Energy Policy 101 (2017) 225–235

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Estimation of European Union residential sector space cooling potential

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ARTICLE INFO

Keywords:
Space cooling
Residential sector
Cooling demand
Energy system
Climate

ABSTRACT

Data on European residential space cooling demands are scarce and often of poor quality. This can be concluded from a review of the Comprehensive Assessments on the energy efficiency potential in the heating and cooling sector performed by European Union Member States under Art. 14 of the Energy Efficiency Directive. This article estimates the potential space cooling demands in the residential sector of the EU and the resulting impact on electricity generation and supply systems using the United States as a proxy. A georeferenced approach was used to establish the potential residential space cooling demand in NUTS-3 regions of EU. The total potential space cooling demand of the EU was estimated to be 292 TW h for the residential sector in an average year. The additional electrical capacity needed was estimated to 79 GW. With proper energy system development strategies, e.g. matching capacity of solar PV with cooling demand, or introduction of district cooling, the stresses on electricity system from increasing cooling demand can be mitigated. The estimated potential of space cooling demand, identified in this paper for all EU Members States, could be used while preparing the next iteration of EU MS Comprehensive Assessments or other energy related studies.

1. Introduction

The demand for space cooling is growing rapidly worldwide. The International Panel on Climate Change (IPCC) estimates that the demand for residential space cooling will rise from 300 TW h in 2000 to 4000 in 2050 and 10,000 in 2100 (Arent et al., 2014). Cooling demand is the fastest growing end use in buildings. The EU Heating and cooling strategy also foresees a strong increase in residential cooling consumption, i.e. from about 35 TW h in 2015 to 137 TW h in 2050 for the reference scenario and 78 TW h the energy efficiency scenario[2] in 2050 (European Commission, 2016).

Nevertheless, the space cooling demand in the Member States of the European Union is often not well established or even unknown today. Also, at the European level, Eurostat does not monitor energy use for cooling in their energy balances. This is due to the fact that most space cooling is provided by electric air-conditioned units, while European statistics do not differentiate how the electricity is used, e.g. for cooling, lighting or other purposes.

Accurate data on existing and future cooling demands are elementary for realistic and good energy policy decisions. For example, the Article 14 of the Energy Efficiency Directive (EED) 2012/27/EU (European Parliament, 2012) requires Member States of the European Union to carry out Cost-Benefit Analyses (CBA) on the economic efficiency potential in the heating and cooling sectors. Based on the outcome of the CBA Member States should design energy strategies, policies, and measures so as to realise the identified economic efficiency potential. The lack of knowledge of the current and projected cooling demand is a major obstacle for many Member States when performing their CBAs[3] and designing their policies. In this case, more than half of the Member States could not establish their present cooling demand and only five provided a forecast of future residential space cooling demand.

The lack of knowledge about cooling is a source of uncertainty for related sectors too. For example, a large increase in cooling demand requires more power generation capacity and sometimes it may also necessitate reinforcements of electrical transmission grids. Nevertheless, with proper energy planning the extent of grid reinforcements required by greater cooling demand can be mitigated or even avoided. One mitigation factor could be to ensure an appropriate local solar PV electricity generation since it has the characteristic to coincide with usage of electric air-conditioning units. Another potent option could be to promote district cooling grids in urban areas, since such grids require less electricity, they can be used to balance electrical load, and they facilitate the introduction of low carbon heating and cooling

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[1] The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

[2] EE27 cooling.

[3] https://ec.europa.eu/energy/en/topics/energy-efficiency/cogeneration-heat-and-power.

http://dx.doi.org/10.1016/j.enpol.2016.11.047
Received 12 May 2016; Received in revised form 11 November 2016; Accepted 28 November 2016

supply.

There are several policy initiatives to reduce energy consumption in buildings, e.g. the Energy Performance of Buildings Directive (EPBD). The EPBD requires that all new buildings will be near zero energy buildings by 31 December 2020 and renovation of new buildings follow certain rules in order to improve energy efficiency in buildings. Member States have to ensure that energy performance of buildings is set at cost-optimal levels. Heating demand will have to decrease with time since it is the largest share of energy demand for heating and cooling. With regard to cooling, the requirement of cost-optimisation might at first not affect the trajectory much since it is a small share of the cost. Hence, in this phase improving thermal insulation of windows and walls might actually increase cooling demand. Gradually, as cooling demand increases, the efficiency measures to slow cooling demand become more tangible. Then other measures that reduce the cost for cooling become more important, e.g. shading, passive cooling. As was discussed by (Aebischer et al., 2007) the effect of insulation improvement on cooling demand is not clear. On the one hand, probability of overheating is increased due to more heat being trapped inside of the building. On the other hand, proper use of ventilation, especially at night, might negate potentially negative impact of building insulation improvement. Due to the uncertainty about the trajectory for cooling demand, it was decided to focus on setting a ceiling for the cooling demand in this study.

Several studies have been performed on present cooling demand and a few on future cooling demands (JRC, 2012; Odysee-Mure, 2014). The methodologies used for their analyses differ as well as the cooling demand estimated. The difference in results is often substantial, i.e. up to a factor two in the residential sector of the EU, which is a good illustration about the uncertainties involved. This paper chooses a new approach for estimating the potential cooling demand in the residential sector of the EU by using the US as a proxy. It employs a geo-referenced approach to establish a relationship between the cooling demand and the number of cooling degree days in 3141 counties of the US. This relationship is then used to provide an estimation of potential cooling demand in 1335 NUTS-3 regions of the EU using their number of cooling degree days as the input parameter.

Space cooling in the USA is more common in all the sectors of the economy, including households. It has been analysed in greater detail in the US since it is a greater part of the energy system and because more data is publicly available there than in Europe. The space cooling demand in the EU and the US differs for several reasons such as different habits concerning comfort levels for cooling and possible differences in thermal characteristics of the buildings. During the preparation of this article it was assumed that under the same climatic conditions in USA and EU building energy performance would be of the similar level. As was demonstrated by (Berkland, 2014) that the building codes in USA and Europe are of comparable levels at equivalent energy performance requirements.

This paper has the following structure: (1) description of the methodology used, (2) describe the current space cooling demand in the EU, (3) climatic conditions and energy consumption for residential space cooling in the US, (4) climatic and potential cooling demand in the EU, (5) impact of potential residential cooling demand on energy generation and supply systems of EU countries, (6) uncertainties and method limitations, and finally (7) to present conclusions and policy implications.

2. Methodology

2.1. General methodological considerations

The analysis of this article comprises the following methodological steps, see Fig. 1. The activities from Fig. 1 are explained in more detail below in the text.

The most common climatic indicator of the heating and cooling demand is the degree day, which is a measure of the average temperature departure from a set base temperature (Issac and van Vuuren, 2009) and are widely used when describing relationship between space cooling demand and climatic conditions (Kemna and Acedo, 2014). Cooling degree days are calculated as an accumulated temperature difference above a set base temperature. The base temperature was set at 18 °C in this study. If the mean temperature for a given day is greater than this base temperature, the difference between these two temperatures is counted as a number of degree days of that particular day. If the temperature is less, then the degree days of such a day are equal to 0.

2.2. Space cooling indicators using data on USA

In order to determine the relation between energy consumption for space cooling and climatic conditions, cooling degree day (CDD) values were calculated for 834 metrological stations located across mainland USA territory. The CDDs were calculated using daily temperature information, derived from databases of US Historical Climatology Network (Menne et al., 2015) according to the formula:

$$CDD=\sum_{O=1}^{n}(\theta_0-\theta_H) \tag{1}$$

here n is a number of hot season days when outdoor temperature is above the base temperature; θ_H – base temperature for CDD, °C; θ_o –an average outdoor temperature of a particular day, °C.

