlation between CDH and solar irradiance

1 Spain

CDH in Spain, as was shown in an example for Madrid in Section 2.3, mainly occur from July to September, while solar irradiance peaks from June to August (see Section 2.3). With the adjustment of the weather data by the time lag of 2 h, as discussed in Section 2.4, the correlation coefficient can be increased in all seasons relevant for CDH – summer, spring and autumn – by 15–52%.

Analysing the hourly correlation for different time-periods according to A1, in A Coruña (1), Burgos (3) and Vitoria Gasteiz (6) the results in the summer season increase with the considered time-period from day to season (see Fig. 8). This means that daily and weekly patterns of hourly data match less than the hourly pattern of the whole summer season. The other locations Barcelona (2), Madrid (4) and Tomelloso (5) show decreasing results with increasing time-periods and a better daily than weekly or seasonal fit of hourly data. In Madrid and Tomelloso, the correlation is very strong on a daily basis with an average coefficient in summer above 0.80, followed by Barcelona with a strong correlation of 0.63. Calculating the solar irradiance and CDH correlation with daily and weekly storage for the summer season, as well as monthly storage across the whole year (A2) and comparing it to the hourly correlation for the summer season (A1) also suggests a strong hourly fit. Regarding daily or weekly storage (A2) weekly total solar irradiance and CDH all locations apart from A Coruna (1) achieve a moderate correlation above 0.4. In autumn, the hourly fit is very weak for all time-periods (A1) but weekly aggregated data results in a moderate to very strong correlation. The monthly total solar irradiance throughout the year correlates strongly with CDH, exceeding 0.60 in all locations but A Coruña (1). This leads to the conclusion that for CDH to be covered by solar power in summer, 2-hourly to daily storage is sufficient, while for cooling needs in autumn and also spring, which may be relevant in Spain specifically with rising temperatures in the future, weekly storage might be required.

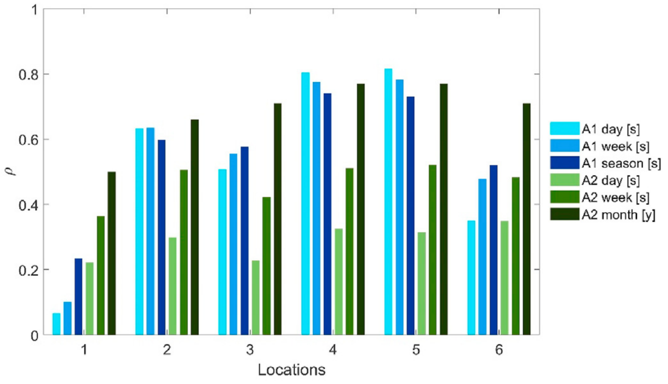


Fig. 8. Spain: Solar irradiance and CDH correlation coefficient (ρ) in summer season [s] applying approach 1 (A1) and approach 2 (A2) for the locations 1–6 as described in Section 2.1 (monthly correlation across the whole year [y]).

Table 10 describes the CDH and solar irradiance relationships between the locations in summer on an hourly basis adjusted by the lag. The correlation between the locations indicates the potential of external energy supply to achieve a stronger correlation than the local self-correlation. Burgos would benefit from a connection with the solar energy supply from Vitoria Gasteiz (6) and reach a coefficient of 0.63 compared to its self-correlation of 0.58. The value of exchange through the energy grid is, however, low in all cases.

2. Austria

In Austria, the cooling demand is much lower than in Spain, due to the lower temperature level, and mostly occurs during July and August. Accounting for the 2-h time-lag between solar irradiance and CDH, an improvement of the correlation results in summer season of around 30% can be achieved.

In contrast to Spain, for the hourly CDH and solar irradiance correlation for different time-periods (A1) in the summer season all selected locations in Austria show a similar pattern increasing with the length of the time-period from day to season (see Fig. 9). Bregenz (1), Klagenfurt (3), Nickelsdorf (4) and Vienna (6) achieve strong results above 0.60 on a seasonal basis. This means that the hourly solar irradiance pattern during the whole summer season matches CDH better than the weekly or specifically the daily one. Nickelsdorf (4), with rather high solar irradiance, reaches the highest result for the daily time-period at 0.50 closely followed by Vienna (6).

In Austria, weekly storage (A2) achieves strong correlation between CDH and solar irradiance in summer in all locations reaching a coefficient of above 0.7 in Klagenfurt (3) in the south

Table 10
Hourly solar irradiance and CDH correlation between locations in Spain (top numbers 1–6 refer to locations as numbered on the left)

	CDH							
No.	Location		1	2	3	4	5	6
1	A Coruña	**Solar irradiance**	0.23	0.48	0.48	0.69	0.69	0.35
2	Barcelona		0.20	0.60	0.58	0.71	0.70	0.47
3	Burgos		0.21	0.57	0.58	0.76	0.75	0.45
4	Madrid		0.19	0.57	0.55	0.74	0.74	0.43
5	Tomelloso		0.20	0.57	0.55	0.73	0.73	0.43
6	Vitoria Gasteiz		0.22	0.56	0.63	0.74	0.73	0.52

of the country, followed by Bregenz (1) in the far west and Ried i. Innkreis (5). Monthly total solar irradiance gain correlates well with CDH across the whole year.

Concerning the relationships between locations, the self-correlation in the framed cells in Table 11 is usually higher than allowing for external solar energy supply. Even if there are strong relationships between the CDH in Bregenz (1), Klagenfurt (3) and Vienna (6) with the solar irradiance of other locations improvements are limited.

3. Region comparison

   Fig. 10 describes the results for the solar irradiance and CDH correlation in summer as an average across all locations. The average hourly solar irradiance and CDH correlation in Spain (ESP) does not improve significantly by considering longer time-periods (A1) than a day, although for some locations it would as described earlier in this Section. In Austria (AUT), by contrast, an increase was visible for all locations implying that daily patterns match less than the weekly and seasonal ones.

   While in Spain, the hourly correlation is already moderate to strong on all time scales (A1), in Austria, weekly storage (A2) achieves the strongest correlation with 0.68. This points to a stronger hourly relationship in the south than in central Europe. Regarding autumn and spring with lower cooling needs but also lower solar irradiance levels both countries' results improve towards weekly aggregation or storage, implying high storage needs for daily balancing.

   Fig. 11 describes the seasonality of the correlation based on the hourly correlation for monthly time-periods. CDH and solar irradiance patterns match best during the main cooling season from June to August, which is convenient. With increasing solar irradiance and cooling needs towards summer, also the average hourly correlation increases to a strong level in July at 0.62 in Spain and 0.64 in Austria.

3.1.2. Correlation between HDH and wind speed

1. Spain

   In Madrid, HDH reach their high between December and February, while wind speed is high in November and reaches its highest average level in February and March, after a minor interruption in December and January (see Section 2.3). The hourly correlation between wind speed and HDH (A1) in winter season shows a similar pattern in all locations with a weak (around 0.2) positive result on a daily basis, decreasing further towards longer time-periods (see Fig. 12). This means that an increase in wind speed does not necessarily cause lower temperatures and heating needs immediately. It can even be observed that winds often bring about warmer temperatures, which is also explained in our literature review in Section 1. Data aggregation assuming daily and weekly storage (A2) results in a negative correlation in almost all locations (around 0.2), implying that the amount of wind speed does not match the heating needs. In spring and autumn, seasons in which HDH still occur even in this southern European region (see 2.3), daily and weekly storage achieve moderate results below 0.52 in Burgos (3) and Vitoria Gasteiz (6) with very high wind speed levels and also Barcelona (2). Wind speed and HDH only reach solid moderate relationships with monthly storage across the year (0.56 in Vitoria Gasteiz (6) followed by Barcelona (2) and Burgos (3) with 0.51). The correlation between locations also shows no substantial improvement. The results remain weak and the benefit of the energy network is, in this case, limited.

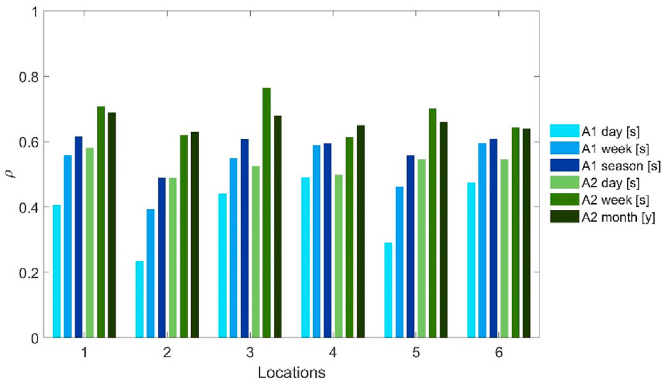


Fig. 9. Austria: Solar irradiance and CDH correlation coefficient (ρ) in summer season [s] applying approach 1 (A1) and approach 2 (A2) for the locations 1–6 as described in Section 2.1 (monthly correlation across the whole year [y]).

