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Cooling the buildings – past, present and future

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ABSTRACT

Cooling of buildings currently represents a considerable fraction of the total energy consumption in the world. Global and local climate change in combination with the projected population increase and economic development is expected to increase tremendously the future cooling energy demand of buildings and make it the dominant energy component. The present paper aims to present and discuss the details of the framework which defines the present and future cooling energy consumption of the building sector. The more recent quantitative and qualitative data concerning the penetration of air conditioning around the world are presented and analyzed. The main technological, economic, environmental and social drivers that determine the market penetration of air conditioning are identified and their impact is investigated. The potential future evolution of the main parameters that define the cooling energy consumption and in particular climate change, the population increase, income growth, potential technological improvements and the main socioeconomic drivers are investigated and existing forecasts are presented. Proposed methodologies to predict the future cooling energy consumption of the building sector are reported and discussed, while existing estimates and predictions regarding the future cooling energy consumption of individual buildings as well as of the total building sector are documented, evaluated and analyzed. Based on the explored inputs and forecasts, a model to predict the future cooling energy consumption of both the residential and commercial sector is developed. Three scenarios based on low, average and high future development, compared to the current development, are created and the range of the expected cooling energy demand in 2050 is predicted under various boundary assumptions. It is calculated that the average cooling energy demand of the residential and commercial buildings in 2050, will increase up to 750% and 275% respectively.

1. Introduction

Convective gains caused by high ambient temperatures, solar and internal heat inputs, latent heat loads and heat losses to low temperature heat sinks determine the thermal balance of buildings and may cause increased indoor temperatures, beyond the comfort levels. Overheating of the indoor environment results in excessive thermal discomfort and health problems while reduce significantly the productivity and the well being of the inhabitants [1,2]. To prevent indoor overheating, natural and passive techniques may be employed. Passive cooling techniques are based on the application of solar and heat control systems, dissipation of the excess heat into low temperature natural sinks like the air, the ground and the water and the amortization of the heat surplus through the use of additional thermal mass in the buildings [3,4]. The cooling potential of natural techniques is proving to be very significant and passive techniques may contribute to significantly decrease the cooling demand of buildings [5]. However, the overall performance of the passive cooling techniques is heavily climatic dependent and may not be enough to satisfy the proper indoor comfort requirements under all climatic conditions. Under these circumstances the use of mechanical cooling is necessary to decrease indoor temperatures and regulate humidity levels and comfort conditions.

Mechanically driven air conditioning devices were first commercialized in the second decade of the last century. Until 1955, almost 2% of the American residences were equipped with mechanical cooling systems, which were considered as luxury devices. However, the serious economic growth between 1950 and 1980 in combination with the favorable energy prices and the increasing affordability of the cooling devices, have boosted the air conditioning market and in the eighties almost half of the American residences were equipped with air conditioning systems [6]. Currently, the air conditioning industry represents a huge business sector approaching a total annual turnover close to 100 billion US Dollars [7], and presents very significant prospects for further developments and market expansion.

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Although the penetration of air conditioning is very high in USA and Japan, approaching almost the highest possible saturation levels, the world average diffusion of mechanical cooling is quite low and the potential for further expansion of the market is very significant. In fact, a very rapid penetration of air conditioning, much faster than the corresponding income growth, is currently observed, mainly in cooling dominated developing zones of the planet. For example, annual sales of room air conditioners in India are growing at about 20% per year [8], while in China, the penetration of air conditioning in the urban households has increased from 1% in 1990 to 63% in 2003 [8], and almost 100% in 2010 [9].

The future growth and development of the air conditioning industry depend strongly on several drivers affecting the penetration of the systems. Among them, local climatic conditions, global and local warming, increase of the earth's population, growth of the local income and GDP, electricity and equipment prices and efficiency and energy performance of the equipment are the most important.