Mean CDD values were calculated for each meteorological station as a 20 year average for annual CDD (1995–2015) and imported into a GIS map of USA. A raster surface was generated through using an inverse distance weighted (IDW) interpolation[4] from GIS Spatial analysis tools. The resolution of the resulting raster was 1 km^2. It was joined with the administrative map layer of USA counties (USCB, 2015) using GIS Spatial join tool. This allowed establishing CDD values for each county in mainland USA, 3141 counties in total. Mean CDD values in each county were used to calculate a CDD value for each state using household count in counties as a weighting factor according to the formula:

$$CDD_j=\sum\frac{h_{ij}}{h_j}\bullet CDD_{ij} \tag{2}$$

here CDD_j – mean cooling degree days of the state j; h_j – household count of the state j; h_{ij} – household count of the county i located in the state j; CDD_{ij} – mean cooling degree days of the county i located in the state j.

Information about the total number of households and population number in each county was taken from (USCB, 2015).

The specific energy consumption for cooling, $Q_{cooling}$, and cooling penetration *PNT* were calculated for the state or group of states using data from US Energy Information Administration (USEID, 2012) database, which contains information about energy consumption per household and square foot per household in different states as well as the share of houses where air conditioning (AC) is used.

Final energy consumption was recalculated into useful cooling demand based on information about the age of used AC systems (USEID, 2012) as well as seasonal energy efficiency ratio (SEER) values.[5] The SEER values were calculated assuming that air conditioners met the minimum energy efficiency requirements of a particular year as set in the Code of Federal Regulations 10 CFR 430.32(c)(1) (USA Government, 2012). The average SEER value of AC equipment

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[4] This interpolation method assumes that the mapped variable (mean CDD values of different weather stations in this case) decreases in influence with the distance from its sampled location.

[5] SEER is defined as the overall energy efficiency ratio of a space cooling unit over the whole cooling season and is calculated as the ratio of annual cooling demand and annual electricity consumption for cooling.

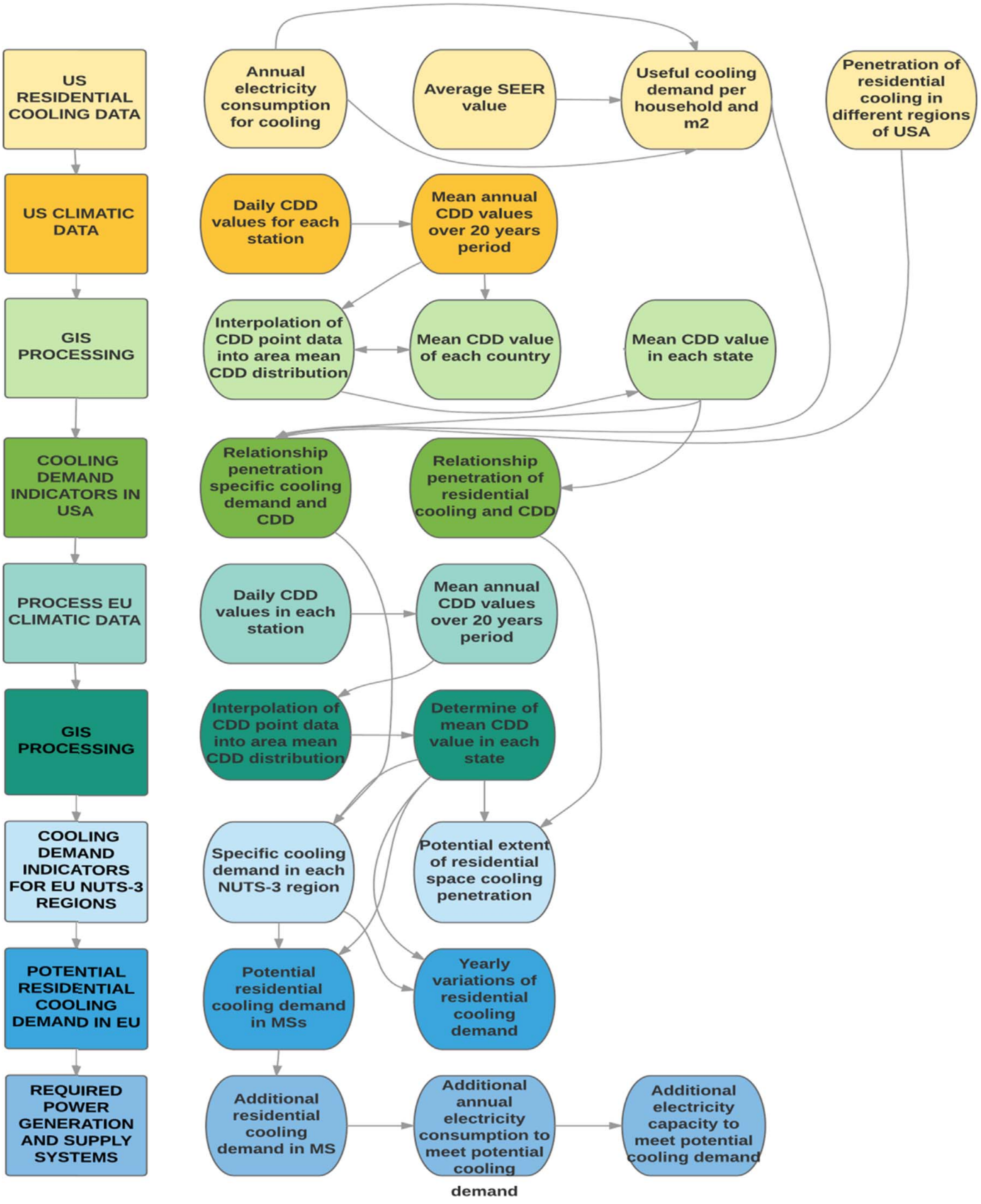

Fig. 1. Successive activities performed during preparation of the article.

currently used in USA was calculated to be equal to 2.85.

2.3. Estimating residential space cooling demand potential in EU

Mean CDD values for EU were calculated for 894 meteorological stations for the years 1995–2015, located throughout EU, Norway, Switzerland and other neighbouring countries, such as Balkan countries, Turkey, Russia etc., using European Climate Assessment and Dataset (Klein Tank and Coauthors, 2002). Mean CDD values for all the Member States were determined using GIS tools following the same procedure as described for USA. The colour scale of the European maps was retained as for the US maps.

The European residential space cooling demand potential was estimated using 1335 NUTS-3 regions based on cooling indicators determined from using data on USA households. The following formula was used:

$$Q_{cooling}^{useful}=Q_{cooling}\bullet A\bullet PNT \tag{3}$$

here $Q_{cooling}^{useful}$ –annual residential space cooling demand potential in particular NUTS-3 region, kWh/a; $Q_{cooling}$ – specific cooling demand, which depends on CDD value of a particular NUTS-3 region, kW h/m^{2}a; A – residential building stock in a particular NUTS-3 region, m^2; PNT – estimated percentage of households using AC as a function of CDD value of a particular NUTS-3 region.