2. Austria

   The correlation between wind speed and HDH on hourly basis in Austria is similar to that of Spain. Again, wind speed and HDH during winter season do not correlate significantly at daily time-periods and are even negative on weekly and seasonal basis. In almost all locations, an extension of the time-period leads to an even lower correlation. The best fit of lag-adjusted, hourly wind speed and HDH according to A1 in winter occurs on a daily basis (see Fig. 13). In spring and autumn, all the same, the correlation is weak. Daily and weekly storage (A2) does not achieve a positive fit between supply and demand. Only monthly data aggregation throughout the year leads to moderate results in Gmünd (2) and Ried i. Innkreis (5).

   Spatial integration hardly improves the results. Only the HDH in Bregenz (1) correlate slightly better with potential wind power supply from Klagenfurt (3), and HDH of Ried i. Innkreis (5) with the wind supply in Klagenfurt (3), Nickelsdorf (4) and Vienna (6). Still the spatial integration has little benefit.

3. Northern Europe

   In northern Europe, the HDH and wind speed correlation without accounting for the 16-h time lag is even more negative than in Spain and Austria. Also after an adjustment for the lag, northern Europe shows the least significant results on a daily basis (see Fig. 14).

   The negative weekly and seasonal relationships of hourly data (A1) are even stronger than in central and southern Europe. Since in winter season, no positive relationship between HDH and wind speed can be achieved irrespectively of the regarded time-period, storage will be required also in this region to match supply and demand.

   Assuming daily and weekly storage of potential power from wind speed (A2) does not achieve a positive correlation with heating needs in winter. This means that the amount of wind speed in the respective time-period does not match the heating needs. Only the monthly amounts of wind speed throughout the year correlate with heating needs. In the north, also the summer season is a relevant heating period with cold temperatures. Here weekly storage leads to a moderate correlation in two Swedish locations, Kiruna (5) and Stockholm (6).

   To show the correlation between the locations, summer represents the season with the most vivid results on hourly basis (see Table 12). The highest improvement from the local self-correlation with external supply of wind speed can be reached within Norway between Bodø (1) and Trondheim (3). An interaction, therefore, could be valuable. For all other locations, a potential exchange via the energy grid does not have a significant benefit.

Table 11
Hourly solar irradiance and CDH correlation between locations in Austria (top numbers 1–6 refer to locations as numbered on the left)

			CDH					
No.	Location		1	2	3	4	5	6
1	Bregenz	Solar irradiance	0.62	0.38	0.50	0.46	0.48	0.49
2	Gmünd		0.58	0.49	0.59	0.58	0.55	0.62
3	Klagenfurt		0.57	0.44	0.61	0.58	0.51	0.59
4	Nickelsdorf		0.53	0.45	0.59	0.59	0.49	0.60
5	Ried i. Innkreis		0.61	0.47	0.58	0.55	0.56	0.59
6	Vienna		0.55	0.46	0.58	0.59	0.52	0.61

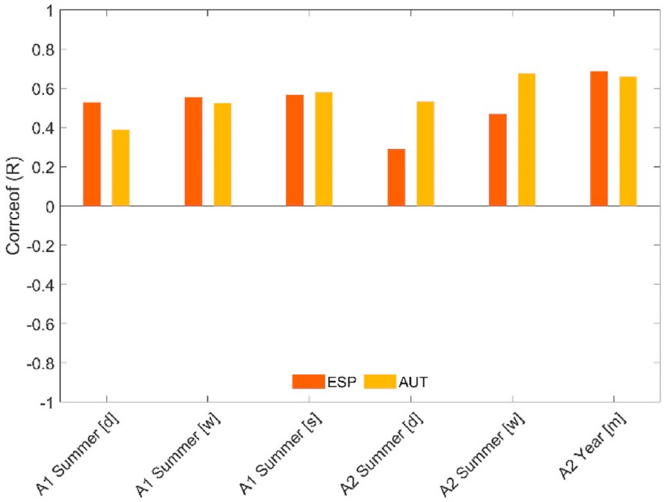


Fig. 10. Hourly solar irradiance and CDH correlation coefficient (ρ) per climate region for different time-periods (day [d], week [w], season [s], month [m]) applying approach 1 (A1) and approach 2 (A2).

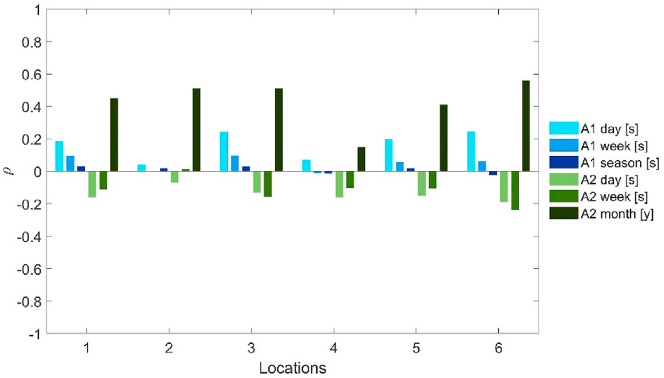


Fig. 12. Spain: Wind speed and HDH correlation coefficient (ρ) in winter season [s] applying approach 1 (A1) and approach 2 (A2) for the locations 1–6 as described in Section 2.1 (monthly correlation across the whole year [y]).

4. Region comparison

Fig. 15 shows that the correlation between HDH and wind speed is insignificant to negative in winter irrespectively of the chosen approach or time-period in all three climate regions throughout the year. Only monthly storage leads to a moderate positive correlation. Weekly amounts of HDH and wind speed in northern Europe almost reach a strong negative relationship (A2). These results show the need for monthly to seasonal storage to match power from wind speed with heating needs.

The hourly wind speed and HDH correlation in Spain is moderate during spring season and negative to insignificant during winter season, when the heating demand is most relevant (see Fig. 16). In Austria, the correlation in winter is negative between November and January. The strongest season in Austria is again spring. In northern Europe, the seasonal pattern of the hourly correlation between HDH and wind speed is extremer. In this region, hourly HDH and wind speed correlate negatively from October until March. Paired with strong heating needs in northern Europe, this implies substantial storage requirements to cover demand with wind power.

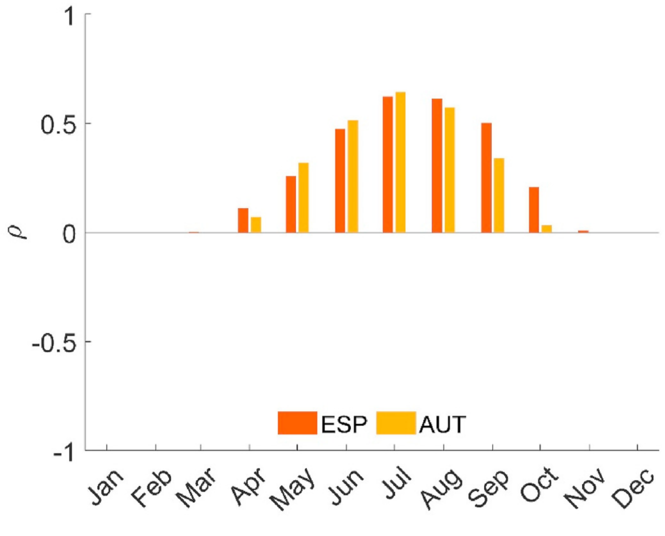


Fig. 11. Seasonality: Hourly solar irradiance and CDH coefficient (ρ) per month (A1).

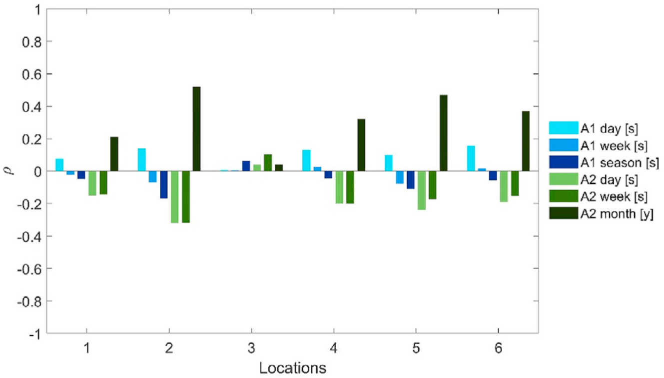


Fig. 13. Austria: Wind speed and HDH correlation coefficient (ρ) in winter season [s] applying approach 1 (A1) and approach 2 (A2) for the locations 1–6 as described in Section 2.1 (monthly correlation across the whole year [y]).

