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HEATING AND COOLING DEGREE-DAYS VS CLIMATE CHANGE IN YEARS 1979-2021. EVIDENCE FROM THE EUROPEAN UNION AND NORWAY

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ABSTRACT: Energy consumption depends strongly on weather conditions. Thus, to formulate energy-related policy goals, it is crucial to monitor changes related to the heating degree days (HDD) and cooling degree days (CDD) – widely applied indicators of climate change. The study investigated the impact that climate change (global warming) exerted on the number of HDD and CDD, as well as the weather-related final energy consumption of the European households (EU-27 and Norway), based on data derived from Eurostat for the period 1979-2021. The results indicate that the changes in HDD and CDD constituted non-linear functions of the country's average temperature, with the largest percentage changes observed in the warmest (in the case of HDD) and the coldest (in the case of CDD) portion of European countries. As indicated by estimations based on first-difference linear regression models, climate change has contributed so far to the net decrease in weather-related energy consumption of households.

KEYWORDS: heating degree-days, cooling degree-days, climate change, energy consumption, energy security, sustainable development

Introduction

Human activity, especially that which has been taking place since the beginning of the last century, causes mega-scale changes to the land, oceans and atmosphere, with dramatic and long-term effects on human life, living organisms and the environment. The past two years have seen four key climate change indicators set new record highs: greenhouse gas concentrations, rising sea levels, ocean warming, and ocean acidification. A significant contribution to the effective treatment of such a crisis is expected to be made by ending our dependence on energy produced from fossil fuels since it is one of the main causes of the observed climate change.

Climate change, energy consumption, and energy security are the greatest challenges for mankind. Human activities, which produce heat-trapping gases, are expected to be the main driver of climate change, which refers to long-term shifts in temperatures and weather patterns and influence heating and cooling energy demand. On the other hand, the heating and cooling degree days vary by different climate zones. This article focuses on the EU and Norway due to the available regional data. Degree-day is a quantitative index demonstrated to reflect the demand for energy to heat or cool households.

Energy security and energy consumption are critical aspects for states and communities, and thus, proper policy actions are seen as a requirement. This article deals with two indicators of weather-related energy consumption, heating degree-days (HDD) and cooling degree-days (CDD), and how climate change affects the number of HDD and CDD in countries and how the impact differs depending on the countries' climate profile. The main analysis was supplemented with an attempt to estimate the weather-related energy savings of the household sector – the main end-user of heating and cooling-related energy. The study refers to the EU-27 and Norway due to the availability of regional data and uniform base temperature, and the analysis was performed with the use of data retrieved from Eurostat's energy statistics database for the period 1979-2021.

Literature review

Heating and cooling degree-days as indicators of weather-related energy consumption

Climate, which refers to the state of the atmosphere of a given place over many years, is the average state of weather expressed by temperature, pressure, pollution, humidity, precipitation, wind speed and other meteorological elements. By retrospecting the climate change over the past 100 years, the temperature on our planet has been steadily increasing (Earth Observatory, 2020). The human impact is assumed to have caused the global temperatures to rise by around 1.0°C, and, according to current global trends, the increase is likely to reach 1.5°C between 2030 and 2052 (IPCC, 2018). Energy-related greenhouse gas emissions, along with changes in urbanisation and land use, are indicated as major causes of climate change (Karl & Trenberth, 2003; Bush & Lemmen, 2019; Chidiac et al., 2022). Global warming, causing more extreme temperatures and a long-term rise in global average temperatures, is estimated to increase the demand for refrigeration services and the energy needed to deliver them (IEA, 2018; Colelli & Cian, 2020) and affect the thermal comfort outdoors (Petri & Caldeira, 2015).

The effects of global warming influence energy consumption in households and cause relevant impacts in many sectors (Chun-sheng et al., 2012; Yating et al., 2018; Roshan et al., 2019; Lam et al., 2022; del Pablo-Romero et al., 2023). Worldwide, household energy consumption accounts for about a third of the total energy use. Much of the energy consumed in buildings is directed to heating, ventilation and air conditioning (HVAC) (Mehregan et al., 2022). Heating remains the main application of the energy consumed by households, but the demand for cooling-related energy rises rapidly, both in high-income countries and in emerging economies such as India and China (Isaac & Vuuren, 2009). Trends in energy demand for heating and cooling can be very important for the development of the energy system and related emissions (Isaac & Vuuren, 2009).

In the course of the analysis, two indicators of weather-related energy consumption were considered: heating degree-days (HDD) and cooling degree-days (CDD). They are weather-based quantitative indices designed to reflect the demand for energy requirements to heat or cool. HDD is designed

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to describe the need for the heating energy requirements of buildings, and CDD refers to the need for the cooling requirements of buildings (air-conditioning). Heating and cooling degree days are derived from meteorological observations of air temperature, interpolated to regular grids at 25 km resolution for Europe. HDD and CDD are presented on NUTS-2 level and also on NUTS-3 level (for years 2017 and 2018) and are based on observations from about 3000 weather stations across Europe. Data concerning heating and cooling degree-days are presented as ˚C temperature sums (Eurostat, 2023). Lower or higher energy consumption is determined by the behaviour of households, businesses or other issues regarding heating and cooling degree-days.

HDD index means the severity of the cold in a specific time period, taking into consideration outdoor temperature and average room temperature. This indicates the need for heating. The calculation of HDD relies on the base temperature, which is defined as the lowest daily mean air temperature, not leading to indoor heating. The value of the base temperature depends on several factors associated with the building and the surrounding environment. By using a general climatological approach, the base temperature is set to a constant value of 15°C in the HDD calculation. If Tm ≤ 15°C Then [HDD = $\sum_i(18°C - T^i m)$] Else [HDD = 0] where $T^i m$ is the mean air temperature of day i. For example, if the daily mean air temperature is 13°C, for that day, the value of the HDD index is 5 because 18-12=5, and if the daily mean air temperature is 16°C, for that day, the HDD index is 0. CDD index means the severity of the heat in a specific time period, taking into consideration outdoor temperature and average room temperature. This indicates the need for cooling. The calculation of CDD relies on the base temperature, which is defined as the highest daily mean air temperature, not leading to indoor cooling. The value of the base temperature depends on several factors associated with the building and the surrounding environment. By using a general climatological approach, the base temperature is set to a constant value of 24°C in the CDD calculation. If $T_m \geq 24°C$, Then [CDD = ∑iTim – 21°C)] Else [CDD = 0] where Tim is the mean air temperature of the day i. For example, if the daily mean air temperature is 27°C, for that day, the value of the CDD index is 6 because 27-21=6, and if the daily mean air temperature is 22°C, for that day the CDD index is 0 (Eurostat, 2023). The aim of analysing the heating and cooling degree days is to track climate change and the use of energy, which is the basis of life.

Climate change and energy demand

There have been efforts to analyse energy demand for heating and cooling in relation to climate change at a global scale (Isaac & van Vuuren, 2009; Hekkenberg et al., 2009; Mastrucci et al., 2021). The impact of climate change on energy demand has been reviewed under the relation between energy demand and outdoor temperature (Sailor & Pavlova, 2003; Amato et al., 2005; Hadley et al., 2006; Aebischer et al., 2007; Silva et al., 2020), while the impact of climate changes on the urban environment can be evaluated by calculating the variations in energy production and consumption for daily operations as heating and cooling (Cartalis et al., 2001). It is seen that energy demand is found to be dependent on outdoor temperature in a 'U' shaped shape. Such a U-shape indicates that climate change may have vague outcomes for any future energy demand since higher outdoor temperatures may reduce heating demand; however, they may also increase cooling demand. Based on spatial and seasonal variations in the relative meaning of such opposing effects, the outcome of the total balance for energy demand could differ regionally and seasonally (Hekkenberg et al., 2009).

There are several studies regarding energy demand modelling related to households and buildings, and such research focuses on simply forecasting future demand or increasing energy efficiency, while it deals with the effect of weather or climate sensitivity of demand or the impact of the current climate on demand (Dirks et al., 2015). The main impact of climate change on energy use and emissions at a global scale seem to be quite small, since any decrease in heating is ideally balanced relatively increases in cooling. But, when considering the effects on heating and cooling individually, then heating energy demand is expected to decrease by around 34% by 2100 as a result of climate change while cooling energy demand is to increase by 72% on a global scale (Isaac & van Vuuren, 2009). Even though important research development has been done in regard to climate change and, in particular, its effects of linking mitigation and adaptation in the energy sector, it seems that an integrated assessment at both the national and regional levels is still required to be further improved (Taseska et al., 2012). The value of the degree-days (DD) is a measure of weather-related heating and cooling energy needed in residential areas and buildings in general. It directly relates to the outdoor temperature of

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an area and the design's indoor temperature (Indraganti & Boussaa, 2016; Cao et al., 2021). It has been noticed that heat demand may decrease because of changing weather conditions and building renovation policies. However, there have been studies that show the effect of changed weather conditions was much lower than the impact of building renovation. The difference in the parameters rate of decrease/increase was lower than 2% between weather scenarios for the same examined year (André et al., 2017).

The temperature increase caused by the climate change effect can bring a respective decrease in heating demand and an increase in cooling demand. A possible method to calculate energy consumption in households and residential buildings can be found through the approach of degree day, which was developed by Thom (1952, 1954), considering the daily mean temperature. Such a framework has been widely accepted in climate change studies at both global and regional scales since it is an easy method with parameters to calculate. The concept of both heating and cooling degree days involves a temperature threshold, and the threshold used in particular applications may differ based on human physiological needs, energy supply, economic level, temperature characteristics and other parameters (Shi et al., 2018).

A thorough literature review and summary of climate change impacts on building heating and cooling energy demand in the literature have been done by Pérez-Andreu et al. (2018). It is shown the effect of climate change on the energy behaviour of buildings during 2000-2010, based upon published research. Regional climates, frameworks, and other indicators related to the design parameters of buildings may vary, and the conclusions on methods and outcomes may overlap, while they are applicable to the total issue and specific to different estimations and climate types (Pérez-Andreu et al., 2018). The characteristics and consequences of HDD and CDD are the subject of research in many countries and regions of the world (Zheng & Zhang, 2011; Andrade et al., 2021; Yoo & Noh, 2009; Atilgan et al., 2018; Bhatnagar et al., 2018; Indraganti & Boussaa, 2016; Fraisse & Paula-Moraes, 2018). Generally, forecasts indicate potential decreases in heating energy demand and increases in cooling energy demand.