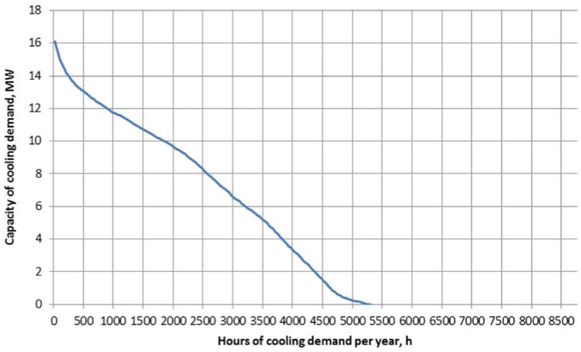

Fig. 2. An example of annual space cooling capacity distribution graph.

2.4. *Electricity generation and supply systems*

The last step of the analysis was to evaluate potential impact of increased space cooling demand on the electricity generation and supply systems per MS. It was assumed that cooling is provided by electrical air conditioners. Annual cooling demand distribution graphs were constructed for each NUTS-3 region assuming a direct relationship between the CDD and estimated space cooling demand $Q_{cooling\ a}^{NUTS-3}$ in that region. The ratio $Q_{cooling\ a}^{NUTS-3}/CDD_{NUTS-3}$between potential residential space cooling demand and the mean CDD value was calculated for each NUTS-3 region. The annual distribution of cooling demand divided in 24 h segments was estimated based on temperature variability data per meteorological station. An example of annual cooling capacity distribution graph is presented in Fig. 2.

3. Description of current residential space cooling demand in EU

There exists only limited data on the consumption of energy for space cooling of buildings in the Member States of the EU or the Union as a whole. Unlike the heating sector, which is well covered and analysed, the space cooling sector has been mostly overlooked, especially in colder climate regions. The data sources provide quite diverging estimates of current EU and separate Member States' demands. Most studies provide just pan European aggregations without or with only limited data on separate countries. The estimated present cooling demand in the EU have been estimated in several studies (JRC, 2012; Odyssee-mure, 2014; Werner, 2015; Kemna and Acedo, 2014), see Fig. 3.

The report of Joint Research Centre of European Commission on Heat and cooling demand (JRC, 2012) estimated that space cooling demand in EU-27 countries in 2009 was equal to 24 TWh/a. The authors stated that the cooling market was predicted to grow at a fast pace of approx. 3.14% per year.

(Werner, 2015) assumed that the residential cooling supply in EU-28 countries in 2010 was equal to 47 TW h/a. This paper also included estimated cooling supplies breakdown per EU country.

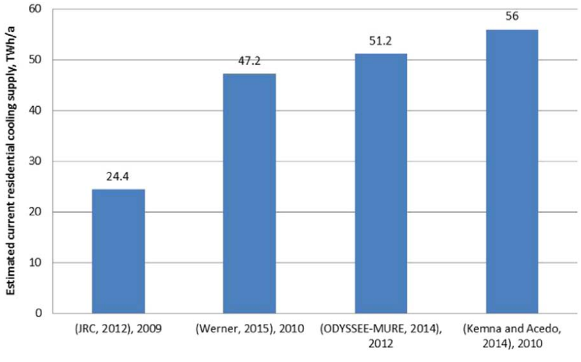

Fig. 3. Estimation of current residential cooling supply in EU as made by different authors. Year corresponds to the year for which estimation was made.

A report published as a part of ODYSSEE-MURE project (Odyssee-Mure, 2014) estimated that the energy consumption for space cooling in households of EU in 2012 amounted to 17 TW h/a. This is 0.5% of the total energy consumption in households and corresponds to 51 TW h/a of useful residential cooling demand. That same report indicates that significant energy consumption for cooling exists only in southern and south-eastern EU countries (Malta, Cyprus, Bulgaria, Italy, etc).

EU residential space cooling demand was estimated by (Kemna and Acedo, 2014) to be equal 56 TW h/a in 2010. The authors based their estimation on the assumption that room air conditioners are used for residential cooling while central air conditioners are used in service sector.

There are also some attempts to estimate cooling demand on much lower dimension. (Day et al., 2009) estimated current and future cooling demand in London area. The authors assumed that the cooling demand of buildings in the UK is equal to 15 TW h/a of energy demand, 11% of it accounted for in London. These numbers seem to be much higher than reported in other studies. This also points to the fact that precisely estimating cooling demand is not easy even on region or country scale.

An Austrian study (EEG, 2011) estimated that in residential buildings of Austria electricity consumption for cooling in 2007 was equal to 0.019 GW h/a which would correspond to useful cooling demand of 0.057 TW h/a. The same study forecasted an increase in residential cooling demand in Austria up to 1.37 TW h/a by 2030.

Accurate and exhaustive information about the cooling demand in general and in the residential sector in particular were expected to be presented in the Comprehensive Assessments on the energy efficiency potential in the heating and cooling sector, prepared by December 2015 as required by Article 14 of the Energy Efficiency Directive 2012/27/EU (European Parliament, 2012). The results of these analyses should be used by Member States in shaping policies for implementation of efficient heating and cooling systems and implementing identified potential of efficient heating and cooling technologies. One of the main requirements of EED Article 14 and related Annexes of EED is the description of heating and cooling demand of Member States. However, Member States had great difficulties in providing such results.[6] Out of 28 Member States only 8 reported values of current space cooling demand in the residential sector, further 3 assumed that no such demand exists, and the remaining 17 included no analysis of residential space cooling or even cooling in general. The main reasons stated were often the lack of statistical data on cooling demand at both local and national level and insufficient knowledge of space cooling prevalence.

Table 1 presents different studies that estimated the residential cooling supply in different EU countries.

4. Climatic conditions and energy consumption for residential space cooling in the United States

4.1. *Description of available data*

One of the most reliable data sources on energy consumption in the households of the US is the series of residential energy consumption surveys, performed by US Energy Information Administration, the most recent being for 2009 (USEID, 2012). Analysis of these databases shows that in 2009 more than 87% of the households in USA (out of the total 113.6 mill. households) had AC equipment installed. In comparison, in 1993 68% of households were equipped with AC units.

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[6] https://ec.europa.eu/energy/en/topics/energy-efficiency/cogeneration-heat-and-power.

Table 1
Estimations of current residential cooling supply from different studies.

Country	Current residential cooling demand, TW h/a		
	(JRC, 2012)	(Werner, 2015)	Comprehensive assessments
Austria	0.03	0.23	N/A
Belgium	0.61	0.23	0.08
Bulgaria	1.25	1.51	N/A
Croatia	n.a.	1.08	0.78
Cyprus	0.17	2.34	1.68
Czech Republic	0.89	0.12	N/A
Denmark	0.00	0.05	N/A
Estonia	0.00	0.00	N/A
Finland	0.75	0.08	0.12
France	10.33	3.52	N/A
Germany	0.19	1.91	N/A
Greece	0.56	3.23	3.28
Hungary	0.00	0.46	N/A
Ireland	0.00	0.00	0
Italy	4.19	15.50	4.01
Latvia	0.00	0.02	N/A
Lithuania	0.00	0.03	N/A
Luxembourg	0.00	0.00	N/A
Malta	0.03	0.63	0.14
Netherlands	0.75	0.48	N/A
Poland	0.83	0.19	N/A
Portugal	0.42	1.12	N/A
Romania	0.33	0.90	N/A
Slovakia	0.14	0.04	N/A
Slovenia	0.00	0.47	N/A
Spain	2.08	11.92	2.23
Sweden	0.83	0.13	N/A
United Kingdom	0.00	1.05	0
EU-28	24.38	47.24	–

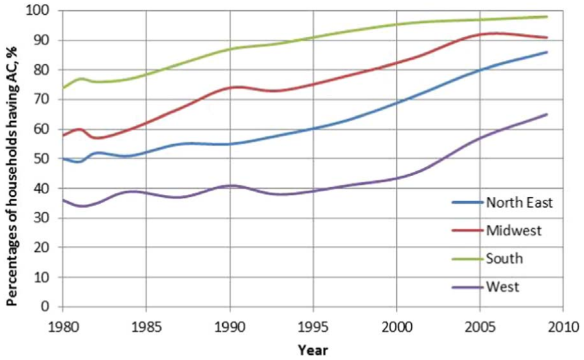

Fig. 4. Households using air conditioners in different regions of USA.