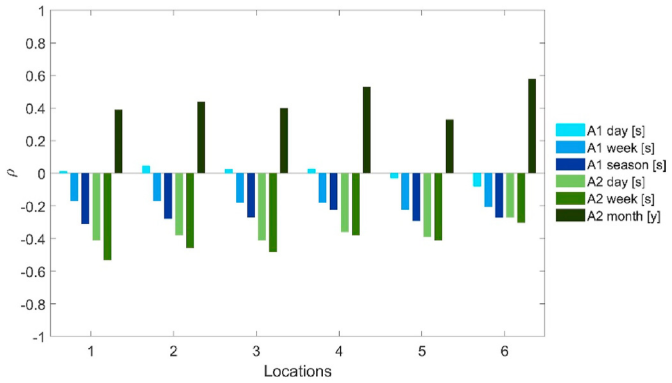


Fig. 14. Northern Europe: Wind speed and HDH correlation coefficient (ρ) in winter season [s] applying approach 1 (A1) and approach 2 (A2) for the locations 1–6 as described in Section 2.1 (monthly correlation across the whole year [y]).

3.1.3. *Correlation between HDH and solar irradiance*

1. Spain

Without adjusting the weather data by the time lag of 16 h between HDH and solar irradiance, the hourly relationship is strongly negative. This seems logical since temperature usually increases with solar irradiance. Spain reveals the strongest positive results after the time discrepancy is removed and the solar irradiance peak at noon matches the highest heating needs in the early mornings.

The investigation of the hourly solar irradiance and HDH correlation (A1) during different time-periods in winter season shows strong levels on a daily basis right above 0.60 in Barcelona (2), Madrid (4) and Tomelloso (5), while for the week and season they remain moderate. Nevertheless, the relation to heating needs is more promising than that of wind speed (see Fig. 17). The stronger results for the daily than for the weekly and seasonal time-period imply a good daily fit of the solar irradiance and HDH pattern and a weaker relationship across longer time-periods. Spring season also achieves positive results.

Daily and, even more so, weekly storage of solar irradiance (A2) leads to insignificant correlations in winter and stronger negative correlations in spring and autumn. It can be concluded that in winter the HDH and solar irradiance patterns do match quite well if balanced to the extent of the time lag of 16 h. It is not surprising, though, that the monthly solar irradiance correlates with HDH on a strong negative level throughout the year and even reaches very strong levels below -0.8.

A connection between locations cannot significantly improve the local self-correlation between solar irradiance and HDH. Therefore, there is little benefit of a spatial integration via the distribution grid.

2. Austria

For daily time-periods (Fig. 18), the lag adjusted hourly solar irradiance and wind speed correlation (A1) in winter season is moderate in Bregenz (1), Klagenfurt (3) and Nickelsdorf (4). The daily patterns of hourly solar irradiance and HDH obviously match better than the weekly ones or those of the whole season.

Daily and weekly aggregated solar irradiance and HDH (A2) correlate negatively in most cases, since higher heating needs usually come with lower solar irradiance. Spring and autumn show more extreme results with hardly any positive correlation on hourly basis and strong negative correlation with aggregated

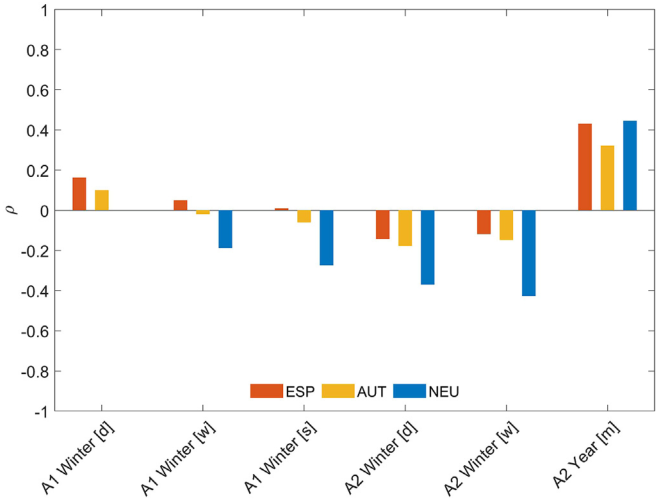


Fig. 15. Hourly wind speed and HDH correlation coefficient (ρ) per climate region for different time-periods (day [d], week [w], season [s], month [m]) applying approach 1 (A1) and approach 2 (A2).

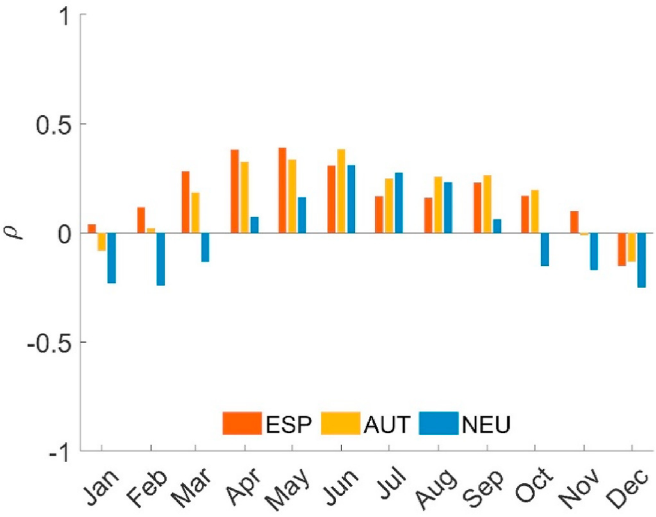


Fig. 16. Seasonality: Hourly wind speed and HDH correlation coefficient (ρ) per month (A1).

Table 12
Hourly wind speed and HDH correlation between locations in northern Europe (top numbers 1–6 refer to locations as numbered on the left)

			HDH					
No.	Location		1	2	3	4	5	6
1	Bodø	**Wind speed**	0.27	0.22	0.35	0.14	0.27	0.08
2	Oslo		0.32	0.28	0.34	0.23	0.27	0.10
3	Trondheim		0.18	0.14	0.26	0.08	0.21	0.08
4	Gothenburg		0.24	0.18	0.26	0.17	0.26	0.12
5	Kiruna		0.22	0.21	0.20	0.18	0.37	0.30
6	Stockholm		0.11	0.09	0.08	0.10	0.25	0.33

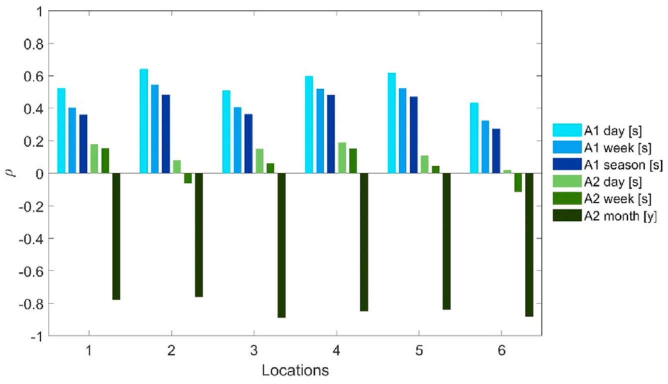


Fig. 17. Spain: Solar irradiance and HDH correlation coefficient (ρ) in winter season [s] applying approach 1 (A1) and approach 2 (A2) for the locations 1–6 as described in Section 2.1 (monthly correlation across the whole year [y]).

data. Throughout the year, monthly solar irradiance and HDH correlate on a strong negative basis in all locations. Like in Spain, also in Austria hourly HDH and solar irradiance patterns match best on a daily basis (A1) after adjustment for the time lag.

The analysis of the HDH and solar irradiance correlations for winter between the locations does not show any benefit through interaction between the locations.

3. Northern Europe

The hourly correlation between solar irradiance and HDH (A1) is much lower in northern than in central and southern Europe for all time-periods. This can be explained by the low solar irradiance level and higher temperature dependent heating demand. The difference between the time-periods in winter season, however, is similar with stronger results for the daily than for the weekly and seasonal time-period (see Fig. 19).

In contrast to the other European regions, daily and weekly storage (A2) here lead to weak positive results. Nevertheless, monthly storage again shows the expected strong negative correlation between heating needs and solar irradiance throughout the year. Eventually, the use of solar energy for heating needs seems less feasible in northern Europe than towards the south.

Kiruna (5) in the north of Sweden benefits the most from an external supply of wind energy from Bodø (1) and Trondheim (3) in northern and central Norway but also Gothenburg (4) in the far south of Sweden (see Table 13). The exchange with Gothenburg would require longer distance transmission and only accounts for a moderate correlation. All relationships are at most moderate and therefore the value of spatial integration is interpreted to be low.