Higher ambient temperatures induced by the global and local climate change seem to be the main driver defining the future needs of air conditioning. Climate change decreases the potential of passive cooling techniques like ventilative cooling and enhances the use of mechanical cooling [10]. Increased use of air conditioners to satisfy indoor comfort conditions raises the electricity consumption while it has a disproportionate impact on the peak electricity demand. As a result, utilities are obliged to built additional power plants to satisfy the extra requirements. In India, forecasts about the electricity consumption from the air conditioning in 2030, are close to 239 TWh/yr, which corresponds to an extra peak electricity demand of 143 GW [11]. To satisfy such an additional capacity almost 300 new coal fired electricity power plants of 500 MW each, have to be built [11]. At a global planetary level, it is estimated that a possible increase of the average ambient temperature of 1 K may result in an energy consumption for cooling costing 75.1 billion dollars [12,13]. In Europe, it is predicted that the cost of the additional electricity for cooling just to compensate the global and local warming by 2050 is between 22 and 89 billion of euros per year, while the necessary investment costs for the purchase of the new air conditioners are close to 8 and 20 billion by 2050 and 2100 respectively [14].

The foreseen significant growth of the air conditioning demand in the developing countries induced by climatic change and the potential income growth is further amplified by the expected increase of the local population. In fact, it is predicted that by 2030, almost 52% and 34% of the additional population will live in Asia and Africa respectively. The combination of the global warming, population increase and income growth may have a tremendous impact on the energy consumption for cooling. The expected potential cooling demand just for the city of Mumbai in India is estimated to be close to 24% of the entire cooling demand of the United States [15].

To counterbalance the impact of climatic change, population increase and income growth on the global cooling energy demand, the efficiency of the air conditioning systems as well as the energy performance of the buildings has to improve significantly. In fact, very significant improvements in the efficiency of the cooling systems have been achieved during the last decades [16]. In parallel, more efficient and strict building performance standards and requirements applied in many countries, in combination with the use of high performance energy saving and production systems, have permitted to reduce significantly the cooling demand of the modern buildings despite the significant increase of the internal loads of the commercial buildings [17–19]. Increase of the efficiency of mechanical cooling systems can result in very significant energy savings. For example, it is estimated that the potential use of very high efficiency room air conditioners in India could save 118 TWh by 2030, reduce the peak electricity demand by 60 GW and avoid the construction of 120 new power plants of 500 MW each [11]. However, despite the very significant energy savings, it is quite doubtful if the potential improvements in the energy efficiency are sufficient to compensate, even partly, the future growth of the cooling energy consumption in the world.

The present article aims to investigate and analyze in depth the present and future developments and trends related to the cooling of the residential and commercial buildings. The current market developments are presented and discussed, while the available knowledge on the current impact of the major economic, climatic, technological and social drivers influencing the air conditioning penetration and the corresponding cooling energy consumption are analyzed in details. The potential future evolutions and developments for each of the main drivers determining the penetration of mechanical cooling, including climate change, population and income growth, housing size and efficiency improvements, are thoroughly investigated and discussed. Existing models and studies predicting the future cooling energy consumption both of individual buildings and the whole building sector, are presented and analyzed in a comparative way. Finally, a detailed holistic model is developed to forecast the future cooling energy demand of both the residential and commercial buildings. The results are presented with parametric and sensitivity analysis and compared against the available predictions are performed.

2. Energy consumption for cooling and the world air conditioning market

As already mentioned, the penetration of the air conditioning varies as a function of several climatic, economic and social parameters. Although the saturation of air conditioning is quite high in the some countries like USA and Japan exceeding 70% and 85% of the residential building stock, respectively, the overall diffusion in the whole world is still quite low [8]. The current penetration of air conditioning in European residences is less than 8%, but it is growing fast, while in China in 2010, it corresponded to almost 1,07 air conditioners per urban household and 0,12 per rural household [6], while figures are increasing very fast. The market value of the global air conditioning products has in 2014 has exceeded 97 billion US$ presenting a total increase close to 7% compared to 2013 [7]. Almost 128,5 million units have been sold worldwide. Most of the increase occurred in China and the Asia – Pacific zone where the global sales of air conditioning correspond almost 58% of the world market. China and Japan represent almost 83% of the total market in this area while significant growth rates are observed in Myanmar, Vietnam, Hong Kong and Malaysia. An serious drop of the whole market figures is observed in Europe. The total air conditioning sales reached 11,2 billions US$, a drop close to 5% compared to 2013, mainly because of the significant economic crisis in the European South and Russia. A significant annual increase of 22% is observed in the UK, mainly because of the higher sales in the commercial sector. The serious climatic problems caused by the El Niño in South America skyrocketed air conditioning sales is South America and mainly in Brazil, where the annual increase was close to 29%. In parallel, the US market grown by 6% compared to 2013. Air conditioning sales in the Middle East, India and Africa presented a considerable increase, reaching a total value close to 9,2 billion US$ compared to 8,5 billions of 2013. India was the leading country in air conditioning sales mainly because of the serious improvement of the economic and business conditions.