In the following Table 1, a summary of the main arguments and the methodological aspects of the current studies is given:

Table 1. Summary of the main arguments and the methodological aspects of the current studies

Indication	Literature	Indication	Literature
Increase of the global temperature is likely to reach 1.5°C between 2030 and 2052	IPCC (2018)	The impact of climate change on energy demand in relation between energy demand and outdoor temperature	Sailor and Pavlova (2003); Amato et al. (2005); Hadley et al. (2006); Aebischer et al. (2007); Silva et al. (2020)
Energy-related greenhouse gas emissions, along with changes in urbanization and land use, are indicated as a major cause of climate change	Karl and Trenberth (2003); Bush and Lemmen (2019); Chidiac et al. (2022)	The impact of climate changes on the urban environment can be evaluated by calculating the variations in energy production and consumption for daily operations as heating and cooling	Cartalis et al. (2001)
Global warming is estimated to increase the demand for refrigeration services and the required energy	IEA (2018); Colelli and Cian (2020)	The outcome of the total balance for energy demand could differ regionally and seasonally	Hekkenberg et al. (2009)
Global warming affects the thermal comfort outdoors	Petri and Caldeira (2015)	Several studies regarding energy demand modeling related to households and buildings that focuses on simply forecasting future demand or increasing energy efficiency	Dirks et al. (2015)
The effects of global warming influence on energy consumption in the households and cause relevant impacts in many sectors	Chun-sheng et al. (2012); Yating et al. (2018); Roshan et al. (2019); Lam et al. (2022); del Pablo-Romero et al. (2023)	Heating energy demand is expected to be decreased by around 34% by 2100 as a result of climate change while cooling energy demand to be increased by 72% on a global scale	Isaac and van Vuuren (2009)

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Indication	Literature	Indication	Literature
Much of the energy consumed in buildings is directed to heating, ventilation and air conditioning	Mehregan et al. (2022)	The value of the degree-days (DD) is a measure of weather-related heating and cooling energy needed in the residential areas and buildings in general.	Indraganti and Boussaa (2016); Cao et al. (2021)
Heating remains the main application of the energy consumed by households, but the demand for cooling-related energy rises rapidly	Isaac and van Vuuren (2009)	The effect of changed weather conditions was much lower than the impact of building renovation	André et al. (2017)
Energy demand trends for heating and cooling can be very important for the development of the energy system and related emissions	Isaac and van Vuuren (2009)	Method to calculate energy consumption in households and residential buildings through the approach of degree day	Thom (1952, 1954)
Analysis of energy demand for heating and cooling in relation to the climate change at a global scale	Isaac and van Vuuren (2009); Hekkenberg et al. (2009); Mastrucci et al. (2021)	The threshold used in particular applications may differ based on human physiological needs, energy supply, economic level, temperature characteristics and other parameters	Shi et al. (2018)
Thorough literature review and summary of climate-change impacts on building heating and cooling energy demand	Pérez-Andreu et al. (2018)	The characteristics and consequences of HDD and CDD are the subject of research in many countries and regions of the world	Zheng and Zhang (2011); Andrade et al. (2021); Yoo and Noh (2009); Atilgan et al. (2018); Bhatnagar et al. (2018); Indraganti and Boussaa (2016); Fraisse and Paula-Moraes (2018)
The decrease in HDD will outbalance the increase in CDD over most of Europe, and the related energy demand is expected to decrease	Spinoni et al. (2018)	An integrated assessment at both national and regional level is still required to be further improved	

It has been suggested that an integrated assessment at both national and regional levels is still required to be further improved. The existing research can be further enriched by additional data concerning the weather-related energy savings in the household sector as one affected by heating and cooling days and energy savings that finally contribute to sustainable development. The characteristics and consequences of HDD and CDD are the subject of research in many countries and regions of the world. In this context it is very important to answer the question concerning affecting of climate change (global warming) on the number of HDD and CDD across European Union and Norway and estimating savings of energy consumption in households.

Research Methodology

The impact of climate change on the weather-related final energy consumption of European households was investigated within a two-staged analytical framework, which included:

I. evaluation of the effect which global warming exerted on the annual numbers of HDD and CDD based on historical data from the 1979 to 2022,
II. estimation of how the HDD and CDD changes translated into the households' energy use.

Both steps of the analysis were performed on a national level, with the use of the data retrieved from Eurostat's energy statistics database, which offers a uniform degree day calculation methodology. The timeframe of the investigation was set as the longest period available, which equals to the years 1979-2021 for annual HDD and CDD observations and the years 1990-2021 in case of the households final energy consumption. Similarly, our research sample corresponds to the full spatial scope of Eurostat's HDD and CDD datasets, which include the EU-27 and Norway. Despite its existence, the study did not employ the data pertaining directly to the heating and cooling household energy use due to its poor availability – numerous gaps and significantly shorter length of the time series (2010-2018).

Evaluation of changes in HDD and CDD

In the first step of the analysis, the severity of the climate change in the context of households' energy requirements was expressed two fold:

- as the difference between the annual number of degree days (HDD, CDD) observed at the beginning (1979) and at the end (2022) of the research period,
- as the cumulative sum of the annual deviations from the initial observation (1979).

The former of the approaches is aimed to illustrate the general tendency in relation to the degree day levels – pertaining to both the direction of the change, as well as its severity. To enhance objectivity of the assessment (and avoid concluding from two single observations), the subtraction was performed on the first and the last data points derived from previously fitted linear time trends. The original values and intrinsic volatility of the HDD and CDD time series was retained in the second variant of the analysis, where the differences for an individual country were expressed in the cumulative form:

$$d_j^c = \sum_{t=2}^{43} \left(x_{tj} - x_{1j}\right), \tag{1}$$

where:
$j \in \{1, 2, ..., 28\}$

Estimate of energy savings

The second part of the empirical investigation was intended to demonstrate the effects of the climate change in a more tangible way, in terms of its impact on the historical households' energy consumption. The first step in the analysis comprised the investigation of the average typical response of the households' energy use to the changes in HDD/CDD, conducted individually for each of the European countries. Thus, the analysis was carried out with the use of the set of 28 single linear regression models conducted on the transformed, first order differenced time series of the:

dependent variable: the year-to-year changes of the annual households' final energy consumption in 28 European countries in the time frame of 1990-2021,

independent variable: the year-to-year changes of the HDD/CDD in the timeframe of 1990-2021.

Under the proposed specification, the statistical relationship between the variables can be described as follows:

$$\Delta y_{it} = (\Delta x_{it})\beta_1 + \Delta\varepsilon_{it}, \tag{2}$$

where:

β_1 – denotes the coefficient of Δx_{it}, $\Delta y_{it} = y_{it} - y_{i(t-1)}$, $\Delta x_{it} = x_{it} - x_{i(t-1)}$, $\Delta\varepsilon_{it} = \varepsilon_{it} - \varepsilon_{i(t-1)}$ and $t \in \{2, 3, \dots, 43\}$.

The main purpose of employing the first order differencing process was to remove the effects of general non-stationarity of the HDD and CDD time series confirmed at the previous stage of the analysis. In case of the statistically significant (at a rather liberal significance level and properly specified regression models, the obtained relationship was used to predict the shift in the households' energy consumption resulting from the previously established HDD/CDD changes between 1979 and 2021. Consequently, to the analytical framework undertaken in the stage one, the estimation was applied both to the trend-indicated, as well as the cumulative changes of the degree days determined in the previous part of the investigation.

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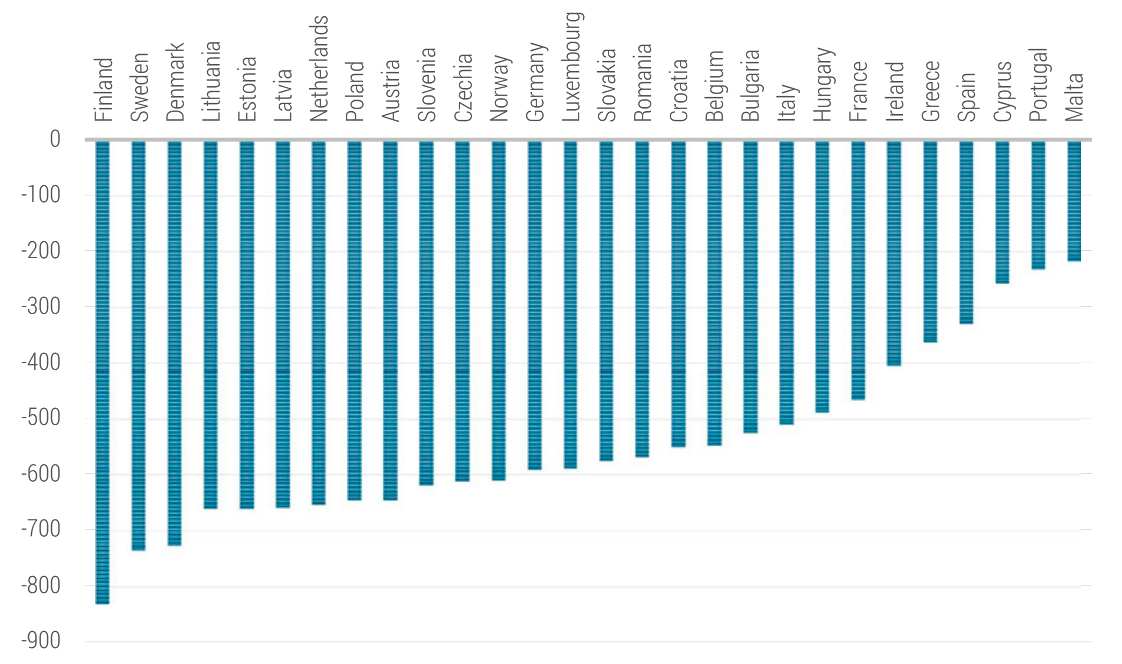
Results and Discussion

Evaluation of changes in HDD

Under the trend-based approach the global warming contributed to the decrease of the HDD number for all of the European countries analysed. The absolute values of the inter-period discrepancies ranged between 218 to 833 and were relatively weakly dispersed, with the coefficient of variation equal to 28% of the mean. Consequently, the general rate of decrease was rather mild, as the only exceptional HDD changes were limited to the coldest (Finland, to a lesser degree, Sweden and Denmark) and warmest European regions (Cyprus, Portugal, Malta). Due to the properties above the statistical distribution of the trend-indicated HDD differences can be described as normal, slightly right-skewed and platykurtic (short-tailed), without the presence of any significant outlying observations. As indicated in the Figure 1, the inter-periodical differences in relation to the HDD levels were heavily determined by the standard climate conditions.