4. Region comparison

According to Fig. 20, the lag adjusted hourly solar irradiance and HDH correlation is moderate on daily basis in Spain and Austria and weak in northern Europe and decreases towards longer time-periods in all regions (A1). This means either that the weekly and seasonal correlation are characterised by stronger variability, leading to a lower average result, or the correlation is weak throughout. In general, in Spain hourly solar irradiance and HDH fit best, while in Austria and specifically northern Europe more flexibility on all time scales is required. In northern Europe daily and weekly storage (A2) lead to a fit of the demand and supply patterns which is similar to the hourly correlation per day (A1 winter [d]). In Austria and Spain, the daily and weekly totals assuming storage do not (A2) match as much. Monthly solar irradiance and HDH show a strong negative correlation as described earlier.

The seasonality of the hourly correlation between HDH and solar irradiance shows moderate positive results throughout the year (see Fig. 21). This indicates that less storage is required to use solar power to cover HDH in winter than for wind power. The correlation is lower in Austria and NEU than in Spain, but all three regions show a very similar pattern with the highest results in April and a dip in July and August. During the winter months, the correlation is relatively weak in Austria and northern Europe.

3.2. Climate change effect

3.2.1. Impact on the weather variables

To draw conclusions on the climate change effect with respect to the weather variables and their relationships, we use projected weather data by CMIP5 for the scenario RCP 4.5 (see Section 2.5). The analysis is carried out for one exemplary location per climate region: Madrid, Vienna and Stockholm. This Section first analyses the overall development of the weather variables with a 5-year trend. Since the data only provides daily temporal resolution, we will talk of heating and cooling degree-days in the following (HDD and CDD). The second part will evaluate the correlation coefficients from 2020 to 2100.

Fig. 22 describes the relative change in the mean temperature towards 2100 compared to 2020. For all three areas, a clear increasing trend can be observed. In Madrid, the projected CMIP5 weather data estimates an increase in the mean temperature of more than 10% until 2100. Additionally, the maximum temperature

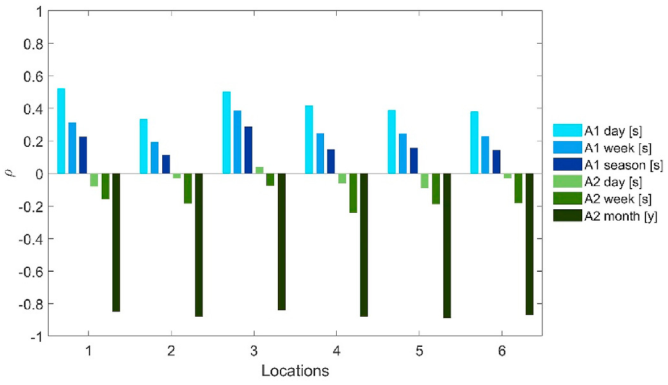


Fig. 18. Austria: Solar irradiance and HDH correlation coefficient (ρ) in winter season [s] applying approach 1 (A1) and approach 2 (A2) for the locations 1–6 as described in Section 2.1 (monthly correlation across the whole year [y]).

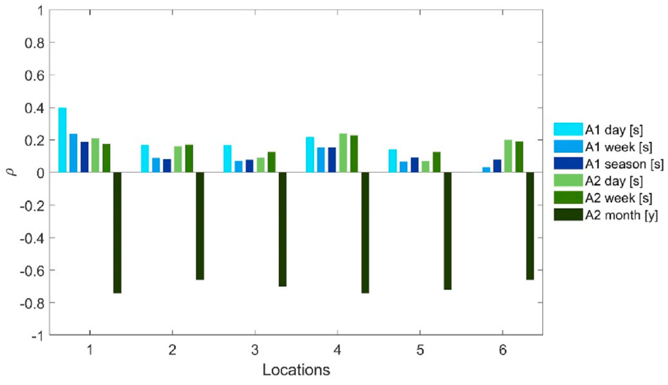


Fig. 19. Northern Europe: Solar irradiance and HDH correlation coefficient (ρ) in winter season [s] applying approach 1 (A1) and approach 2 (A2) for the locations 1–6 as described in Section 2.1 (monthly correlation across the whole year [y]).

Table 13
Hourly solar irradiance and HDH correlation between locations during summer season in northern Europe (top numbers 1–6 refer to locations as numbered on the left)

			HDH					
No.	Location		1	2	3	4	5	6
1	Bodø	**Solar irradiance**	0.46	0.22	0.33	0.48	0.48	0.32
2	Oslo		0.37	0.16	0.28	0.38	0.41	0.27
3	Trondheim		0.46	0.25	0.33	0.45	0.48	0.34
4	Gothenburg		0.45	0.19	0.31	0.43	0.45	0.28
5	Kiruna		0.40	0.17	0.26	0.42	0.39	0.29
6	Stockholm		0.42	0.20	0.30	0.40	0.35	0.14

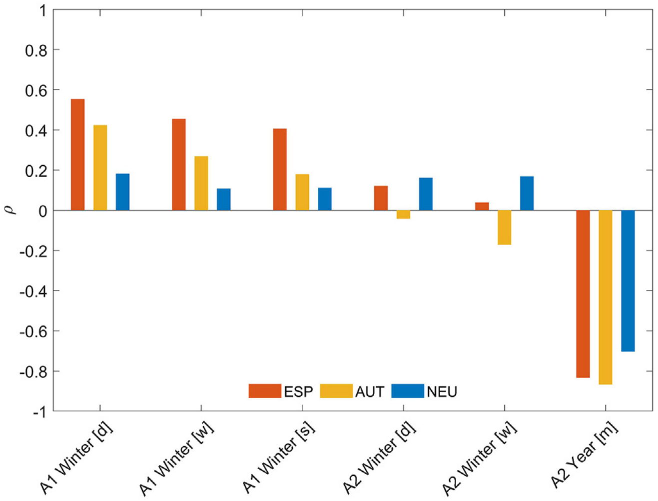


Fig. 20. Hourly solar irradiance and HDH correlation coefficient (ρ) per climate region for different time-periods (day [d], week [w], season [s], month [m]) applying approach 1 (A1) and approach 2 (A2).

rises by 8% in the last third of the 21st century. This is specifically concerning because of the overall high temperature level in Madrid, compared to that of Vienna, which experiences a similar relative development. The long-term trend also shows a significant mean and maximum temperature increase in Stockholm of about 5% towards 2100. The minimum temperature level rises most remarkably (5–6 fold) in Madrid, while Vienna and Stockholm experience a rise of about 45%.

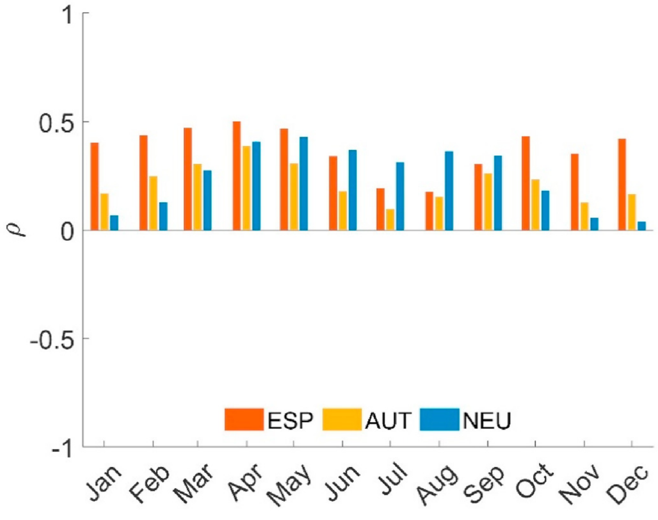


Fig. 21. Seasonality: Hourly wind speed and HDH correlation coefficient (ρ) per month (A1).

As described in the introduction, solar irradiance is subject to decadal brightening and dimming, which may explain the less obvious development of solar irradiance from decade to decade. The long-term trend, shown in the relative change of the mean solar irradiance compared to 2020, however, indicates an increase at least for Madrid (see Fig. 23). In Vienna and Stockholm, the development of solar irradiance seems to be rather variable and often lower compared to 2020. Madrid and Vienna show several time-periods with higher mean wind speed compared to 2020 as described in Fig. 24. Furthermore, a slow but steady increase can be observed in the maximum wind speed in Stockholm.

The trend in the HDD towards 2100 shows the expected significant decrease, with the strongest relative change compared to 2020 in Madrid of almost 20% followed by Vienna at about 10% (see Fig. 25). In the long term, cooling is still only expected to be relevant for Vienna and Madrid. The increase in the mean CDD towards 2100 in Fig. 26 is substantial in both locations with about 180% and 250% respectively compared to 2020, while also the maximum CDD increase by around 45%.