The use of AC equipment has risen constantly over the last decades, although rates varied for different climatic regions of USA, as presented in Fig. 4. The rising cooling demand was associated with: housing boom, improved energy efficiency standards of equipment, shift of the population to hotter and more humid regions (USEID, 2011). It should be noted that the increase in space cooling saturation in USA is tempered by regional usage patterns. Households in the Southern region are much more likely to use space cooling equipment as those of the western region.

Total electricity consumption for cooling in the whole USA in 2009 was equal to 186.1 TW h/a. In 1993 it was equal to 134.8 TW h/a, which is a rise by 38%.

The largest amounts of electricity of AC units in 2009 have been consumed in the South census region of USA – 128.7 TW h/a or 69% of the total consumption. It includes 16 states, such as Texas, Florida, Georgia, Virginias and others as well as District of Columbia. Its population is 117.2 million, 36.5% of the total population of USA.

4.2. Climatic conditions in USA

Fig. 5 is GIS map displaying the average CDD values for a period of 20 years. Peak values can be found in the southern states of Texas and Florida, where CDD is more than 2400 CDD. Around the Great Lakes and in the mountainous areas the CDD is practically zero.

4.3. Determining residential space cooling indicators

Dependency of final energy consumption for space cooling and useful cooling demand on mean CDD values is presented in Fig. 6. A CDD value for each point was calculated as the weighted average of particular state taking into account the number of households, actually using AC equipment in a particular county. It should be noted that Fig. 6 contains 37 data points while there are 48 states in mainland USA. Statistical data for USA (USEID, 2012) is available for separate states as well as their groups. This is particularly the case for Eastern USA states which have small territories.

As can be seen in Fig. 6, specific cooling demand in residencies is highly dependent on climatic conditions and can be generalised using linear equation. Linear regression was used to describe the data distribution. As can be seen in Fig. 6, the linear regression line explains almost 87% of all identified response variable variations.

$$Q_{cooling}=0.051\bullet CDD+1.483 \tag{4}$$

here $Q_{cooling}$ – specific residential cooling demand, kW h/m^{2}a; CDD – cooling degree days of particular locality.

USEID databases contain statistical information about households having AC equipment and their usage. Dependency on the share of households using AC equipment in different states on climatic conditions is generalised in Fig. 7. Each data point represents mean CDD values over 20 year period.

Fig. 7 shows that different regression methods were chosen for two intervals of CDD. Dependency of AC use on climatic conditions is non-linear until at approx. 920 CDD. At this point almost full penetration of AC equipment is reached. The initial part (from 0 till 920 CDD) of the curve can be generalised by the following logarithmic equation:

$$PNT=26.33*\mathrm{LN}(CDD)-81.69 \tag{5}$$

here PNT – percentage of households using AC equipment, %.

In the second interval of data linear regression was used. This means that in locations were mean CDD value exceeds 920, almost all households use AC equipment (average maximum penetration is 97.3%).

When forecasting cooling demand it is important to know when households begin to use cooling equipment, e.g. what climatic conditions encourage people to install and use such equipment? An observation from Fig. 7 is that in colder climates, there is a tendency that a larger mean CDD values causes significant increase in space cooling equipment use. For instance, in counties with CDD values of 100, which in USA are classified as belonging to cold/very cold climatic region, approx. 40% of households are still using space cooling. As CDD increases till 200 would correspond to the space cooling penetration increase till approx. 58%.

5. Climatic conditions and potential cooling demand in European Union

5.1. Climatic conditions in European Union

The map of the EU with the mean CDD values determined for each NUTS-3 region using data from 894 meteorological stations and GIS spatial analysis tools is presented in Fig. 8. Here parts of Northern Scandinavia are omitted due to the low mean CCD values obtained and low population density.

The highest mean CDD values were registered for Cyprus in Nicosia

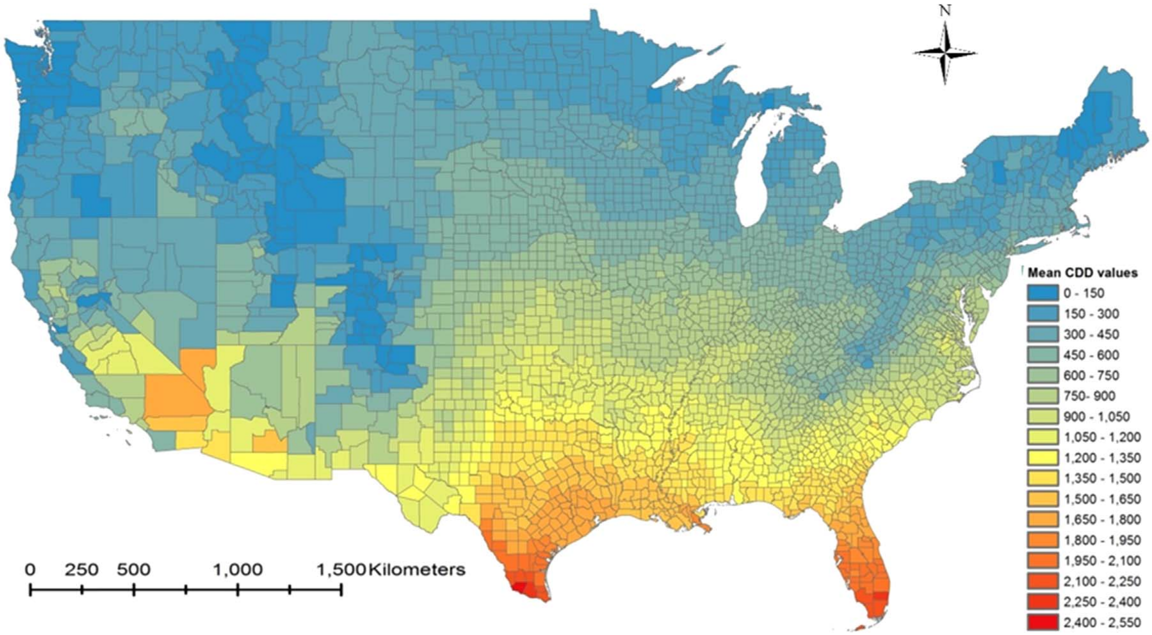

Fig. 5. Distribution of CDD values in USA mainland counties.

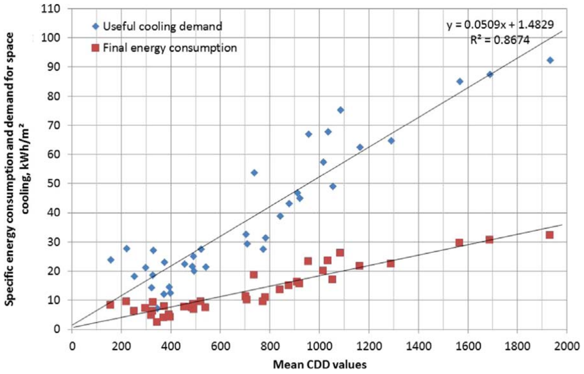

Fig. 6. Dependency of final specific energy consumption for cooling and useful cooling demand in residencies of USA on climatic conditions.