Split systems presented the highest share of the market with a total sales close to 74,5 billion US$. Variable Refrigerant Flow, VRF, systems presented an significant growth as well, reaching a total market value close to 9,7 billion US$. A considerably lower share were observed for the PTAC, indoor packaged and windows air conditioning systems.

The world annual energy consumption for cooling in 2010, was close to 1,25 PWH [20,21]. Almost 55% of the energy was consumed by the residential and the rest by the commercial buildings. Cooling energy consumption represents almost 2,9% and 6,7% of the total energy consumption of the residential and commercial buildings respectively. The distribution of the energy consumption for both the residential and the commercial sectors in the major geographic zones of the world is given in Fig. 1 [20]. Almost 37% of the total cooling energy consumption takes place in the non OECD countries, 35% in the Americas, 17% in Europe and the rest in the OECD Pacific countries. In the Americas, cooling represents almost 7% of the total residential and 6,1% of the commercial energy consumption. In the rest of the world, cooling is responsible for the 2–3% of the total residential energy consumption and 6,0–9,3% of the global commercial sector.

For the residential sector, the highest average energy intensity for cooling is observed in the Northern American Countries, with 8,1 kWh/m^2/y, followed by the Latin American Countries, (8 kWh/m^2/y),and the Middle East and Northern Africa zone, (4 kWh/m^2/y). Much lower energy intensity are observed for the Pacific Asia, (3 kWh/m^2/y), and the Western European Countries, (2,2 kWh/m^2/y) [63]. The highest energy intensity for the cooling of the commercial buildings is presented at the Middle East and Northern African zone, (42 kWh/m^2/y), followed by Latin American countries, (38 kWh/m^2/y), North America, (34 kWh/m^2/y), and Pacific Asian countries, (33 kWh/m$^{2/}$y), while the corresponding figures for Europe are quite low, (10 kWh/m^2/y) [20]. The above data refers to the average energy consumption and not to the peak demand.

3. Factors affecting the cooling demand and the penetration of the air conditioning

The energy demand for cooling, as well as the penetration levels of air conditioners in the market, depend on several economic, climatic, demographic, policy and technological factors. Economic and financial parameters like the family income, the price of air conditioning equipment as well as the electricity prices affect significantly the demand for cooling and air conditioning. Higher family income increases the purchases of energy consuming equipment including air conditioners, while increasing equipment and electricity prices have a negative impact on the sales of cooling equipment. Climatic factors and mainly the ambient air temperature and solar radiation are determinant factors defining the air conditioning demand. Warm climatic zones present a much higher demand for cooling and an increased potential for air conditioning sales than the heating dominated climatic zones. Technological factors, like the thermal quality of buildings define at large their specific cooling load. Poorly designed buildings present a significantly higher demand for cooling than buildings of high thermal performance. The efficiency of the air conditioners, EER, The EER is the ratio of the cooling capacity (in Btu per hour to the power input, in watts), highly affect the levels of energy consumption, while being a determinant factor for the selection of the specific air conditioning technologies. Policy issues and in particular the applied standards regarding the thermal quality of buildings and the necessary minimum efficiency of air conditioners have a very significant impact on the energy demand for cooling and determine the technological characteristics of the air conditioning market.