3.2.2. Impact on the correlation coefficients

In the following, the absolute correlation coefficients based on the projected data between 2020 and 2100 are analysed for the selected location per climate region: Madrid, Vienna and Stockholm. With the daily resolution for the projected weather data, the results are not directly comparable with the more detailed hourly resolution of the historic correlation analysis. The herein conducted analysis of daily data assumes daily storage. Nevertheless, the development of the correlation coefficients smoothed across ten-year periods shows various trends caused by climate change as described earlier up to 2100. The correlation coefficient between CDD and solar irradiance in Madrid and Vienna for the expected

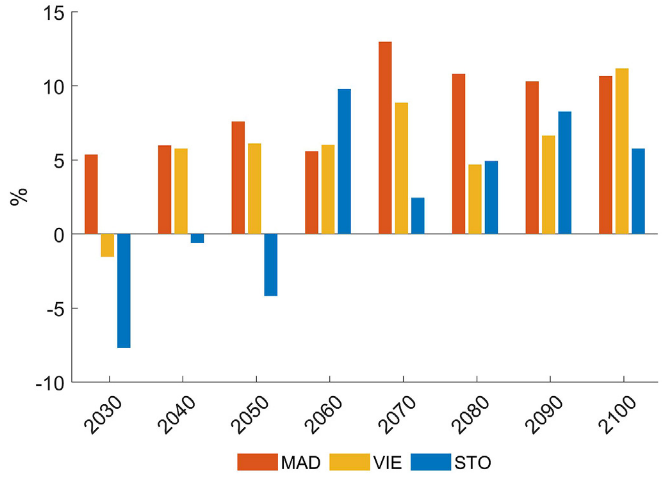


Fig. 22. Relative change in mean temperature compared to 2020.

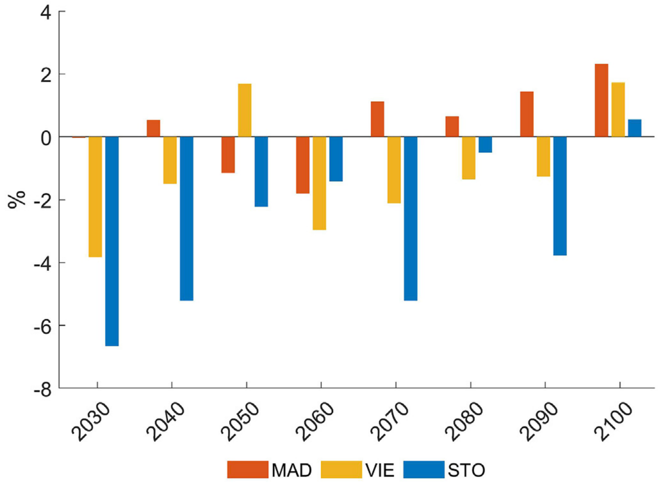


Fig. 23. Relative change in mean solar irradiance compared to 2020

weather data between 2020 and 2100 is described for the summer season in Fig. 27.

As was outlined in Section 3.2.1, the mean temperature is expected to rise significantly in Vienna and Spain for the considered RCP4.5 projections, while at the same time mean solar irradiance tends to increase slightly at these two locations. This also explains the increase of the correlation between CDD and SR, with a higher amount of relevant cooling days by exceeding the cooling temperature of 24 °C more frequently. The increase seems to be slightly more obvious in Vienna, which could be explained by the lower overall temperature level, whereas the cooling needs have already been frequent in Madrid historically. One important development towards 2100 is an extension of cooling needs into September as an extension of the summer, which is again more relevant in Madrid.

While the development of wind speed did not show any real trend, HDD are expected to decrease remarkably at all three locations and most significantly in Spain. This seems to reduce the negative correlation between weekly aggregated HDD and wind speed (see Fig. 28). Fig. 29, however, shows the correlation between daily HDD and solar irradiance in winter, which shows a slightly decreasing trend. With HDD decreasing and solar irradiance tending to increase, their patterns match less in the future and the

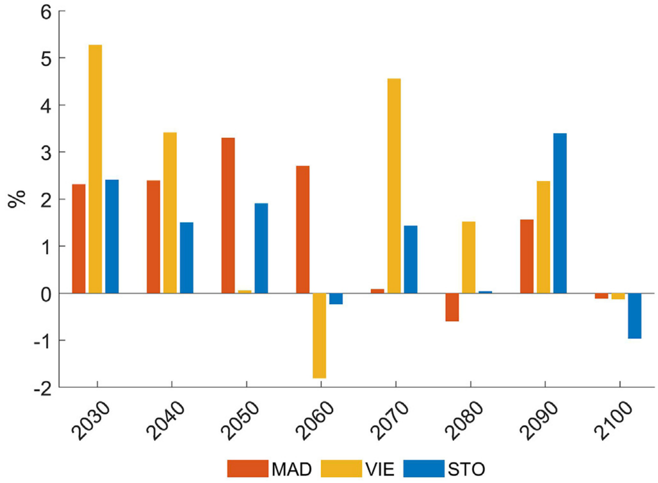


Fig. 24. Relative change in mean wind speed compared to 2020.

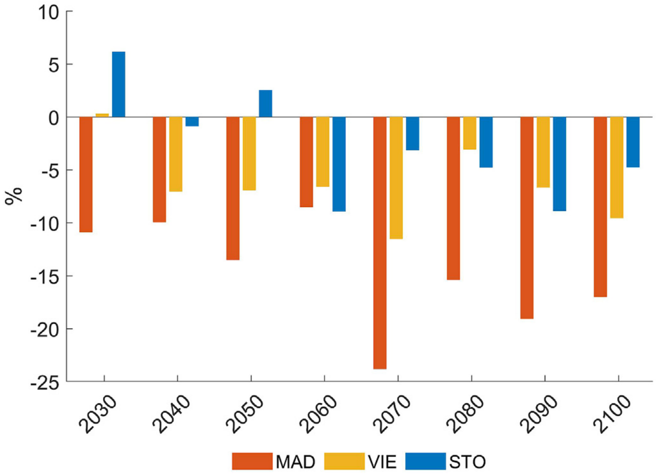


Fig. 25. Relative change in mean HDD compared to 2020

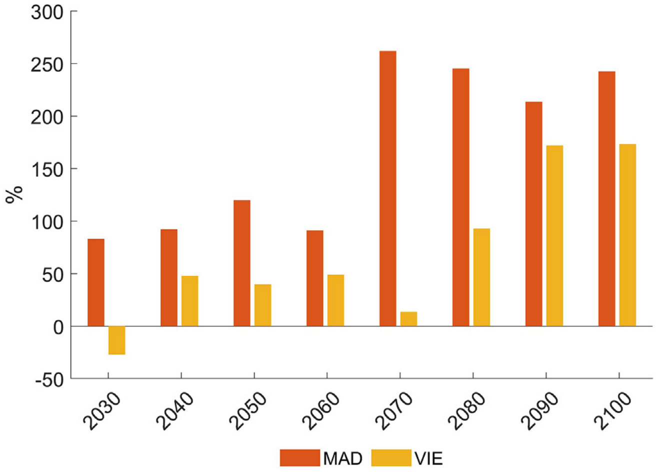


Fig. 26. Relative change in mean CDD change compared to 2020.

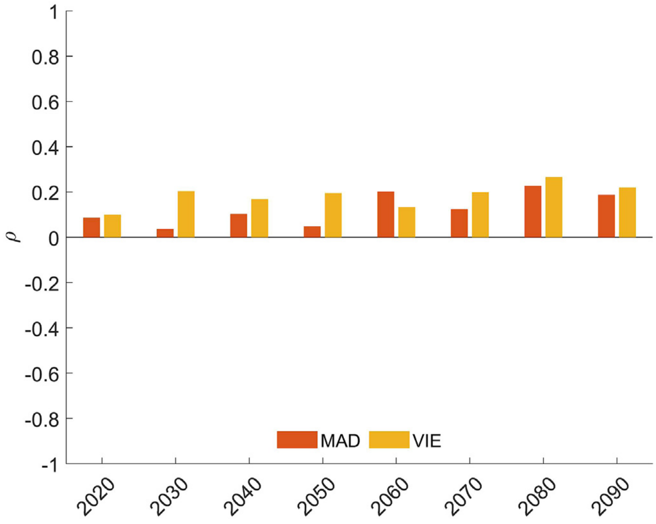


Fig. 27. Projected average CDD and solar irradiance correlation in summer based on daily data (2020–2100).

correlation between HDD and solar irradiance is expected to decrease in winter significantly in all three locations.

In central and specifically in southern Europe, climate change shifts the focus from HDD towards CDD, which means that in winter, less energy will be required to supply heating needs. This will even be supported by higher building standards. In summer, however, where renewable energy from the sun is conveniently available and correlates directly with the temperature increase, cooling needs can be supplied without significant storage needs. The temperature dependent cooling needs will increase substantially with the mean and maximum temperature increase.