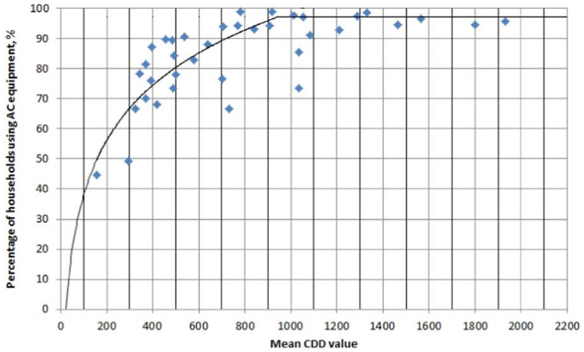

Fig. 7. Dependency of air conditioning equipment use on climatic conditions in mainland USA.

(1617). Mean CDD values for other weather stations in Cyprus were significantly lower, for instance 1325 in Limassol and 1134 in Paphos. This shows that climatic conditions can be very local, but still have a large influence on the energy consumption.

High mean CDD values were also calculated for other stations located in Southern Europe, particularly in Malta, Southern Spain, Greece and Italy. Calculated CDD values for EU Member States are presented in Table 2. Compared to the USA these CDD values are still rather moderate.

The lowest mean CDD values were calculated for Northern and North-western Europe as well as mountainous localities in other regions. The lowest mean CDD values were calculated for the stations located in Ireland, for which all mean CDD values were below 10. In contrast, mean CDD values of 80 were reached by a number of stations in Finland. This can be explained by prevailing maritime climate of Ireland, characterised by cool summers and lack of temperature extremes.

5.2. Estimation of average yearly residential cooling demand potential in EU Member States

The estimation was based on the assumption that under the same climatic conditions space cooling demand potential, characterised by specific cooling demand and AC penetration, would be similar both in USA and European dwellings in the longer perspective.

The estimated potential use of space cooling equipment was calculated as a weighted average of dwelling count in constituting NUTS-3 regions using averaging Eq. (5). For regions where mean CDD values exceeded 920, a penetration of AC equipment equal to 97% was assumed (see Fig. 7).

It should be noted that the specific cooling demand, presented in Table 2, was calculated taking into account potential penetration of space cooling equipment in the residential sector. It can be concluded that the potential penetration of AC equipment in different EU countries varies greatly, but generally follows north-south and to somewhat lesser extent west-east gradients. According to the data presented in Table 2, potential penetration of AC equipment in Ireland is equal to 0, which is the lowest indicator of all EU countries and is directly related with the climatic conditions of Ireland, expressed in the low value of CDD. In the case of other EU countries the potential penetration of residential space cooling ranges from 12% in Sweden till 97% in Cyprus and Malta.

Regionally, the lowest residential space cooling penetration is expected in Nordic (3.7–4.3%) and Baltic countries (4.9–7.3%) as well as portions of Central and Western Europe with maritime climates, such as Netherlands, Belgium and UK (4.7–6.9%). The highest penetration of cooling is expected in countries of Southern Europe such as Cyprus, Malta, Southern Spain, Southern Italy, Greece with 34–97% and Balkan region countries, such as Croatia, Bulgaria and

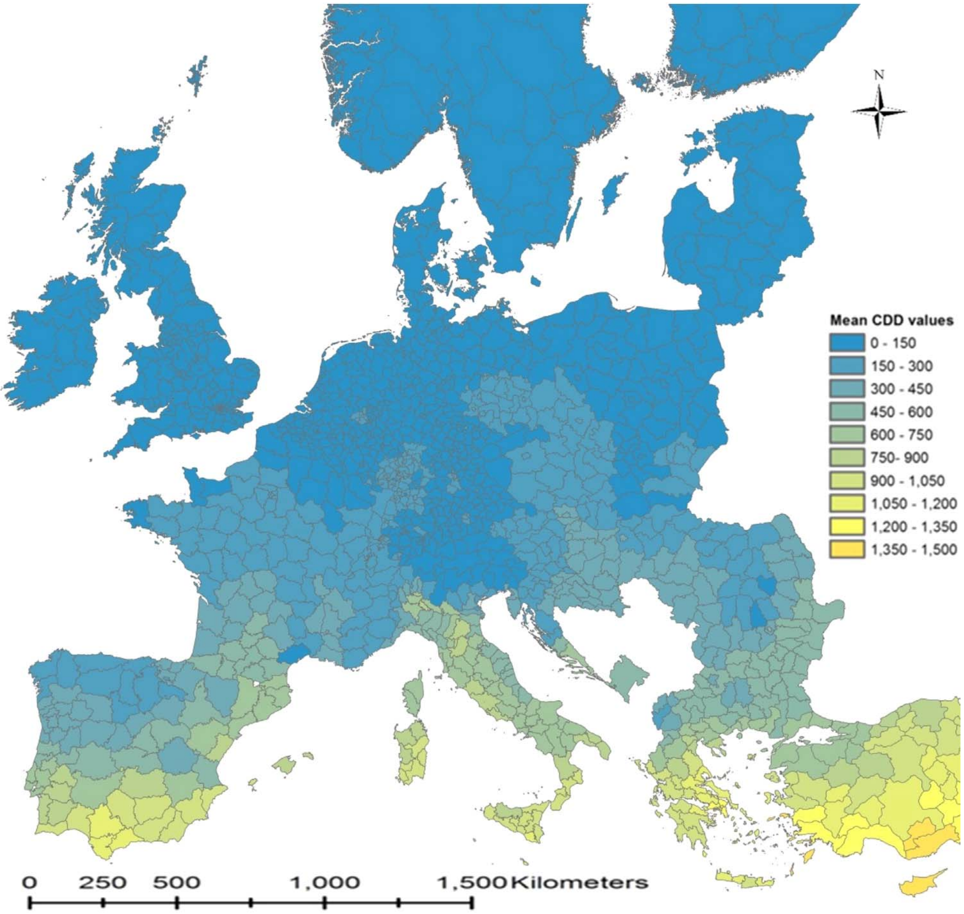

Fig. 8. Distribution of mean CDD values in NUTS-3 regions.

Romania with 20–26%.

Specific cooling demand follows similar tendencies, the lowest (3.7 kW h/m^{2}a) being in the case of Sweden (not counting Ireland which has 0) and the highest (76 kW h/m^{2}a) being in the case of Cyprus, which has highest value of both mean country and NUTS-3 region CDD (1457).

Calculated specific cooling demand, as presented in Table 2, generally agrees well with data on space cooling in European countries. For instance, a report on Definition of the Near Zero Energy Residential Buildings in Cyprus (MECIT, 2012) reveals that specific cooling demand for single family houses is equal to 49.5 kW h/m^{2}a and in apartment buildings to be equal to 69.3–82.9 kW h/m^{2}a. Another report from Cyprus (CYSTAT, 2013) estimated the current specific residential cooling demand to approximately 66 kW h/m^{2}a.

The calculated potential penetration of residential space cooling in different NUTS-3 regions and specific cooling demand were used to estimate the yearly potential cooling demand of each such region. The results were aggregated for each Member State, see Table 3.

The Table 3 contains three types of potential cooling demands. The first one is an average potential yearly cooling demand, based on the mean CDD values, calculated as a 20 year average and presented in Fig. 8. As can be seen in Table 3, the total average yearly cooling demand in EU countries can potentially reach 292 TW h/a. The largest part (70.8% or 207.04 TW h/a) can be expected to be used in four Southern European countries (Italy, Spain, Greece and Portugal). Combined expected cooling demand in Germany and France is 15.2% (44.46 TW h/a) of the total, although this is more due to the size of the housing stock than to the intensity of space cooling need, especially in the case of Germany.