The specific impact of each of the previously mentioned parameters depends on the characteristics of the specific country or state. Several studies aiming to assess the impact of these factors are available, mainly in countries presenting a high penetration of air conditioners, like the USA, where a high mass of statistical data is available. The way each factor is affecting the air conditioning market is assessed in terms of the corresponding elasticity value. In a simplified way, the elasticity of each independent parameter is the corresponding variability of the air conditioning demand resulting from a unitary variation of the specific independent parameter. For example, when the income increases by 10% and the air conditioning demand grows by 5%, the corresponding elasticity is 0,5. Fig. 2, plots the magnitude of the calculated elasticities of the air conditioning market regarding the main economic, climatic and technological parameters. Data are from several USA studies analyzing the air conditioning market [6,22–25,28,31]. As observed, climate and family income present the highest elasticity values and influence the more the air conditioning sales. Detailed information and analysis on the specific impact of each of the identified factors is given in the following sections.

3.1. *Economic factors affecting the penetration of the air conditioners*

The economy is affecting highly the purchase of durable equipment including air conditioners. Three there are the identified main economic parameters influencing more the air conditioning market: The family income, the equipment price and the cost of the electricity supply.

Several studies have attempted to identify the elasticity of the three main economic parameters on the demand for air conditioning. Most of the studies are based on the analysis of the USA air conditioning market, which is by far the biggest in the world. Although, the results vary between the studies as a function of the methodology and the data sample used, it is concluded that the impact of the family income is the higher one, while the equipment and electricity prices present elasticities of the same order of magnitude.

3.1.1. *The relation between air conditioning penetration and family income*

Increase of the family income is associated with a higher capacity of consumption and in particular with a significant increase of the demand for air conditioners [6,22–24]. Analysis of the existing data on air conditioning penetration in the USA, during the period between 1955 and 1980, shown that [6,22], elasticities of the family income are found to vary between 0,44 to 1,15, as a function of the air conditioning system and the type of buildings. A similar elasticity value in regard to income, 0,447, is calculated in Ref. [25], for the air conditioners demand in the USA between 1946 and 1961, while lower income elasticities are calculated, also from the USA market, in Ref. [23]. The income elasticities for central air conditioning was found equal to 0,21 while the corresponding elasticity for room air conditioners was between 0,114 to 0,126 [23]. It is reported by David and Gertler [24] that the percentage of central air conditioning availability, in selected zones of the State of California, increased from 39%, to 60%, 73% and 87%, for family income less than 15,000 $, 15–30,000 $, 30–75,000 $, and higher than 75,000 $, respectively.

An analysis of the specific relation between family income and air conditioning availability in Mexico [107], reported a strong relation between income, climate and air conditioning saturation. For the warmer zones of the country, it is estimated that ownership of air conditioning is increasing by 2,7% per 1000 US Dollars of annual family income. Also, air conditioning is increasing with a as a function of income while a 2% annual income growth in the warm areas increases the saturation levels close to 100%.

The income sensitivity on air conditioning adoption in 29 provinces in China is reported in Ref. [26] It is found that changes in income have increased considerably the spread of air condition-