N (obs.): 28	Mean: -545.72
Min: -832.52	Std. deviation: 154.21
Max: -217.57	Skewness: 0.67
Median:-581.81	Kurtosis: 2.85

Figure 1. The impact of climate change on the HDD levels for the 28 European countries. The trend-indicated differences, along with basic descriptive statistics

Source: authors' work based on Eurostat (2023).

The statistical relationship between the trend-indicated HDD change and the average yearly number of HDD (representing the average air temperatures) exhibits apparent nonlinearity, where can bebest described as quadratic function of in its declining part, with the turning point (vertex) placed slightly outside of the data range (x = 5772). Under the proposed specification, the rate of the HDD change is the fastest in the initial range of observations and it decreases along with the movement towards the largest values on the axis (Figure 2). It indicates that, in relative terms, global warming benefited the most the warmest portion of the European countries analyzed. The highest relative changes of HDD (expressed as the percentage of initial observation) were observed for Malta (33.8%), Cyprus (28.3%) and Italy (22,5%), whereas the lowest for Norway (10,3%), Sweden (12,9%)

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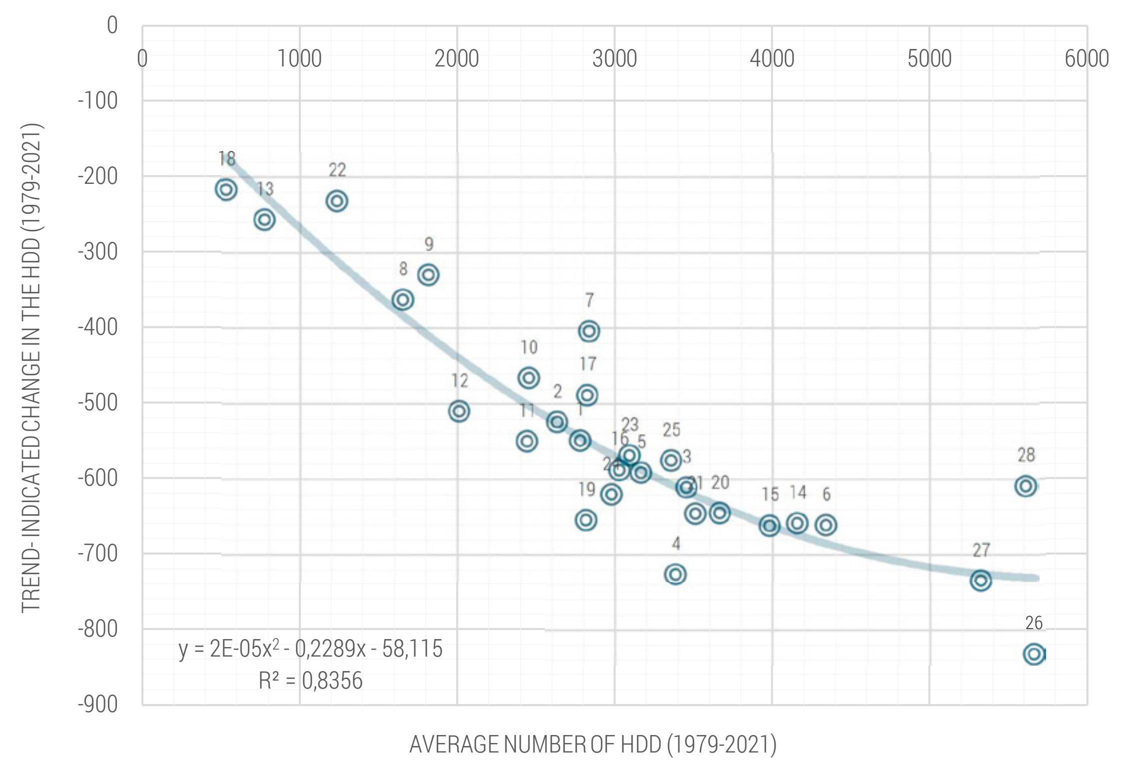
and Ireland (13,3%) with the sample average of 17.8%. The detailed presentation of the HDD changes expressed in relative terms is provided in Appendix 1.



Model specification:
o Functional form: $y_i = 0.00002x_i^2 - 0.2289x_i + 58.115$
O Coefficient of determination: $R^2 = 0.8356$

Explanatory notes:
(1) – Belgium; (2) – Bulgaria; (3) – Czechia; (4) – Denmark; (5) – Germany; (6) – Estonia; (7) – Ireland; (8) – Greece; (9) – Spain; (10) – France; (11) – Croatia; (12) – Italy; (13) – Cyprus; (14) – Latvia; (15) – Lithuania; (16) – Luxembourg; (17) – Hungary; (18) – Malta; (19) – Netherlands; (20) – Austria; (21) – Poland; (22) – Portugal; (23) – Romania; (24) – Slovenia; (25) – Slovakia; (26) – Finland; (27) – Sweden; (28) – Norway.

Figure 2. The trend-indicated changes in the HDD levels under different typical climate conditions

Source: authors' work based on Eurostat (2023).

The cumulative differences of the HDD paint a slightly different picture of the energy-related impact of climate change, which suggests significant individual differences in the properties of time series. First, the observations are generally higher in the absolute value, relatively more dispersed (coefficient of variation=69.5%), with the values ranged from large negative values (-27246.5 [Denmark]) to even positive ones (5025.3 [Cyprus]). Also, the rate of change is steadier across the sample, with a slight exception observed in the lowest portion of the classification (Figure 3). The cumulative differences remain statistically related to average air temperature under the same functional form (*y* as a quadratic function of *x*) but the strength of the relationship is much weaker than obtained under a trend-based approach (Figure 4).

On an individual level, the biggest change in relation to the HDD decrease was observed in Finland, Slovenia and Romania, which moved successively by 12, 10 and 9 positions down the ranking. The opposite was true for Ireland, Belgium and Portugal, which under the cumulative approach occupied the positions 17, 11 and 10 lower than indicated by the previously reported trend analysis. A most distinctive case constituted Cyprus, where the variability of the HDD time series has completely reversed the potential energy savings indicated by the decreasing trend. The positive cumulative value of the Cypriot HDD change was the result of two factors: a low starting data point (1979) and a periodic upward trend ending with a single spike in HDD number observed in 1992. A visual representation of the HDD change reported for each of the countries is available in Appendix 2.