5.3. Sensitivity analysis

While average potential cooling demand values give an indication of demand on average year, it will not show the cooling demand in extreme years, with which the energy supply system of a country will have to cope eventually. Therefore Table 3 includes a second indicator – maximum yearly cooling demand. This indicator was calculated using yearly CDD value which is the highest over 20 year period 1995–2015) in a given NUTS-3 region. In 35% of included weather stations this was 2003, followed by 2006 (19%) and 2014 (16%). Geographical distribution of the highest CDD values is presented in Fig. 9.

The calculation of maximum yearly cooling demand of EU countries was done assuming that the potential penetration (in %) of residential space cooling will remain the same as in the case of mean CDD days, as explained previously. The rationale behind such an assumption being that inhabitants would likely opt for cooling equipment installation in their home or apartment based on long term cooling demand and not on a single year. Therefore potential cooling demand in Ireland would still be equal to 0.

As we can see in Table 3, potential maximum residential cooling demand in EU might reach 404 TW h/a, which is almost 40% higher than the average demand. Cooler climate countries would likely experience higher climatic divergences leading to increased cooling demand in some years and, as a consequence, increased electricity consumption in space cooling equipment.

However, there are years when cooling demand is much lower than the average and therefor Table 3 includes the third indicator – minimum potential yearly cooling demand. Similarly to maximum CDD values, this indicator was calculated using yearly CDD value which is the lowest over 20 year period 1995–2015) in a given NUTS-3

Table 2
Estimated potential specific residential cooling demand and air conditioning penetration in dwellings of EU.

Country	NUTS-3 region with the highest CDD value	NUTS-3 region with the lowest CDD value	Mean CDD value	Potential penetration of space cooling, %	Specific cooling demand, kW h/m^2a
Austria	11	338	188	58.2	14.1
Belgium	83	130	94	40.4	6.9
Bulgaria	399	560	418	80.3	25.6
Croatia	195	691	299	74.0	22.1
Cyprus	1457	1457	1457	97.3	75.8
Czech Republic	56	288	134	54.8	11.6
Denmark	41	61	42	23.1	4.3
Estonia	53	73	68	28.7	4.9
Finland	14	61	14	16.3	4.0
France	69	680	95	59.7	15.5
Germany	30	266	53	46.1	8.8
Greece	542	1360	612	95.7	55.5
Hungary	214	395	236	69.4	17.6
Ireland	3	14	3	0	0
Italy	62	1059	107	82.5	34.4
Latvia	70	98	74	35.0	5.9
Lithuania	89	113	104	39.8	7.3
Luxembourg	98	98	98	39.0	6.5
Malta	1173	1181	1173	97.3	61.7
Netherlands	58	128	68	34.1	5.8
Poland	60	193	64	44.5	8.2
Portugal	313	1093	324	82.0	31.9
Romania	2	561	336	70.0	20.2
Slovakia	73	298	73	53.7	12.5
Slovenia	65	378	285	56.7	13.0
Spain	152	1328	223	84.7	36.7
Sweden	3	57	3	11.7	3.7
United Kingdom	2	106	2	16.9	4.7

Table 3
Estimated values of potential residential cooling demand in dwellings of EU countries.

Country	Average potential yearly cooling demand, TW h/a	Maximum potential yearly cooling demand, GW h/a	Minimum potential yearly cooling demand, GW h/a
Austria	3.63	5.96	2.10
Belgium	1.84	3.40	1.14
Bulgaria	5.82	8.64	3.85
Croatia	1.79	2.71	1.13
Cyprus	4.49	4.97	3.94
Czech Republic	2.35	3.60	1.36
Denmark	0.33	0.59	0.14
Estonia	0.06	0.14	0.02
Finland	0.16	0.35	0.07
France	29.04	48.89	18.68
Germany	15.42	27.61	9.53
Greece	29.98	34.47	25.89
Hungary	4.14	6.29	2.50
Ireland	0	0	0
Italy	83.01	110.87	61.46
Latvia	0.14	0.30	0.05
Lithuania	0.23	0.45	0.09
Luxembourg	0.07	0.14	0.05
Malta	1.43	1.69	1.24
Netherlands	1.58	2.94	0.94
Poland	3.54	5.64	1.92
Portugal	16.31	20.46	12.40
Romania	5.49	8.74	3.22
Slovakia	1.14	1.78	0.67
Slovenia	0.50	0.83	0.27
Spain	77.74	98.81	57.59
Sweden	0.22	0.39	0.09
United Kingdom	1.88	3.56	1.02
Total EU-28	292.34	404.21	211.35

region. In 37% of weather stations this was the year 1996, followed by 1998 (32%) and 2008 (9%).

Similarly to maximum CDD values, here it was assumed that the penetration of residential air cooling equipment in different NUTS-3 regions (in %) would be the same as in the average CDD calculation case.

As it can be seen in Table 3, the minimum potential annual residential cooling demand in EU countries can be as low as 211 TW h, i.e. 28% lower than the average potential cooling demand. The difference is smaller than in the case of maximum demand which means that the impact of "heat waves" on cooling demand is much higher.

As it can be seen, the largest difference between potential average and minimum cooling demand is likely to occur in cooler climate countries. This indicates that in warm climate countries space cooling needs are more predictable than in cooler climate countries. This can also be seen in Fig. 10, which presents the summary of estimated potential average, maximum and minimum residential cooling demand in EU-28 countries.

5.4. Comparison of future space cooling demands in EU Member States

Only one previous study estimated the future space cooling demand of all EU Member States (Werner, 2015). It estimated that if all households would be using space cooling (full penetration), the potential demand would be equal to 450 TW h/a in the EU28. The (Rescue, 2014) study estimated that residential space cooling demand can potentially be equal to 710 TWh/a in EU28.

Our study shows that given residential space cooling penetration as calculated for each NUTS-3 region with the US situation as a proxy the average residential cooling demand might reach 292 TW h and might vary from 211 to 404 TW h/a depending on climatic conditions of a given year.

The main difference between our study and (Werner, 2015) and (Rescue, 2014) is that we take into account that the full penetration of space cooling is never achieved, even in hot climate regions. In addition, our study makes a more detailed assessment of the CDD per MSs due to the high geographical resolution of data points.

Comprehensive Assessments of EU Members States under Art.14 of EED provided only limited information about forecasted residential cooling demand. Only 5 reports contained such forecasts: Cyprus, Croatia, Greece, Malta and Belgium Wallonia region. The most detailed forecast was presented by Cyprus (JRC, 2015). The forecast was prepared using energy demand models taking into account different factors, such as population change, composition and changes of building stock, GDP change, etc. The forecasted residential space cooling demand in Cyprus by 2050 is 3.57 TW h/a. This value seem to correspond well with the potential cooling demand identified in our study, especially taking into account that demand curves in (JRC, 2015) are increasing during all analysis period. Thus it can be expected that cooling demand in Cyprus will still be increasing after 2050 and eventually will reach its potential, estimated in this paper.

6. Impact of potential residential cooling demand on energy generation and supply systems of EU countries

6.1. Expected impact of potential residential cooling demand on electricity generation and supply systems of EU

In order to assess the impact on Member States' energy supply systems from potential residential cooling demand, additional residential cooling demand was calculated for each EU Member State. Additional cooling demand was calculated for each country as a difference between estimated potential yearly cooling demand as presented in Table 3 and current demand as presented in Table 1.