3.2.3. Discussion

The steepest increase in the mean and maximum temperatures is expected in Madrid and at the same time solar irradiance is expected to increase. This would lead to higher solar resource availability to cover higher cooling needs in southern Europe, which is favourable. The correlation between solar irradiance and CDD increases, specifically in Madrid, from 0.2 to almost 0.3. The results are still low given the rough daily time resolution. Vienna experiences the highest impact on this relationship from 0.1 to almost 0.3. An increase in the maximum temperature with an already high level as in Madrid, nevertheless, can also have a negative impact on the efficiency of PV power systems as described in Section 1 [53]. This would yet again require an increase in the installed capacity for the same output. In Austria, temperatures are also expected to increase while for solar irradiance no obvious trend is visible. A measure to avoid the direct representation of warmer temperatures in the energy demand for cooling is the improvement of building standards in form of insulation and similar measures to prevent buildings form heating up, such as shading through trees, which also provides cooling outside the building. Especially for the warming temperatures in Madrid, with an increasing amount of days passing the cooling temperature of 24 °C, this approach could be one solution to limit and adapt to the expected 200% increase in CDD in the long term.

The projected increase of the minimum temperature could lead to an increased potential of wind power generation in northern Europe, which is often subject to icing in very cold temperatures, as described in Section 1 [58]. This is favourable at least to meet a growing amount of the still substantial heating needs with a renewable power source. In Madrid, HDD are expected to decrease at about 20% towards 2100 compared to 2020, followed by Vienna with a 10% decrease.

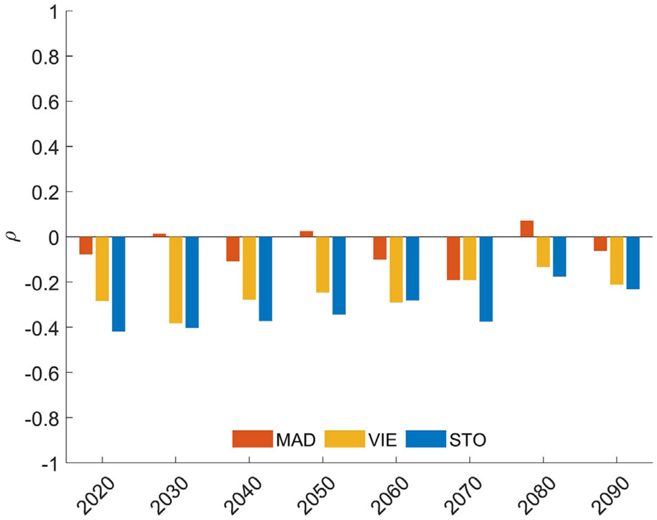


Fig. 28. Projected average HDD and wind speed correlation in winter based on weekly aggregated data (2020–2100)

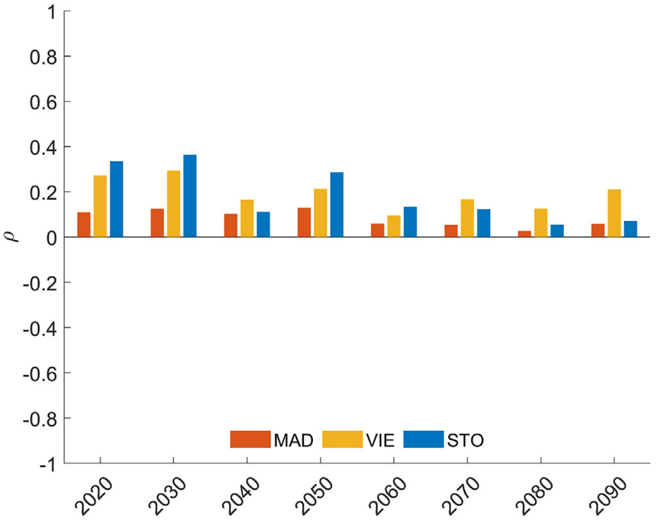


Fig. 29. Projected average HDD and solar irradiance correlation in winter based on daily data (2020–2100).

An expected decrease in the energy needs for heating through climate change will even be exaggerated by an improvement in building standards, which could lower the heating threshold due to better building insulation.

The correlation between HDD and wind speed tends to decrease slightly, similarly in all three cities with a decrease in cold days below the heating temperature of 12 °C.

3.3. Limitations of the study

This work analyses the correlation between its main supply sources wind speed and solar irradiance—without estimating potential power production or defining areas of potential wind power plants and urban areas with limited technical wind power potential—and HDH and CDH as temperature based heating and cooling needs without estimating final energy demand. Since this work is based on weather variables only, implications for actual energy demand need consideration of additional parameters, such as energy efficiency measures on building insulation, comfort during longer periods of heat and cold, impacts of other energy demand sectors with progressive integration of the energy system.

The selection of locations has not been associated to the location of wind plants or specific demand locations, but was oriented towards covering a broad set of historic average solar irradiance and wind speed levels, directions across the country, inland and coastal locations, choosing capital cities. The differences between locations can also be connected by the electricity grid, both on national level and with connections to other power systems, which is not considered in the paper. With respect to that, our approach tries to obtain the raw or pure correlations between the natural source availability and temperature dependent heating and cooling needs. Another limitation is that we only consider a subset of locations, which may not exactly represent the characteristics of the energy systems involved.

The identified time lag between solar irradiance or wind speed and CHD or HDH is based on an average calculation across all locations. We did not detect a significant difference for different locations in our analysis of wind speed or solar irradiance patterns and the patterns of heating and cooling needs based on temperature. Our work did not reveal a significant improvement of the local correlation between solar irradiance or wind speed profiles and CDH or HDH profiles by investigations between locations in most cases (see Table 10 - Table 13).

4. Conclusions

This work was conducted to address the research gap in the analysis of the correlation between potential natural energy sources, wind speed and solar irradiance, and — motivated by their interrelations with climate — temperature derived heating and cooling needs not only historically but also for future projections. It aims at proving the hypothesis that there is an obvious relationship between solar irradiance and wind speed and temperature related heating and cooling needs. The results emphasize the importance of considering differences in climate regions when it comes to analysing the relationship between VRE and energy demand. With the case studies in Spain - southern Europe, Austria – central Europe and Norway and Sweden – northern Europe, the correlations were analysed in three very different climates.

Our results confirm that the hourly correlation between solar irradiance and CDH as a consequence of rising temperatures is moderate to strong on a daily basis in Austria and Spain reaching a strong coefficient of 0.8 in summer in some locations in Spain. The correlation between solar irradiance and heating needs so far has hardly been investigated so far but reveals substantial value in renewable energy systems. After accounting for the time lag between the peak of heating needs in the morning in form of a temperature decrease and the solar irradiance peak at noon, Spain and Austria achieved moderate (0.40–0.59) results in winter. The relationship between wind speed and temperature derived heating needs, however, turned out to be more complex, specifically in winter — the strongest heating period. The analysis did not show an obvious correlation. Only monthly aggregated wind speed and HDH data across the whole year match moderately at least in Spain (0.41–0.56) and northern Europe (0.39–0.58). Assuming a potential distribution of wind speed or solar irradiance among the locations via the energy grid, our correlation results show that its value is limited apart from some cases in northern Europe.

Understanding these relationships provides a basis for appropriate planning and forecasting in smart energy systems, with an aim to use large-scale renewable energy sources, which naturally cause temperature changes, most efficiently for heating and cooling needs. With the analysis of the climate projections provided in daily resolution and development of the correlations in the future, the time-period for storage of wind and solar power can be assessed. Madrid is expected to experience the strongest mean temperature increase (about 10%) towards 2100, accompanied by growing solar irradiance. A decrease in the yearly HDD and an even more substantial increase in CDD can be estimated in all three climate regions, most substantially in Madrid (−20% HDD and +100% CDD), followed by Vienna and Stockholm. The increase in CDD, through temperatures exceeding the cooling threshold more frequently, causes an increase in the correlation with solar irradiance. At the same time, the correlation between solar irradiance and HDD is expected to decrease in all regions. From the supply side, the decreasing temperatures in northern Europe might lead to less icing and reduce its negative impact on wind power efficiency. Since this study is based on the mere natural resources and temperature-derived heating and cooling needs, an investigation of consequent energy demand needs to consider efficiency gains as much as potential intensifications of the energy need through, e.g. very long heat periods in summer or PV system efficiency losses caused by very high temperatures. Smart energy systems, therefore, should embrace the positive correlation between solar irradiance and CDH as well as HDH, and account for at least monthly storage of potential wind power to efficiently use VRE for heating and cooling.

Author contributions

Conceptualization, Jasmine Ramsebner, Pedro Linares, Reinhard Haas; Formal analysis, Jasmine Ramsebner; Funding acquisition, Methodology, Jasmine Ramsebner, Pedro Linares, Reinhard Haas; Project administration, Software, Jasmine Ramsebner; Supervision, Pedro Linares; Visualization, Jasmine Ramsebner; Writing—original draft, Jasmine Ramsebner; Writing—review & editing, Jasmine Ramsebner, Pedro Linares, All authors have read and agreed to the published version of the manuscript.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2021.100038.