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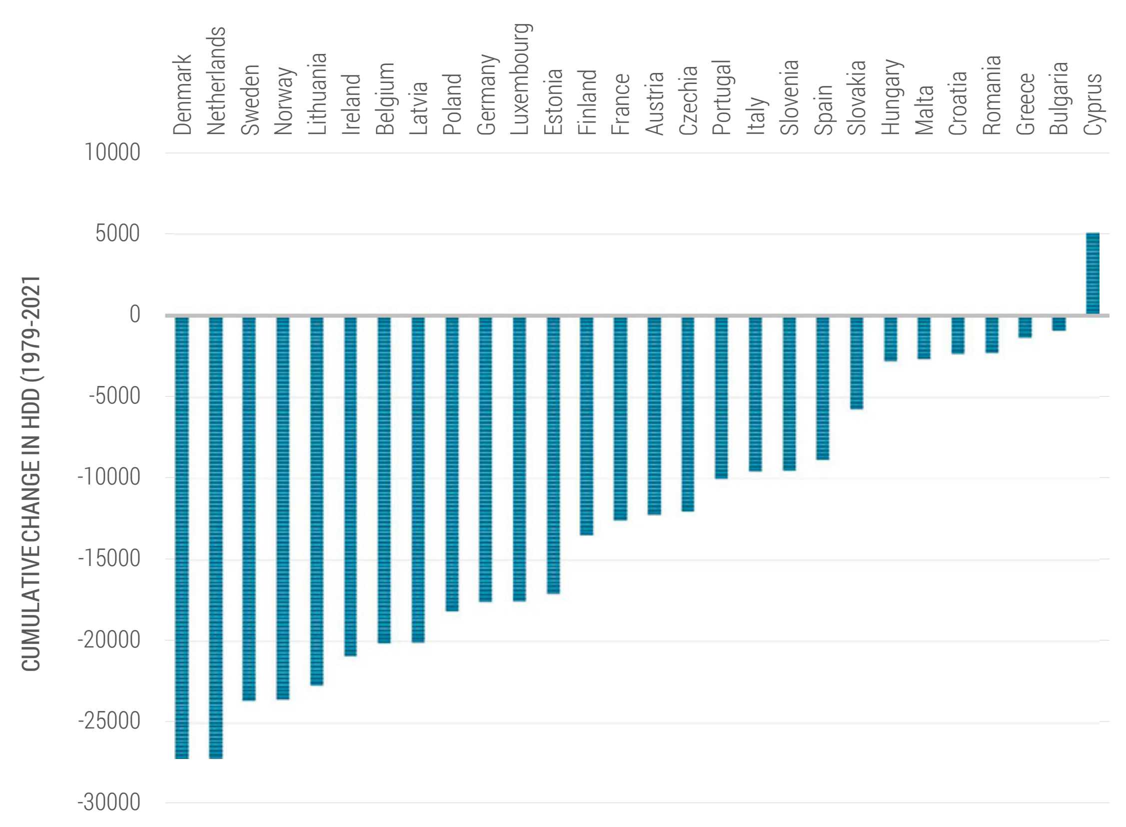
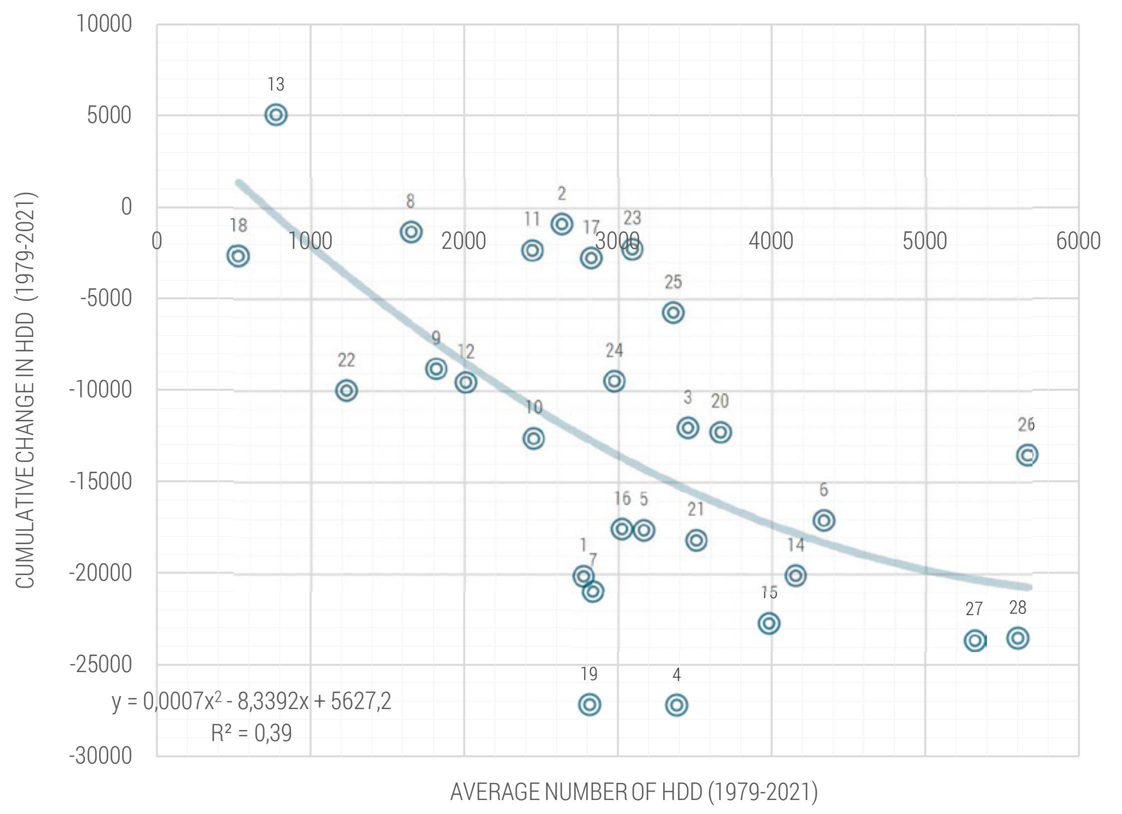


N (obs.): 28	Mean: -12761.39
Min: -27246.49	Std. deviation: 8874.05
Max: 5025.25	Skewness: 0.12
Median: -12436.37	Kurtosis: 1.99

Figure 3. The impact of climate change on HDD levels for the 28 European countries. The cumulative differences, along with basic descriptive statistics (1979-2021)

Source: authors' work based on Eurostat (2023).



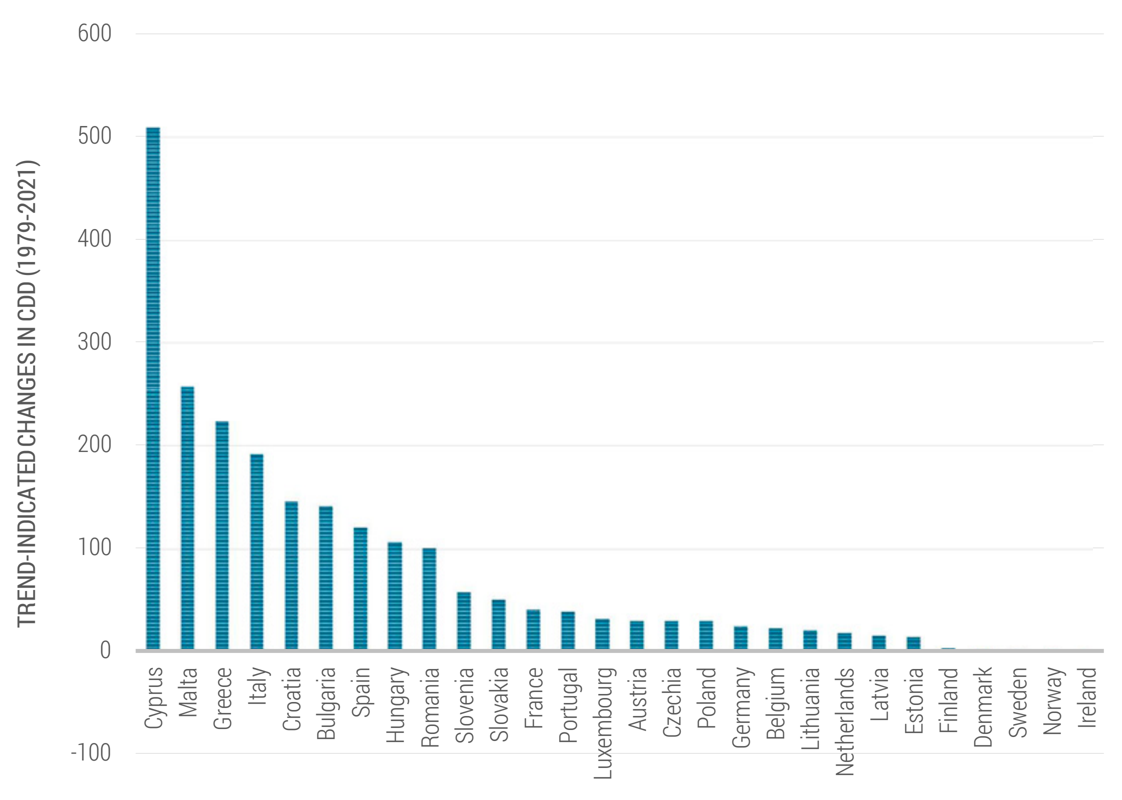
Model specification:
o Functional form: $y_i = 0.0007x_i^2 - 9.3392x_i + 5627.2$
O Coefficient of determination: $R^2 = 0.39$

Explanatory notes:
(1) – Belgium; (2) – Bulgaria; (3) – Czechia; (4) – Denmark; (5) – Germany; (6) – Estonia; (7) – Ireland; (8) – Greece; (9) – Spain; (10) – France; (11) – Croatia; (12) – Italy; (13) – Cyprus; (14) – Latvia; (15) – Lithuania; (16) – Luxembourg; (17) – Hungary; (18) – Malta; (19) – Netherlands; (20) – Austria; (21) – Poland; (22) – Portugal; (23) – Romania; (24) – Slovenia; (25) – Slovakia; (26) – Finland; (27) – Sweden; (28) – Norway.

Figure 4. The cumulative changes in HDD levels under different typical climate conditions (1979-2021)
Source: authors' work based on Eurostat (2023).

Evaluation of changes in CDD

In line with the expectations, global warming contributed to the inter-period CDD growth for the overwhelming majority of European countries. The trend-derived differences in CDD were much more dispersed than analogous changes pertaining to HDD, with the values ranging from 508.95 (Cyprus) to small decimal numbers – both on the positive (Norway, Sweden) and negative side (Ireland). The rate of CDD growth changed in a non-linear manner, with clear distinctions between the warm Southern European countries, countries with temperate climates, and the coldest Nordics. In the context of descriptive statistical analysis, the properties described above result in the non-normal, deeply right-skewed and long-tailed distribution, with the presence of significant outlying observations (Figure 5).

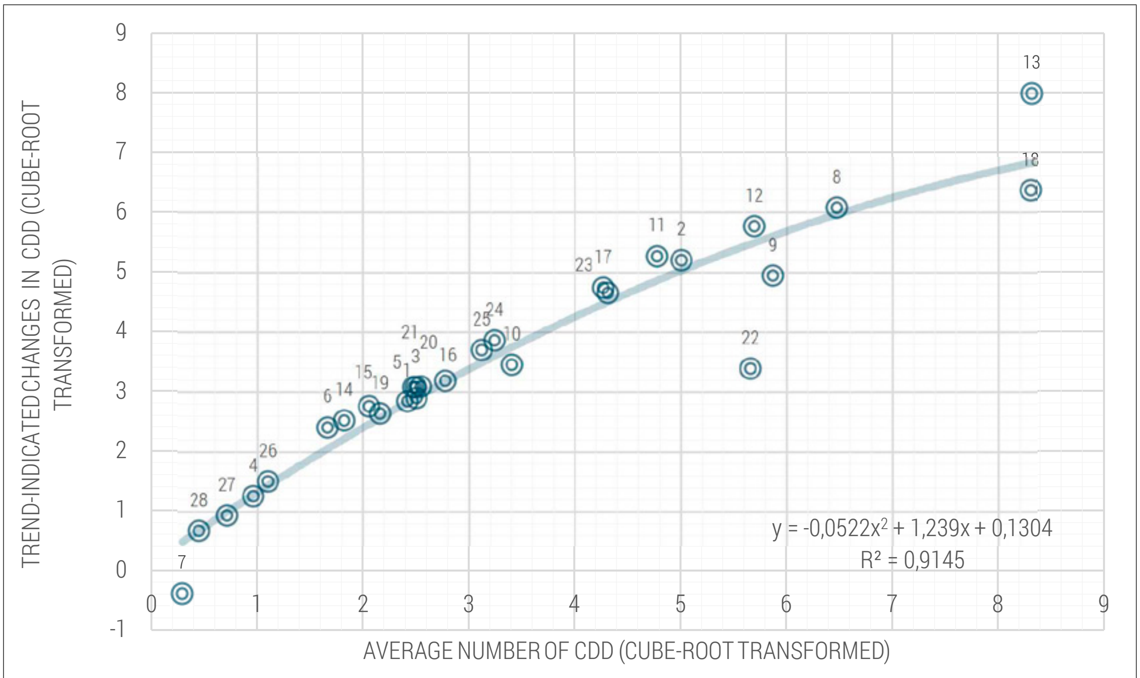


N (obs.): 28	Mean: 79.42
Min: 0.06	Std. deviation: 110.09
Max: 508.95	Skewness: 2.42
Median: 30.70	Kurtosis: 9.41

Figure 5. The impact of climate change on CDD levels for the 28 European countries. The trend-indicated differences, along with basic descriptive statistics (1979-2021)

Source: authors' work based on Eurostat (2023).