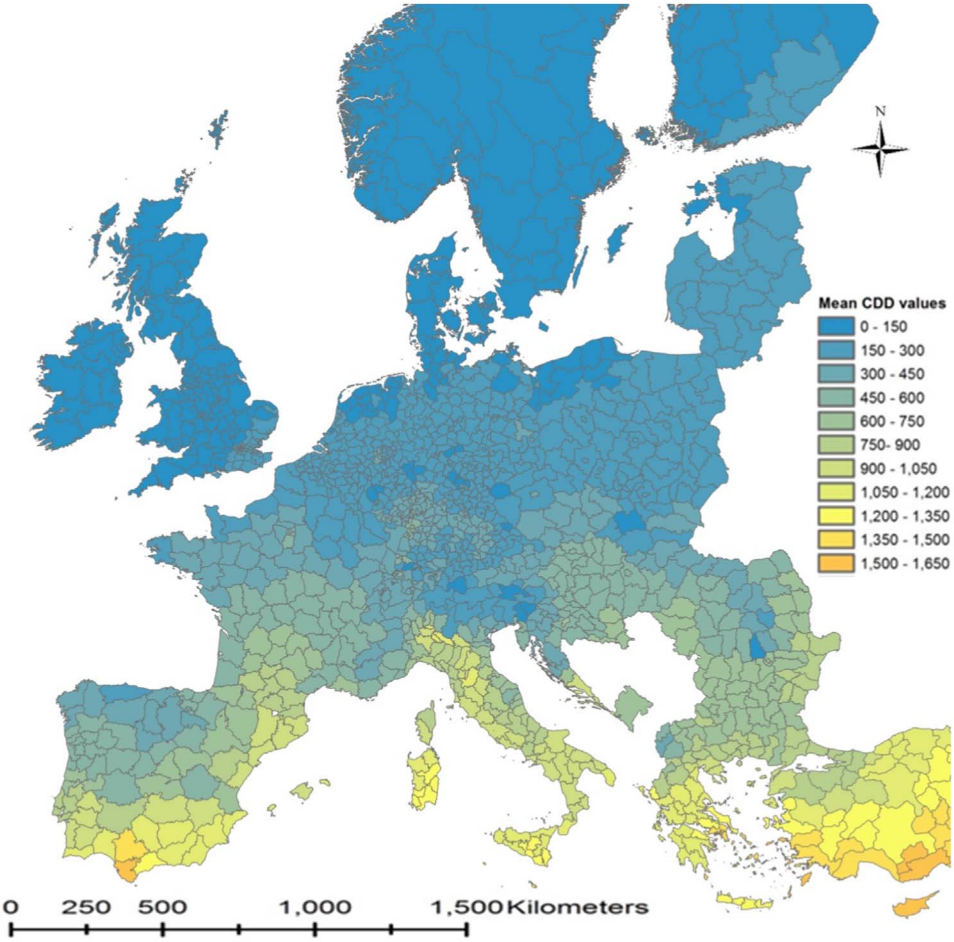

Fig. 9. Distribution of maximum CDD values in NUTS-3 regions.

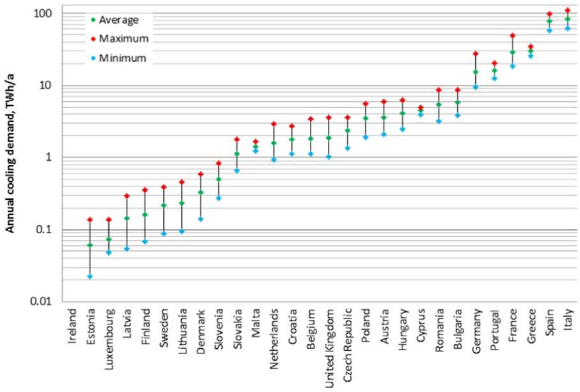

Fig. 10. Estimated average, maximum and minimum residential cooling demand potential in EU-28 countries.

The data presented in Fig. 2 and Table 1 show that the estimates of current demand from different sources vary significantly. For consistency reasons it was decided to use as a current demand indicators the values, estimated in most current demand estimate (Werner, 2015). The results of calculation are presented in Table 4.

In order to evaluate the impact of the cooling demand potential on energy supply systems of EU countries, additional cooling demand was converted into final energy consumption for cooling. As a first step it was assumed that all the residential space cooling equipment would be electric AC. A SEER value of 3.6 was assumed. The resulting final electricity consumption for residential cooling is presented in Table 4. If estimated cooling potential would be fully achieved it might increase electricity consumption by 68 TW h/a in the whole EU. The largest increase might be expected to occur in Italy and Spain.

On European scale such an increase in cooling demand would raise the electricity consumption of households by almost 9%, since current electricity consumption is equal to 785 TW h/a (Eurostat, 2015). The overall electricity consumption of the EU would increase by 2.5% (current electricity consumption is 2706 TW h/a). However, the increase in residential cooling demand might have more severe impact on electricity systems of some countries as presented in Table 4. Although the potential increase in electricity consumption by residencies is quite small in some of the countries, it is very significant in Southern and South-eastern European countries, such as Cyprus, Portugal, Spain or Romania, reaching maximum value of 43.3% in Greece.

The impact on the electricity systems of the EU countries might be more significant in some years, as was discussed previously, due to higher values of CDD in particular years. Electricity generation and supply systems would also have to cope with consumption in those years. Therefore the potential need for additional maximum electricity generation capacity was calculated based on the values of maximum potential yearly cooling demand presented in Table 3 for each country and is presented in Table 4 as well. As it can be seen, the additional electricity generation capacity in EU caused by increased residential cooling might be estimated to reach 80 GWe. According to Eurostat, current maximum electricity generation capacity in EU-28 countries is equal to 994 GW. As such, realisation of residential space cooling demand potential might cause an increase in the required electricity generation capacity by 8% in comparison with the current situation.

Table 4
Additional potential residential cooling demand in EU-28 countries.

Country	Additional potential residential cooling demand, TW h/a	Additional final electricity consumption for residential cooling, TW h/a	Additional electricity consumption in residential sector, %	Additional electricity generation capacity required, GW
Austria	3.4	0.94	5.4	1.35
Belgium	1.61	0.45	2.4	1.25
Bulgaria	4.31	1.20	11.3	1.45
Croatia	0.71	0.20	3.6	0.29
Cyprus	2.15	0.60	42.1	0.30
Czech Republic	2.23	0.62	4.4	1.14
Denmark	0.28	0.08	0.8	0.28
Estonia	0.06	0.02	1.2	0.08
Finland	0.08	0.02	0.1	0.14
France	25.52	7.09	4.7	16.03
Germany	13.51	3.75	2.9	12.58
Greece	26.75	7.43	43.3	3.97
Hungary	3.68	1.02	9.8	1.92
Ireland	0	0	0	0
Italy	67.51	18.75	29.2	13.31
Latvia	0.12	0.03	1.7	0.12
Lithuania	0.2	0.06	2.3	0.18
Luxembourg	0.07	0.02	2.1	0.07
Malta	0.8	0.22	34.4	0.15
Netherlands	1.1	0.31	1.4	1.35
Poland	3.35	0.93	3.3	2.70
Portugal	15.19	4.22	35.4	3.25
Romania	4.59	1.28	10.7	2.06
Slovakia	1.1	0.31	6.3	0.52
Slovenia	0.03	0.01	0.3	0.08
Spain	65.82	18.28	25.9	13.32
Sweden	0.09	0.03	0.1	0.10
United Kingdom	0.83	0.23	0.2	1.62
Total EU-28	245.09	68.08	8.7	79.61

6.2. Mitigation of impact on electricity generation and supply systems

Such increase in generation capacity might require significant investments not only in electricity generators but also in electricity transmission systems, especially in Southern European countries where the most additional capacity will be needed. Therefore steps should be taken to mitigate such impact. There are different possibilities and measures which can be implemented. Some might be related with technological aspects of space cooling generation and delivery or energy efficiency improvements in the buildings while others might be related with policies and strategies in the field of space cooling.