References

[1] Bremen LV. Large-scale variability of weather dependent renewable energy sources. In: Troccoli A, editor. Management of weather and climate risk in the energy industry. NATO science for peace and security series C: environmental security. Dordrecht: Springer Netherlands; 2010, ISBN 978-90-481-3691-9. p. 189–206.

[2] Engeland K, Borga M, Creutin J-D, François B, Ramos M-H, Vidal J-P. Space-time variability of climate variables and intermittent renewable electricity production – a review. Renew Sustain Energy Rev 2017;79:600–17. https://doi.org/10.1016/j.rser.2017.05.046.

[3] Emeis S. Wind energy meteorology: atmospheric physics for wind power generation. Springer; 2018, ISBN 978-3-319-72859-9.

[4] Iqbal M. An introduction to solar radiation. Elsevier; 2012, ISBN 978-0-323-15181-8.

[5] Vindel JM, Polo J. Intermittency and variability of daily solar irradiation. Atmos Res 2014;143:313–27. https://doi.org/10.1016/j.atmosres.2014.03.001.

[6] Castillejo-Cuberos A, Escobar R. Understanding solar resource variability: an in-depth analysis, using Chile as a case of study. Renew Sustain Energy Rev 2020;120:109664. https://doi.org/10.1016/j.rser.2019.109664.

[7] Tomson T, Tamm G. Short-term variability of solar radiation. Sol Energy 2006;80:600–6. https://doi.org/10.1016/j.solener.2005.03.009.

[8] Kiviluoma J, Holttinen H, Weir D, Scharff R, Söder L, Menemenlis N, Cutululis NA, Lopez ID, Lannoye E, Estanqueiro A, et al. Variability in large-scale wind power generation. Wind Energy 2016;19:1649–65. https://doi.org/10.1002/we.1942.

[9] Dai A, Deser C. Diurnal and semidiurnal variations in global surface wind and divergence fields. J Geophys Res 1999;104:31109–25. https://doi.org/10.1029/1999JD900927.

[10] Cabello M, Orza JAG. Wind speed analysis in the province of alicante, Spain. Potential for small-scale wind turbines. Renew Sustain Energy Rev 2010;14: 3185–91. https://doi.org/10.1016/j.rser.2010.07.002.

[11] Wooten R Statistical. Analysis of the relationship between wind speed, pressure and temperature. J Appl Sci 2011;11. https://doi.org/10.3923/jas.2011.2712.2722.

[12] Widén J, Carpman N, Castellucci V, Lingfors D, Olauson J, Remouit F, Bergkvist M, Grabbe M, Waters R. Variability assessment and forecasting of renewables: a review for solar, wind, wave and tidal resources. Renew Sustain Energy Rev 2015;44:356–75. https://doi.org/10.1016/j.rser.2014.12.019.

[13] Widén J. Correlations between large-scale solar and wind power in a future scenario for Sweden. IEEE Transactions on Sustainable Energy 2011;2:

177–84. https://doi.org/10.1109/TSTE.2010.2101620.

[14] Bett PE, Thornton HE. The climatological relationships between wind and solar energy supply in Britain. Renew Energy 2016;87:96–110. https://doi.org/10.1016/j.renene.2015.10.006.

[15] Jerez S, Trigo RM, Sarsa A, Lorente-Plazas R, Pozo-Vázquez D, Montávez JP. Spatio-temporal complementarity between solar and wind power in the iberian Peninsula. Energy Procedia 2013;40:48–57. https://doi.org/10.1016/j.egypro.2013.08.007.

[16] Lamb HH. Types and spells of weather around the year in the British Isles : annual trends, seasonal structure of the year, singularities. Q J R Meteorol Soc 1950;76:393–429. https://doi.org/10.1002/qj.49707633005.

[17] O'Hare G, Sweeney J. Lamb's circulation types and British weather: an evaluation. Geography 1993;78:43–60.

[18] Pardo A, Meneu V, Valor E. Temperature and seasonality influences on Spanish electricity load. Energy Econ 2002;24:55–70. https://doi.org/10.1016/S0140-9883(01)00082-2.

[19] Bessec M, Fouquau J. The non-linear link between electricity consumption and temperature in Europe: a threshold panel approach. Energy Econ 2008;30: 2705–21. https://doi.org/10.1016/j.eneco.2008.02.003.

[20] Hekkenberg M, Benders RMJ, Moll HC, Schoot Uiterkamp AJM. Indications for a changing electricity demand pattern: the temperature dependence of electricity demand in The Netherlands. Energy Pol 2009;37:1542–51. https://doi.org/10.1016/j.enpol.2008.12.030.

[21] Le Comte DM, Warren HE. Modeling the impact of summer temperatures on national electricity consumption. 1962-1982 J Appl Meteorol 1981;20: 1415–9.

[22] Sailor DJ, Muñoz JR. Sensitivity of Electricity and Natural Gas Consumption to Climate in the U.S.A.—Methodology and Results for Eight States. Energy 1997;22:987–98. https://doi.org/10.1016/S0360-5442(97)00034-0.

[23] Lam JC, Tang HL, Li DHW. Seasonal Variations in Residential and Commercial Sector Electricity Consumption in Hong Kong. Energy 2008;33:513–23. https://doi.org/10.1016/j.energy.2007.10.002.

[24] Lam JC. Climatic and Economic Influences on Residential Electricity Consumption. Energy Convers Manag 1998;39:623–9. https://doi.org/10.1016/S0196-8904(97)10008-5.

[25] Al-Zayer J, Al-Ibrahim AA. Modelling the Impact of Temperature on Electricity Consumption in the Eastern Province of Saudi Arabia. J Forecast 1996;15: 97–106. https://doi.org/10.1002/(sici)1099-131x(199603)15:2<97::aid-for608>3.0.co;2-l.

[26] Wangpattarapong K, Maneewan S, Ketjoy N, Rakwichian W. The Impacts of Climatic and Economic Factors on Residential Electricity Consumption of Bangkok Metropolis. Energy Build 2008;40:1419–25. https://doi.org/10.1016/j.enbuild.2008.01.006.

[27] Jovanović S, Savić S, Bojić M, Djordjević Z, Nikolić D. The Impact of the Mean Daily Air Temperature Change on Electricity Consumption. Energy 2015;88: 604–9. https://doi.org/10.1016/j.energy.2015.06.001.

[28] Eto JH. On Using Degree-Days to Account for the Effects of Weather on Annual Energy Use in Office Buildings. Energy Build 1988;12:113–27. https://doi.org/10.1016/0378-7788(88)90073-4.

[29] Hart M, de Dear R. Weather Sensitivity in Household Appliance Energy End-Use. Energy Build 2004;36:161–74. https://doi.org/10.1016/j.enbuild.2003.10.009.

[30] Quayle RG, Diaz HF. Heating Degree Day Data Applied to Residential Heating Energy Consumption. 1962-1982 J Appl Meteorol 1980;19:241–6.

[31] Bell WP, Wild P, Foster J, Hewson M. Wind Speed and Electricity Demand Correlation Analysis in the Australian National Electricity Market: Determining Wind Turbine Generators' Ability to Meet Electricity Demand without Energy Storage. Econ Anal Pol 2015;48:182–91. https://doi.org/10.1016/j.eap.2015.11.009.

[32] Coughlin K, Murthi A, Eto J. Multi-Scale Analysis of Wind Power and Load Time Series Data. Renew Energy 2014;68:494–504. https://doi.org/10.1016/j.renene.2014.02.011.

[33] Coughlin K, Eto JH. Analysis of wind power and load data at multiple time scales. LBNL-4147E; 2010. p. 1004166.

[34] Sinden G. Characteristics of the UK Wind Resource: Long-Term Patterns and Relationship to Electricity Demand. Energy Pol 2007;35:112–27. https://doi.org/10.1016/j.enpol.2005.10.003.

[35] Holttinen H. Hourly Wind Power Variations in the Nordic Countries. Wind Energy 2005;8:173–95. https://doi.org/10.1002/we.144.

[36] Holttinen H, Rissanen S, Larsén XG, Løvholm AL. Wind and load variability in the nordic countries. VTT Technical Research Centre of Finland; 2013, ISBN 978-951-38-7986-0.

[37] Leahy PG, Foley AM. Wind Generation Output during Cold Weather-Driven Electricity Demand Peaks in Ireland. Energy 2012;39:48–53. https://doi.org/10.1016/j.energy.2011.07.013.

[38] Suomalainen K, Pritchard G, Sharp B, Yuan Z, Zakeri G. Correlation Analysis on Wind and Hydro Resources with Electricity Demand and Prices in New Zealand. Appl Energy 2015;137:445–62. https://doi.org/10.1016/j.apenergy.2014.10.015.