The clear regional patterns present in the classification (Figure 6) suggest that the changes in CDD were even more strongly determined by the typical climate conditions than the HDD decrease. As the initial properties of the dataset make it rather unsuitable for inferential statistical analysis, both variables underwent a cube-root transformation, which allowed the normalisation of the distribution of the dataset, including a negative observation. As with the trend-indicated changes in HDD, the dependency in question was best described by a nonlinear function – in this case, by a negative quadratic function in its inclining part, with a turning point placed well outside the data range (x=11.87). Analogously to the conclusions referring to HDD, the resulting shape of the statistical dependency denotes a slightly faster rate of CDD growth for the countries with lower average levels of CDD, and thus showing the lowest average annual temperatures in the sample (Appendix X). Noteworthy are very large relative rates of CDD growth, which on average amounted to 932.51% of the initial observation (Appendix 1).

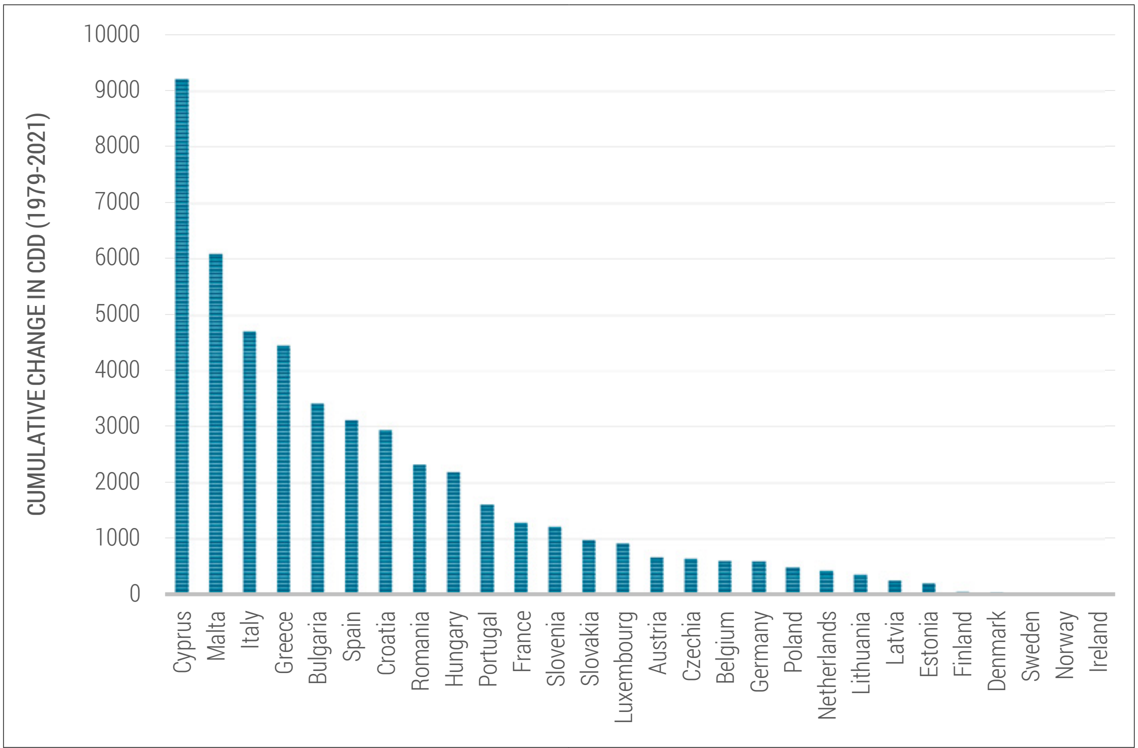


Model specification:
o Functional form: $y_i = -0.0522x_i^2 + 1.239x_i + 0.1304$
O Coefficient of determination: $R^2 = 0.9145$

Explanatory notes:
(1) – Belgium; (2) – Bulgaria; (3) – Czechia; (4) – Denmark; (5) – Germany; (6) – Estonia; (7) – Ireland; (8) – Greece; (9) – Spain; (10) – France; (11) – Croatia; (12) – Italy; (13) – Cyprus; (14) – Latvia; (15) – Lithuania; (16) – Luxembourg; (17) – Hungary; (18) – Malta; (19) – Netherlands; (20) – Austria; (21) – Poland; (22) – Portugal; (23) – Romania; (24) – Slovenia; (25) – Slovakia; (26) – Finland; (27) – Sweden; (28) – Norway.

Figure 6. The trend-indicated changes in CDD levels under different typical climate conditions (1979-2021)
Source: authors' work based on Eurostat (2023).

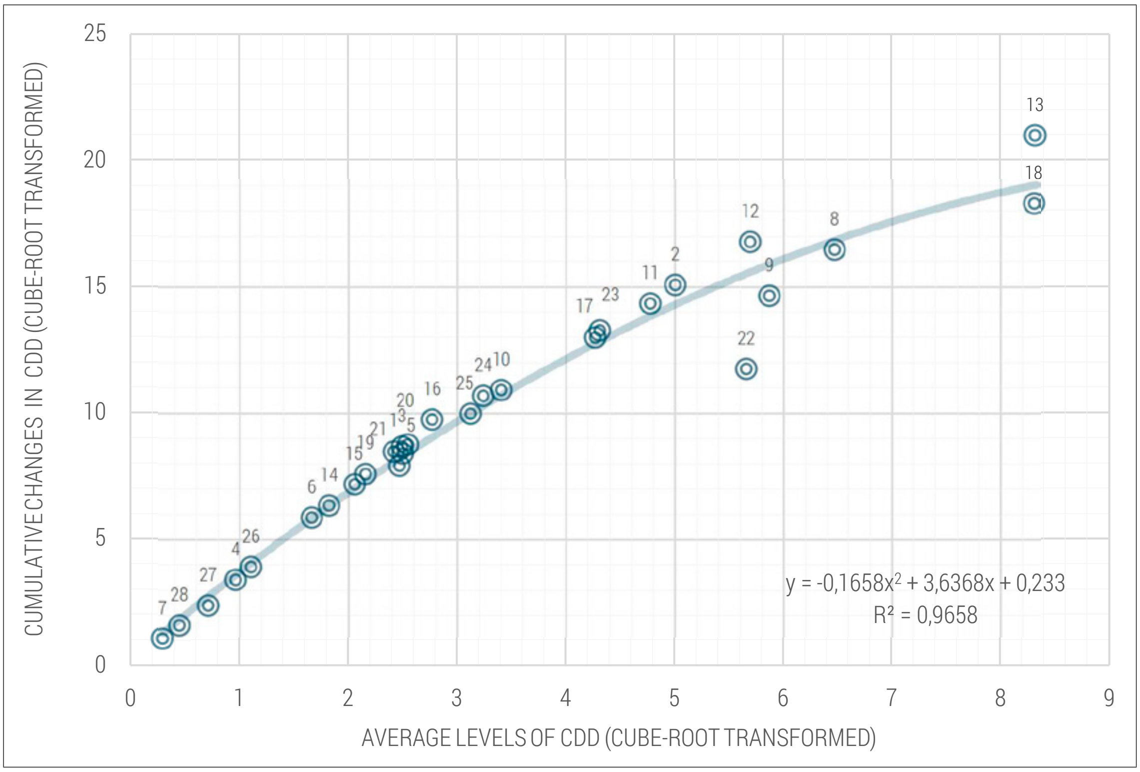
The cumulative CDD increases (Figure 7) presented distributional properties that were very similar to the differences obtained using the trend-based approach. The biggest difference pertains to significantly higher average levels of the CDD change and higher variability of the data, ranging from 1.14 to 9202.73. The similarities can also be extended to the individual ranks of European countries, where the biggest change lies in fall caused by the presence of several relatively cold years at a regular six-year interval. Since the CDD growth in cumulative terms further emphasised the differences between countries, the statistical relationship between the cumulative differences in CDD and the average CDD levels turned out to be stronger than reported under the trend-based approach. The previously observed negative square function is now characterised by an even better fit to the data (, as well as a greater deviation from the linear form (Figure 8).



N (obs.): 28	Mean: 1764.44
Min: 1.14	Std. deviation: 2182.45
Max: 9202.73	Skewness: 1.84
Median: 794.94	Kurtosis: 6.21

Figure 7. The impact of climate change on the CDD levels for the 28 European countries. The cumulative differences, along with basic descriptive statistics (1979-2021)

Source: authors' work based on Eurostat (2023).



Model specification: o Functional form: $y_i = -0.1658x_i^2 + 3.6368x_i + 0.233$ O Coefficient of determination: $R^2 = 0.9658$
Explanatory notes: (1) – Belgium; (2) – Bulgaria; (3) – Czechia; (4) – Denmark; (5) – Germany; (6) – Estonia; (7) – Ireland; (8) – Greece; (9) – Spain; (10) – France; (11) – Croatia; (12) – Italy; (13) – Cyprus; (14) – Latvia; (15) – Lithuania; (16) – Luxembourg; (17) – Hungary; (18) – Malta; (19) – Netherlands; (20) – Austria; (21) – Poland; (22) – Portugal; (23) – Romania; (24) – Slovenia; (25) – Slovakia; (26) – Finland; (27) – Sweden; (28) – Norway.