In the previous sub-section we assumed that all the residential space cooling would be generated using electricity driven air conditioners. They are currently the dominant space cooling equipment and it can be reasonably expected that it will remain so in the nearest future. We assumed that in the future their efficiency will be higher by 20% (SEER value of 3.6), since further progress in this field can also be expected (Bansal, 2015), although as with all technologies, significant improvement becomes increasingly difficult after reaching certain level of performance.

Less stress on the electricity system can be achieved by implementing alternative cooling supply systems, such as district cooling. Other than district heating, district cooling systems currently are used only in limited quantities and only in some countries of EU, most notable example being Nordic countries (Sweden and Finland) (Euroheat and Power, 2015). However, interest in district cooling as more sustainable alternative to traditional space cooling technologies and as a business opportunity for existing and new district heating systems is increasing. District cooling is currently seen as a prominent part of future European energy system and is addressed in a number of European energy legislative documents such as Energy Efficiency Directive (European Parliament, 2012). Since district cooling networks can use different sources of heat instead of electricity as in the case of traditional air conditioners, their wider implementation would mitigate requirements on electricity generation and supply systems. Such systems might utilise different heat sources, such as industrial waste heat, heat from power plants and cogeneration installations or renewable energy (such as solar).

It is difficult to accurately evaluate the potential of district cooling systems. We can assume that district cooling can technically be used in all predominantly urban areas. In different EU countries the share of population living in such predominantly urban areas is very different and ranges from 100% (extreme case of Malta), 68.8% in Belgium and 60.5% in Spain to 11.4% in Romania and Slovakia (Eurostat, 2016). Thus it can be assumed that technically residential district cooling in EU could lower additional final electricity consumption (see Table 4) by 30 TW h/a (44%) and additional electricity generation capacity requirement by 33.4 GW (42%). Economic potential of district cooling, however, is lower. If we would assume that approx. 30% of technical potential would be economically viable, then residential district cooling systems could lower future electricity consumption in EU by 9 TW h/a and generation capacity required by 10 GW. Thus it is essential to identify obstacles for technical and economic feasibility of district cooling and properly as well as timely address them at regional, national as well as European levels.

The broader use of solar energy to cover cooling is another possibility. Peaks in cooling demand occur during daytime hours when the solar irradiation is high. Solar energy can be used for cooling purposes either as a direct thermal input into adsorption chillers or as electricity input from PV panels into conventional AC equipment. Solar electric systems can contribute to the reduction of primary energy consumption by 21–70% depending on the location, size of the building and size of solar panels (Eicker et al., 2015a). However, economic viability of such systems, especially solar thermal ones, currently is low (Eicker et al., 2015b). Coordination of financial and policy incentives would be needed to match the growth of electric AC with solar PV capacity.

Another group of the measures to reduce future negative impact of increased cooling consumption is related with general legislative and institutional view on space cooling. Increased attention on space cooling in European legislation might be viewed as a positive initiative to address issues arising from actually increasing cooling demand in households and in other sectors of EU economy. However, it might also have unintended negative outcomes. Paradoxically in the light of the general drive towards lowering energy consumption of our society and creating more sustainable future, such measures may in fact facilitate increase in energy consumption. Energy suppliers would be encouraged to create cooling supply systems and present possibilities to use space cooling to residents. Consumers, who otherwise would not consider cooling being a necessity, would be encouraged to use it. Therefore along with the legislation intended to make space cooling more efficient and sustainable there should be also a legislation intended to educate population about this relatively new energy system component.

7. Uncertainties and method limitations

As the chosen method of analysis relies on a number of important assumptions, the main uncertainties associated with the final results are:

- One of the assumptions is that under the same climatic conditions energy performance in USA and EU buildings would be of the comparable level. As was demonstrated by (Berkland, 2014) the building codes in USA and Europe are of comparable levels when concerned with energy performance requirements. However, actual buildings are not always conforming to the requirements and there might be significant differences between regions. Also, future changes in building insulation were not taken into account due to the scarcity of the data and uncertainty of influence of insulation improvements on cooling demand level.

- Space cooling demand is heavily influenced by occupant behaviour which in this study is taken into account through estimated penetration of cooling. It is assumed that in the longer perspective expectations of population on comfort level in USA and EU would converge. However, it might be that it will not occur fully thus the estimated cooling potential would be somewhat lower. The results presented in this paper should be interpreted as cooling demand potential and not the forecast of cooling use, thus the uncertainty would be less significant.
- Potential cooling demand in EU was established by using current data on population and households. These indicators will change at a different rate in different countries thus also changing their cooling demand potential.

8. Conclusions and policy implications

This paper estimated the cooling demand potential in the residential sector of the EU using the USA data as a proxy. Climatic conditions and cooling consumption data from the USA were evaluated. The information was used to establish the relationship between electricity consumption for air conditioning and the number of Cooling Degree Days. After that the CDD of the NUTS-3 regions of Europe have been established, cooling demand potential in NUTS-3 regions and EU Member States could be estimated. Based on the average temperatures during the last 20 years, the cooling demand potential in residential sector was estimated to be 292 TW h. The maximum and minimum number of CDDs will vary from year to year based on natural temperature variations. It was determined that the maximum cooling demand potential would be 404 TW h, whereas the minimum demand potential is 211 TW h. Primarily the southern and south-eastern EU Member States show the greatest variations in demand in absolute terms. The electrical capacity needed in case of realisation of estimated demand potential was estimated to 79.6 GWe.

The analysis of Comprehensive Assessments performed under the requirements of the Energy Efficiency Directive (2012/27/EU) Art. 14 revealed that the majority of EU Member States have poor or limited data on current cooling demands and even less knowledge about the future tendencies. Without understanding the future situation it is unworkable to design policies intended to improve the energy efficiency in this sector. Comprehensive Assessments need to be renewed and updated every 5 years, according to the requirements of Energy Efficiency Directive. It is expected that the next iteration of Assessments would address their current deficiencies, thus more knowledge is needed. The estimated potential of space cooling demand, identified in this paper for all EU Members States, could provide additional important information for more accurate forecasts of future space cooling demand. This would facilitate creation of more relevant energy policies. It should be noted that the results of analysis are available at much lower scale than Member State level, i.e. for NUTS-3 region, thus making demand forecast potentially more accurate and detailed.

As all the analysed studies and legislative documents agree, space cooling demand is increasing faster than any other household energy consumption. The only disagreement among existing studies is in rates of increase and final figures. The lack of data increases the risk of misjudgements on the future cooling demand, which could result in less than optimal or less stable energy system compositions. Instead, a good understanding of future cooling demand allows developing better strategies to counteract anticipated imbalances. For example for Member States with expected large increase in cooling demand could add more solar PV to the energy mix since these two technologies have a nearly perfect match between location, load and production. District cooling is another interesting option with limited impact on the electrical grid, which also has the added benefit that it facilitates the introduction of renewables into the heating and cooling supply mix.

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