[39] Ueckerdt F, Brecha R, Luderer G. Analyzing Major Challenges of Wind and Solar Variability in Power Systems. Renew Energy 2015;81:1–10. https://doi.org/10.1016/j.renene.2015.03.002.

[40] Coker P, Barlow J, Cockerill T, Shipworth D. Measuring Significant Variability Characteristics: An Assessment of Three UK Renewables. Renew Energy 2013;53:111–20. https://doi.org/10.1016/j.renene.2012.11.013.

[41] Schaeffer R, Szklo AS, Pereira de Lucena AF, Moreira Cesar Borba BS, Pupo Nogueira LP, Fleming FP, Troccoli A, Harrison M, Boulahya MS. Energy Sector Vulnerability to Climate Change: A Review. Energy 2012;38:1–12. https://doi.org/10.1016/j.energy.2011.11.056.

[42] Wild M, Trüssel B, Ohmura A, Long CN, König-Langlo G, Dutton EG, Tsvetkov A. Global Dimming and Brightening: An Update beyond 2000. J Geophys Res: Atmosphere 2009;114. https://doi.org/10.1029/2008JD011382.

[43] Tobin I, Vautard R, Balog I, Bréon F-M, Jerez S, Ruti PM, Thais F, Vrac M, Yiou P. Assessing Climate Change Impacts on European Wind Energy from ENSEMBLES High-Resolution Climate Projections. Climatic Change 2015;128: 99–112. https://doi.org/10.1007/s10584-014-1291-0.

[44] Pašičko R, Branković Č, Šimić Z. Assessment of Climate Change Impacts on Energy Generation from Renewable Sources in Croatia. Renew Energy 2012;46:224–31. https://doi.org/10.1016/j.renene.2012.03.029.

[45] Tobin I, Greuell W, Jerez S, Ludwig F, Vautard R, van Vliet MTH, et al. Vulnerabilities and Resilience of European Power Generation to 1.5\hspace0.167em°C, 2\hspace0.167em°C and 3\hspace0.167em°C Warming. Environ Res Lett 2018;13:044024. https://doi.org/10.1088/1748-9326/aab211.

[46] Wang Y, Yang Y, Zhao N, Liu C, Wang Q. The Magnitude of the Effect of Air Pollution on Sunshine Hours in China. J Geophys Res: Atmosphere 2012;117. https://doi.org/10.1029/2011JD016753.

[47] Cutforth HW, Judiesch D. Long-Term Changes to Incoming Solar Energy on the Canadian Prairie. Agric For Meteorol 2007;145:167–75. https://doi.org/10.1016/j.agrformet.2007.04.011.

[48] Sanchez-Lorenzo A, Calbó J, Martin-Vide J. Spatial and Temporal Trends in Sunshine Duration over Western Europe (1938-2004). Journal of Climate - J CLIMATE 2008;21. https://doi.org/10.1175/2008JCLI2442.1.

[49] Sanchez-Lorenzo A, Brunetti M, Calbó J, Martin-Vide J. Recent Spatial and Temporal Variability and Trends of Sunshine Duration over the Iberian Peninsula from Homogenized Dataset. J Geophys Res 2007;112. https://doi.org/10.1029/2007JD008677.

[50] Wild M, Gilgen H, Roesch A, Ohmura A, Long CN, Dutton EG, Forgan B, Kallis A, Russak V, Tsvetkov A. From Dimming to Brightening: Decadal Changes in Solar Radiation at Earth's Surface. Science 2005;308:847–50. https://doi.org/10.1126/science.1103215.

[51] Wild M. Global Dimming and Brightening: A Review. J Geophys Res: Atmosphere 2009;114. https://doi.org/10.1029/2008JD011470.

[52] Stanhill G, Cohen S. Global Dimming: A Review of the Evidence for a Widespread and Significant Reduction in Global Radiation with Discussion of Its Probable Causes and Possible Agricultural Consequences. Agric For Meteorol 2001;107:255–78. https://doi.org/10.1016/S0168-1923(00)00241-0.

[53] Wilbanks T, Bhatt V, Bilello D, Bull S, Ekmann J, Horak W, Huang YJ, Levine MD, Sale MJ, Schmalzer D, et al. Effects of climate change on energy production and use in the United States. *Climate change.* 2008.

[54] Wild M, Folini D, Henschel F, Fischer N, Müller B. Projections of Long-Term Changes in Solar Radiation Based on CMIP5 Climate Models and Their Influence on Energy Yields of Photovoltaic Systems. Sol Energy 2015;116:12–24. https://doi.org/10.1016/j.solener.2015.03.039.

[55] Santos JA, Rochinha C, Liberato MLR, Reyers M, Pinto JG. Projected Changes in Wind Energy Potentials over Iberia. Renew Energy 2015;75:68–80. https://doi.org/10.1016/j.renene.2014.09.026.

[56] Breslow PB, Sailor DJ. Vulnerability of Wind Power Resources to Climate Change in the Continental United States. Renew Energy 2002;27:585–98. https://doi.org/10.1016/S0960-1481(01)00110-0.

[57] Watson S. Quantifying the Variability of Wind Energy. WIREs Energy and Environment 2014;3:330–42. https://doi.org/10.1002/wene.95.

[58] Pryor SC, Barthelmie RJ. Climate Change Impacts on Wind Energy: A Review. Renew Sustain Energy Rev 2010;14:430–7. https://doi.org/10.1016/j.rser.2009.07.028.

[59] Totschnig G, Hirner R, Müller A, Kranzl L, Hummel M, Nachtnebel H-P, Stanzel P, Schicker I, Formayer H. Climate Change Impact and Resilience in the Electricity Sector: The Example of Austria and Germany. Energy Pol 2017;103: 238–48. https://doi.org/10.1016/j.enpol.2017.01.019.

[60] Larsen MAD, Petrović S, Radoszynski AM, McKenna R, Balyk O. Climate Change Impacts on Trends and Extremes in Future Heating and Cooling Demands over Europe. Energy Build 2020;226:110397. https://doi.org/10.1016/j.enbuild.2020.110397.

[61] Silva S, Soares I, Pinho C. Climate Change Impacts on Electricity Demand: The Case of a Southern European Country. Util Pol 2020;67:101115. https://doi.org/10.1016/j.jup.2020.101115.

[62] Sailor DJ. Relating Residential and Commercial Sector Electricity Loads to Climate—Evaluating State Level Sensitivities and Vulnerabilities. Energy 2001;26:645–57. https://doi.org/10.1016/S0360-5442(01)00023-8.

[63] Ahmed T, Muttaqi KM, Agalgaonkar AP. Climate Change Impacts on Electricity Demand in the State of New South Wales, Australia. Appl Energy 2012;98: 376–83. https://doi.org/10.1016/j.apenergy.2012.03.059.

[64] Trotter IM, Bolkesjø TF, Féres JG, Hollanda L. Climate Change and Electricity Demand in Brazil: A Stochastic Approach. Energy 2016;102:596–604. https://doi.org/10.1016/j.energy.2016.02.120.

[65] Fan J-L, Hu J-W, Zhang X. Impacts of Climate Change on Electricity Demand in China: An Empirical Estimation Based on Panel Data. Energy 2019;170:880–8. https://doi.org/10.1016/j.energy.2018.12.044.

[66] Dowling P. The Impact of Climate Change on the European Energy System. Energy Pol 2013;60:406–17. https://doi.org/10.1016/j.enpol.2013.05.093.

[67] Girardi G, Mora JCR, Llamas PL. La adaptación del sector energético al cambio

climático. Ekonomiaz: Revista vasca de economía 2020:112–43.

[68] Jrc Photovoltaic Geographical Information System (Pvgis). European Commission. Available online, https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY. [Accessed 27 November 2020]. accessed on.

[69] Global Wind Atlas. Available online, https://globalwindatlas.info. [Accessed 27 November 2020]. accessed on.

[70] Global Solar Atlas. Available online, https://globalsolaratlas.info/map. [Accessed 27 November 2020]. accessed on.

[71] eurostat. Energy Statistics - Cooling and Heating Degree Days. Available online, https://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm. [Accessed 7 October 2020]. accessed on.

[72] Evans JD. Straightforward statistics for the behavioral sciences. Pacific Grove: Brooks/Cole Pub. Co.; 1996, ISBN 978-0-534-23100-2.

[73] European Comission (Ec). CMIP5 Daily Data on Single Levels. Available online, https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip5-daily-single-levels?tab=form. [Accessed 25 February 2021]. accessed on.

[74] Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, et al. The next Generation of Scenarios for Climate Change Research and Assessment. Nature 2010;463:747–56. https://doi.org/10.1038/nature08823.