Figure 8. The cumulative changes in CDD levels under different typical climate conditions (1979-2021)

Source: authors' work based on Eurostat (2023).

Estimate of energy savings

Households' energy use and the changes in HDD/CDD (1990-2021)

The results of the single linear regression models (Appendix 3) showed that the annual changes in the energy consumption of European households reacted rather strongly to the analogous changes in HDD. Out of the 28 regressions carried out, only five remained statistically insignificant at the significance level of 0.1 (Estonia, Romania, Cyprus, Portugal, Malta). The greatest impact of the HDD changes was observed for highly and densely populated countries, which was reflected in the largest coefficients of determination (Netherlands, Denmark, France) as well as the largest regression coefficients (France, Germany, Italy). Similar dependencies could not be observed in the case of annual CDD changes, which exerted much less impact on changes in energy consumption of European households. In this case, the statistical significance of the individual, single regression models was achieved only twice out of 28 analyses made (Italy, Finland).

Estimation results – HDD

As a consequence of the largest coefficients obtained from linear regression, the largest energy savings related to climate change were estimated for European countries with the highest population (Germany, Italy, France, Poland) or remarkable population density (the Netherlands). As indicated in the classification below (Table 2), the extent of HDD drop presented previously in tables (1) and (3) cannot, therefore, be considered as an approximation of the energy savings without taking into account the demographic characteristics of the country. Due to lower regression coefficients (mainly determined by the country's population), the countries that experienced the biggest HDD decrease (Denmark, Finland, Sweden, and especially Norway) were now classified in the upper-middle portion of both rankings. In a relative term, the rate of energy savings remains slightly negatively correlated to the average levels of HDD, with Spearman's rank correlation coefficient equal to -0.39.

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Table 2. Classification of the 28 European countries based on the households' levels of energy savings related to reduced demand for heating (1979-2021)

HDD: Trend-based approach				HDD: cumulative approach			
	Country	Predicted change in energy use*	%**		Country	Predicted change in energy use*	%**
1.	Germany	-5 649.04	-9.03	1.	Germany	-168 134.70	-268.78
2.	Italy	-4 738.24	-15.60	2.	France	-123 597.80	-297.61
3.	France	-4 571.32	-11.00	3.	Italy	-88 596.66	-291.78
4.	Poland	-1 999.78	-9.81	4.	Netherlands	-75 150.9	-697.04
5.	Netherlands	-1 807.34	-16.76	5.	Poland	-56 258.3	-275.87
6.	Belgium	-1 080.30	-12.12	6.	Belgium	-39 599.8	-444.23
7.	Austria	-803.29	-12.26	7.	Sweden	-17 913.2	-237.60
8.	Finland	-617.46	-11.67	8.	Denmark	-16 834.8	-377.43
9.	Greece	-609.79	-13.88	9.	Austria	-15 263.9	-232.86
10.	Czechia	-605.54	-8.81	10.	Czechia	-11 908.3	-173.23
11.	Hungary	-575.29	-9.28	11.	Ireland	-11 830.2	-413.49
12.	Sweden	-556.58	-7.38	12.	Norway	-10 604.8	-259.45
13.	Denmark	-448.98	-10.07	13.	Finland	-10 030.5	-189.54
14.	Spain	-311.54	-2.33	14.	Spain	-8 317.61	-62.08
15.	Croatia	-307.86	-12.76	15.	Hungary	-3 269.56	-52.75
16.	Norway	-273.97	-6.70	16.	Latvia	-3 165.93	-222.37
17.	Ireland	-228.08	-7.97	17.	Lithuania	-2 891.41	-188.26
18.	Bulgaria	-212.54	-9.31	18.	Greece	-2 251.18	-51.24
19.	Slovakia	-157.99	-6.88	19.	Slovenia	-1 645.7	-138.01
20.	Slovenia	-107.76	-9.04	20.	Slovakia	-1 574.05	-68.52
21.	Latvia	-103.74	-7.29	21.	Croatia	-1 305.16	-54.11
22.	Lithuania	-84.19	-5.48	22.	Luxembourg	-1 043.16	-199.07
23.	Luxembourg	-34.94	-6.67	23.	Bulgaria	-368.462	-16.15
24.	Estonia	-		24.	Estonia	-	
24.	Cyprus	-		24.	Cyprus	-	
24.	Malta	-		24.	Malta	-	
24.	Portugal	-		24.	Portugal	-	
24.	Romania	-		24.	Romania	-	

Explanatory notes:
* Unit of measure: Thousand tonnes of oil equivalent.
** as a percentage of average annual households' energy use (1990-2021).

Source: authors' work with the use of Stata 17 BE software.

Estimation results – CDD

The insignificant regression results (Appendix 3) obtained for the vast majority of European countries made it largely impossible to establish the net effect of climate change on the households' energy consumption. The calculation was possible merely for Finland and Italy, where the estimated increase in energy demand was significantly lower in absolute terms than the previously estimated energy savings (Table 3). Although this result could certainly be expected for a Nordic country, the negative net consumption change was also established for a highly populated, South European country, which experienced are latively large increase in CDD. For the remaining 26 European countries, the net effect of climate change can be approximated to the heating-related energy savings presented in Table 2.

Table 3. Estimated increase in the households' energy use related to the CDD growth in European countries. The net effect of climate change on the households' energy consumption

	CDD: trend-based approach		CDD: cumulative approach		Net change in energy use (trend-based)	%**	Net change in energy use (cumulative)	%**
	Predicted change in energy use*	%**	Predicted change in energy use*	%**				
(1)	1121.83	3.69	27561.61	90.77	-3 616.41	-11.91	-61 035.05	-201.01
(2)	118.81	2.25	2086.87	39.43	-498.65	-9.42	-7 943.63	-150.10

Explanatory notes:
(1) – Italy; (2) – Finland.
* Unit of measure: Thousand tonnes of oil equivalent.
** as a percentage of average annual households' energy use (1990-2021).

Source: authors' work with the use of Stata 17 BE software.

Conclusions

Under the trend-based approach, global warming contributed to the decrease of the HDD number for all of the European countries analysed. The general rate of decrease was rather mild, as the only exceptional HDD changes were limited to the coldest and warmest European regions. The inter-periodical differences in relation to the HDD levels were heavily determined by the standard climate conditions. Based on the analysis, the global warming benefited the most the warmest portion of the European countries analysed, with the highest relative changes of HDD observed for Malta (33.8%), Cyprus (28.3%) and Italy (22,5%), whereas the lowest for Norway (10,3%), Sweden (12,9%) and Ireland (13,3%). The biggest change in relation to the HDD decrease was observed in Finland, Slovenia and Romania, while the opposite was true for Ireland, Belgium and Portugal when compared to previously reported trend analysis. In line with the expectations, global warming contributed to the inter-period CDD growth for the overwhelming majority of European countries, while the changes in CDD were even more strongly determined by the typical climate conditions than the HDD decrease. The annual changes in the energy consumption of European households reacted rather strongly to the analogous changes in HDD, while the largest energy savings related to climate change were estimated for European countries with the highest population (Germany, Italy, France, Poland) or remarkable population density (the Netherlands). In regards to CDD, it was found not possible to establish the net effect of climate change on the households' energy consumption with the exemption of Finland and Italy, where the estimated increase of energy demand was significantly lower in absolute terms than the previously estimated energy savings.

The study contributes to the body of knowledge in multiple ways. First, it approaches the subject in a more tangible way, where the calculation of the HDD and CDD changes constituted only an initial phase of the analysis, followed by the more precise estimation of energy savings based on the results of regression analysis. Second, the study proposes a cumulative approach to the calculation of HDD and CDD, which accounts for the volatility of the HDD, CDD and its ability to significantly alter the amount of potential energy savings indicated by the commonly employed trend analysis. In terms of the findings, the study confirms the previous observations assuming a general decrease in HDD and an increase in CDD as a result of global warming, but it puts the results into a unique perspective by expressing the HDD/CDD changes as functions of the country's average temperature. Finally, the outcome of linear regression analysis highlights the rather negligible impact of climate change in the context of energy consumption for cooling, even in the warmest portion of the European countries. This indicates that climate change contributed to the net decrease in weather-related energy consumption of households and emphasises the primary importance of heating efficiency in the context of energy efficiency policy.

The contribution of the authors

Conception, S.P.-K., J.B., F.F., and A.S.; literature review, S.P.-K., J.B., F.F., and A.S.; writing, S.P.-K., J.B., F.F., and A.S.

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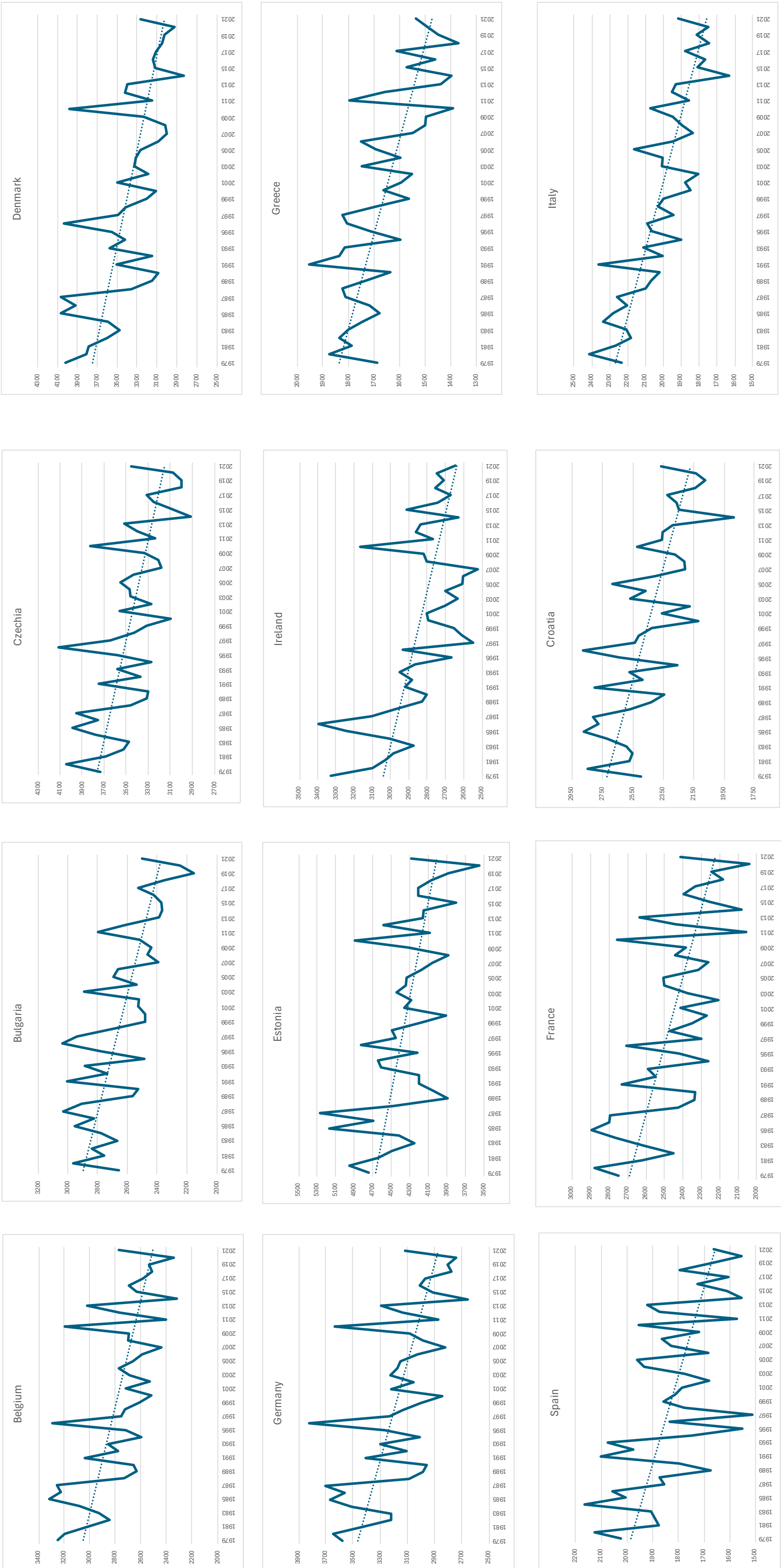
Appendix 1. Detailed results of the HDD and CDD change calculation

	HDD					CDD				
	Trend (1979)	Trend (2021)	Change – trend based	Trend change (%)	Change – cumulative	Trend (1979)	Trend (2021)	Change – trend based	Trend change (%)	Change – cumulative
Belgium	3055.2	2506.2	-549.0	18.0%	-20126.1	2.8	25.6	22.9	824.6%	607.5
Bulgaria	2898.7	2373.8	-524.9	18.1%	-910.1	55.7	196.2	140.5	252.3%	3413.7
Czechia	3763.7	3152.3	-611.4	16.2%	-12022.9	1.1	30.2	29.1	2665.8%	650.2
Denmark	3752.1	3025.5	-726.7	19.4%	-27246.5	-0.1	1.9	2.0	2600.0%	39.1
Germany	3465.1	2873.4	-591.6	17.1%	-17609.4	3.7	27.8	24.1	656.6%	590.0
Estonia	4673.4	4012.2	-661.1	14.1%	-17102.4	-2.3	11.6	13.9	609.2%	200.4
Ireland	3041.8	2637.6	-404.2	13.3%	-20965.0	0.1	-0.0	-0.1	107.2%	1.1
Greece	1837.4	1474.7	-362.7	19.7%	-1339.0	160.0	383.9	223.8	139.9%	4445.9
Spain	1985.0	1654.9	-330.1	16.6%	-8812.5	142.5	262.9	120.4	84.4%	3122.0
France	2688.6	2222,3	-466.4	17.3%	-12609.6	19.2	60.1	40.9	213.0%	1295.5
Croatia	2721.0	2170.4	-550.5	20.2%	-2334.0	36.4	182.1	145.7	400.5%	2935.7
Italy	2268.1	1757.6	-510.5	22.5%	-9544.6	89.3	280.9	191.6	214.6%	4707.6
Cyprus	908.2	651.2	-257.0	28.3%	5025.3	322.7	831.6	508.9	157.7%	9202.7
Latvia	4489.5	3830.6	-658.9	14.7%	-20106,6	-1.8	14.0	15.9	861.9%	252.5
Lithuania	4317.1	3655.4	-661.7	15.3%	-22724.8	-1.7	19.2	20.9	1237.9%	366.5
Luxembourg	3322.8	2734.8	-587,9	17.7%	-17554.3	5.4	37.5	32.2	601.0%	921.9
Hungary	3072.7	2583.9	-488.8	15.9%	-2778.0	25.2	131.1	105.9	420.3%	2188.5
Malta	642.9	425.4	-217.6	33.8%	-2670.1	445.6	703.1	257.6	57.8%	6095.9
Netherlands	3145.5	2491.3	-654.2	20.8%	-27202.1	1.1	19.2	18.2	1725.0%	436.3
Austria	3991.3	3346,0	-645.4	16.2%	-12263.2	2.0	31.2	29.2	1461.3%	668.0
Poland	3835.3	3189.4	-645.9	16,8%	-18170.6	0,6	29.7	29.1	4594.8%	495.1
Portugal	1355.0	1123,0	-232.0	17.1%	-10017.3	162.3	200.9	38.7	23.8%	1612.2
Romania	3378.8	2809.9	-568.9	16.8%	-2264.3	30.3	130.6	100.2	330.3%	2324.5
Slovenia	3289.2	2668.8	-620.3	18.9%	-9473.9	5.6	62.9	57.2	1015.8%	1214.3
Slovakia	3648.6	3072.9	-575.7	15.8%	-5735.3	5.3	55.9	50.5	952.9%	987.2
Finland	6080.8	5248.2	-832.5	13.6%	-13524.0	-0.3	3.0	3.3	1092.8%	58.6
Sweden	5692.6	4957.7	-735.0	12.9%	-23654.8	-0.0	0.8	0.8	2289.7%	13.3
Norway	5914.7	5305.4	-609.3	10.3%	-23582.8	-0.1	0.2	0.3	519.1%	4.0

Appendix 2. The HDD and CDD time series plots along with the linear trends (1979-2021)

HDD



Appendix 3. Detailed results of the single linear regression models measuring the standard households' energy use response to the changes in degree days (1990-2021)

HDD

Country	Obs.	F-test stat.	Prob> F	R-squared	Coefficient	P value
Belgium	31	134.91	0.000	0.818	1.968	0.000
Bulgaria	31	11.93	0.002	0.285	0.405	0.002
Czechia	31	61.08	0.000	0.671	0.990	0.000
Denmark	31	211.39	0.000	0.876	0.618	0.000
Germany	31	47.24	0.000	0.612	9.548	0.000
Estonia	31	1.49	0.232	0.047	0.042	0.232
Ireland	31	17.19	0.000	0.364	0.564	0.000
Greece	31	25.45	0.000	0.459	1.681	0.000
Spain	31	3.84	0.059	0.114	0.944	0.059
France	31	196.79	0.000	0.868	9.802	0.000
Croatia	31	128.98	0.000	0.811	0.559	0.000
Italy	31	82.13	0.000	0.732	9.282	0.000
Cyprus	31	2.62	0.116	0.080	0.047	0.116
Latvia	31	20.19	0.000	0.402	0.157	0.000
Lithuania	31	6.15	0.019	0.170	0.127	0.019
Luxembourg	31	11.68	0.002	0.280	0.059	0.002
Hungary	31	52.01	0.000	0.634	1.117	0.000
Malta	31	0.02	0.899	0.001	0.001	0.899
Netherlands	31	430.20	0.000	0.935	2.763	0.000
Austria	31	176.29	0.000	0.855	1.245	0.000
Poland	31	22.52	0.000	0.429	3.096	0.000
Portugal	31	0.02	0.888	0.001	0.013	0.888
Romania	31	0.01	0.919	0.000	-0.068	0.919
Slovenia	31	12.74	0.001	0.298	0.174	0.001
Slovakia	31	3.80	0.061	0.113	0.274	0.061
Finland	31	93.40	0.000	0.757	0.742	0.000
Sweden	31	30.37	0.000	0.503	0.757	0.000
Norway	30	81.01	0.000	0.736	0.450	0.000

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CDD

Country	Obs.	F-test stat.	Prob> F	R-squared	Coefficient	P value
Belgium	31	0.21	0.654	0.007	2.904	0.654
Bulgaria	31	2.01	0.166	0.063	0.585	0.166
Czechia	31	0.07	0.797	0.002	0.578	0.797
Denmark	31	0.11	0.743	0.004	-2.995	0.743
Germany	31	0.60	0.443	0.020	22.736	0.443
Estonia	31	0.98	0.331	0.032	0.876	0.331
Ireland	31	1.04	0.316	0.034	-647.241	0.316
Greece	31	1.96	0.172	0.061	1.433	0.172
Spain	31	1.63	0.211	0.052	0.244	0.211
France	31	0.00	0.981	0.000	-0.298	0.981
Croatia	31	0.39	0.538	0.013	0.218	0.538
Italy	31	3.29	0.080	0.099	5.855	0.080
Cyprus	31	0.05	0.819	0.002	0.015	0.819
Latvia	31	0.05	0.826	0.002	0.206	0.826
Lithuania	31	1.01	0.323	0.033	0.881	0.323
Luxembourg	31	0.00	0.995	0.000	0.001	0.995
Hungary	31	0.46	0.501	0.015	0.669	0.501
Malta	31	1.48	0.233	0.047	0.012	0.233
Netherlands	31	0.05	0.832	0.002	-2.700	0.832
Austria	31	0.18	0.678	0.006	1.196	0.678
Poland	31	0.05	0.817	0.002	2.547	0.817
Portugal	31	0.03	0.873	0.001	-0.033	0.873
Romania	31	0.02	0.893	0.001	-0.372	0.893
Slovenia	31	1.97	0.171	0.062	0.494	0.170
Slovakia	31	0.02	0.910	0.001	-0.125	0.901
Finland	31	12.96	0.001	0.302	35.588	0.001
Sweden	31	0.95	0.337	0.031	46.347	0.337
Norway	30	0.29	0.597	0.010	-51.928	0.597

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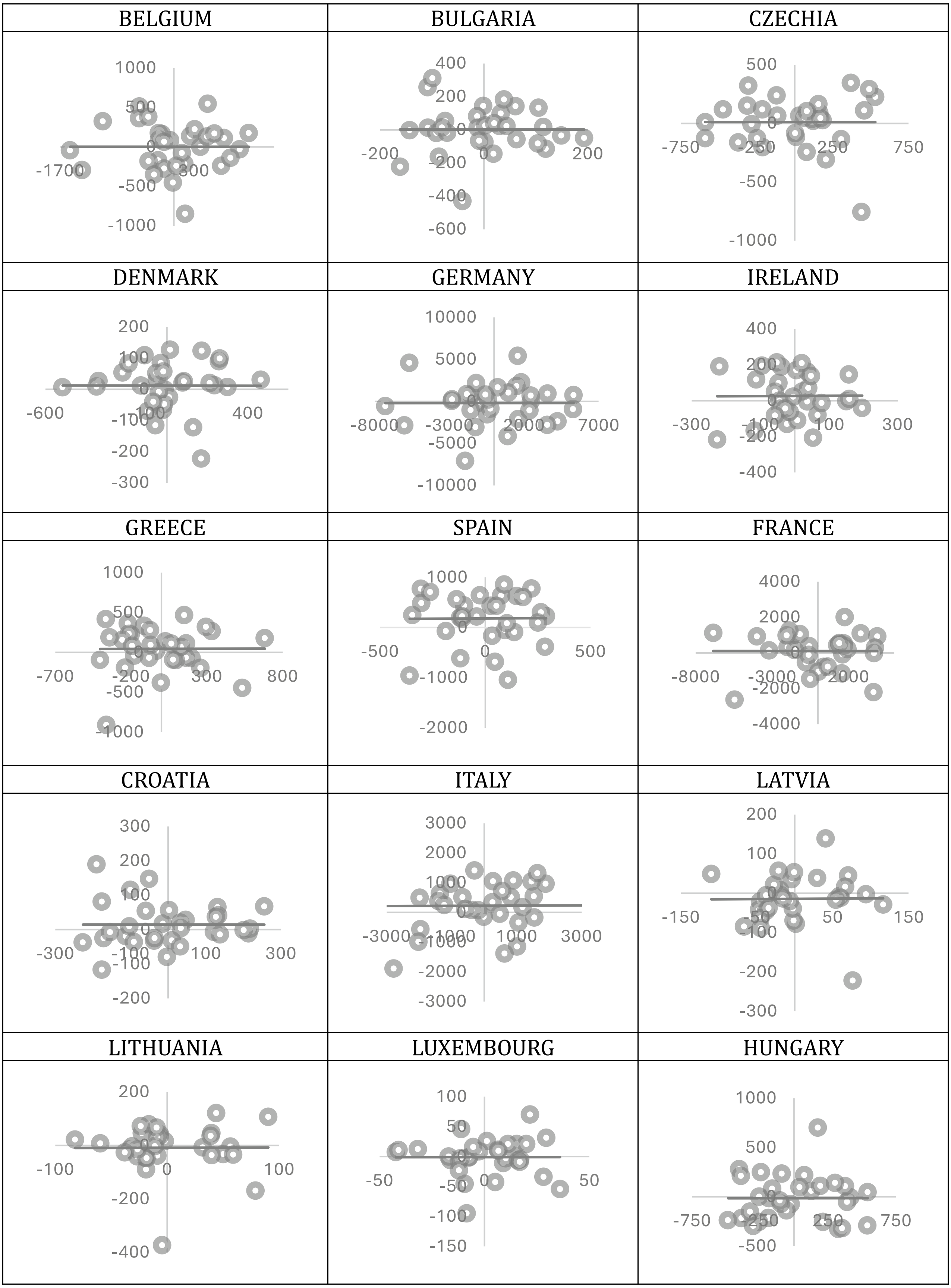
Appendix 4. Regression diagnostics – residual (Y axis) vs fitted (X axis) plots with time trends for the statistically significant regression models

Regression 1. HDD changes as a predictor of households' final energy use



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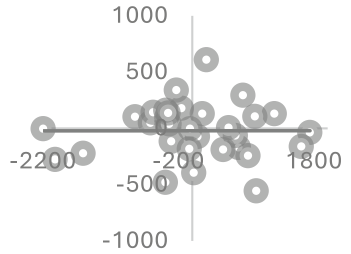
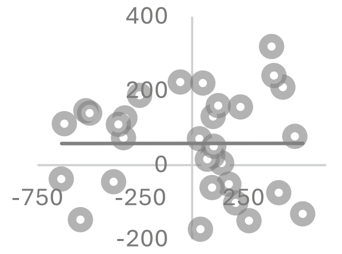
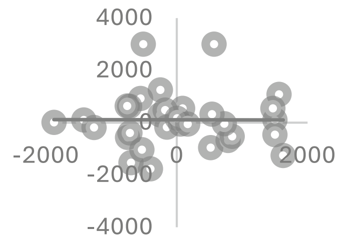
<tr><td>
</td><td>
</td><td>
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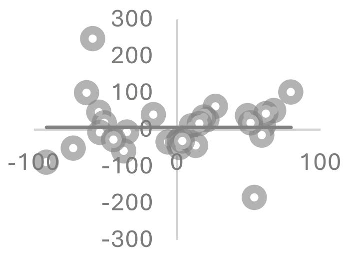
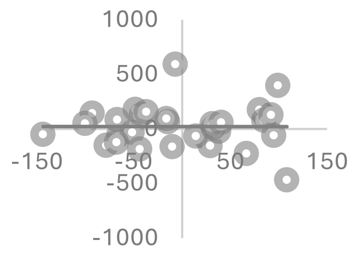
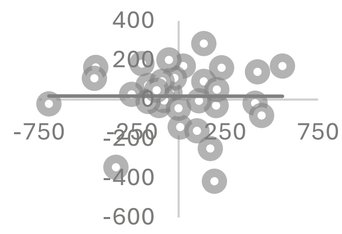
<tr><td>
</td><td>
</td><td>
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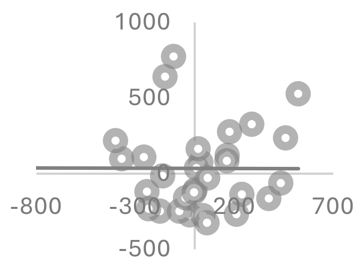
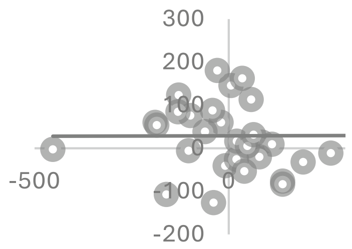
<tr><td>
</td><td>
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Regression 2: CDD changes as a predictor of households' final energy use

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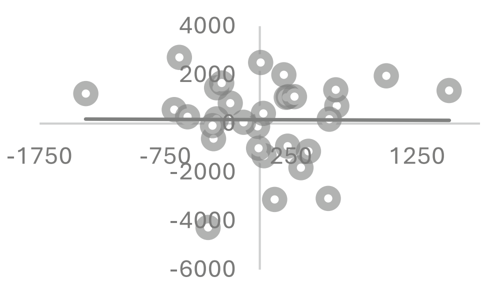
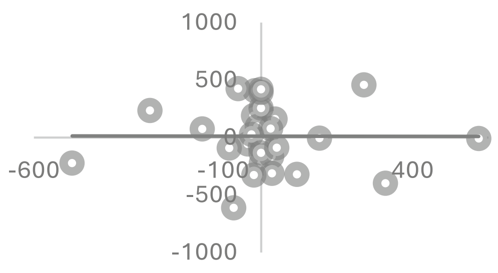
<tr><td>
</td><td>
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Sylwia PANGSY-KANIA • Justyna BIEGAŃSKA • Floros FLOUROS • Aneta SOKÓŁ

STOPNIODNI GRZANIA I CHŁODZENIA A ZMIANY KLIMATU W LATACH 1979-2021. PRZYKŁAD UNII EUROPEJSKIEJ I NORWEGII

STRESZCZENIE: Zużycie energii jest silnie uzależnione od warunków pogodowych. Z tego względu, w celu kształtowania polityki energetycznej kluczowego znaczenia nabiera obserwacja zmian w zakresie stopniodni ogrzewania (HDD) i stopniodni chłodzenia (CDD), powszechnie wykorzystywanych wskaźników zmian klimatycznych. Przedmiotem badania był wpływ zmian klimatycznych (globalnego ocieplenia) na liczbę HDD i CDD, jak również oszacowanie wpływu tych zmian na uwarunkowane pogodowo zużycie energii przez europejskie gospodarstwa domowe (w UE-27 i Norwegii), na podstawie danych Eurostat z lat 1979-2021. Badanie wykazało, iż zmiany HDD i CDD stanowią nieliniowe funkcje przeciętnej temperatury powietrza, a największe zmiany w ujęciu procentowym zaobserwowano w najcieplejszych (w przypadku HDD) i najzimniejszych (w przypadku CDD) regionach UE. Jak wykazały estymacje oparte na indywidualnych regresjach liniowych na pierwszych różnicach zmiennych, zmiany klimatyczne przyczyniły się dotychczas do zmniejszenia uwarunkowanego pogodowo zużycia energii przez europejskie gospodarstwa domowe.

SŁOWA KLUCZOWE: stopniodni grzania, stopniodni chłodzenia, zmiany klimatu, konsumpcja energii, bezpieczeństwo energetyczne, zrównoważony rozwój

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