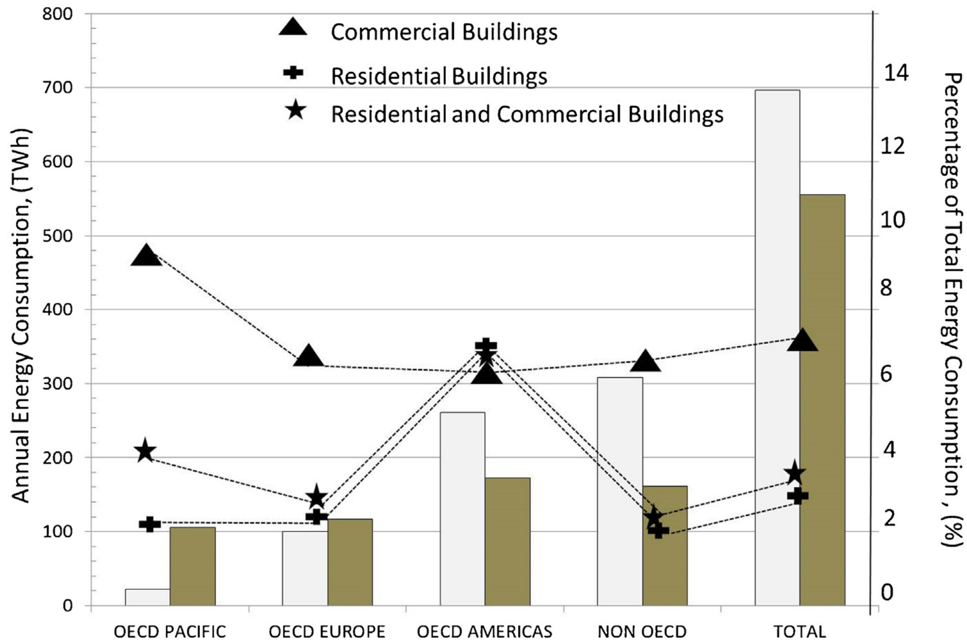

Fig. 1. In the left vertical axis: Annual Energy Consumption for Cooling of the Commercial and Residential Buildings in the major Geographic zones of the world, (TWh/y), Light color bar is the cooling energy of the residential buildings while the dark bar is for the commercial buildings. In the right vertical axis: Share of cooling energy on the total energy consumption in the corresponding zone for the residential, commercial and all buildings, Data from Ref. [20].

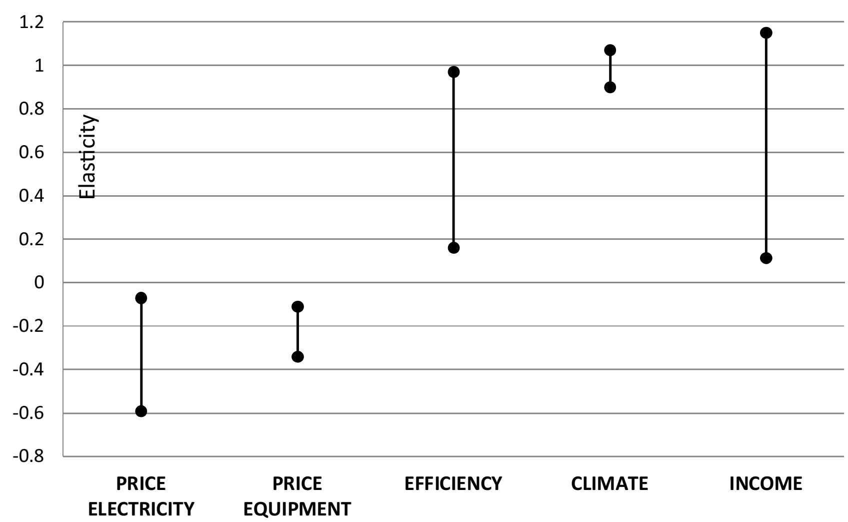

Fig. 2. Calculated Upper and Lower values of air conditioners elasticity regarding the family income, price of electricity and equipment, climate and equipment efficiency. Data on Income elasticity are from Refs. [22–26], on electricity prices from Refs. [6,23,28], on equipment price from Refs. [23,28], on climate from Ref. [31], and on efficiency from Ref. [11].

ers in the country while the correlation coefficient between income and air conditioning penetration is high and close to 0,78. Analysis of the air conditioning availability data in India [11], showed that there is a strong nonlinear relation between income and air conditioning demand. While the average availability of air conditioners in the country is close to 15% of the saturation value, in the relatively rich urban areas, the corresponding availability value varies between 30 and 60%. In parallel, while in 2009–2010, the average availability of air conditioning was close to 20%, the corresponding figures for the poorest and richest 10% income groups was 4% and 45% respectively [11].

Several models have investigated the impact of family income on air conditioning demand. According to Ref. [8], the relation between air conditioning availability and income follows a logistic S – curve with a long delay before a rise in the uptake. The authors used data from 24 countries including USA, Australia and Italy and proposed the relation:

$$\ln\left(\frac{1}{Avail}-1\right)=\ln\gamma+\beta\times \text{Inc} \quad (1)$$

where ln γ = 4.811 and β −1.005, and the Income is given in US$.

As previously mentioned, family income is significantly influencing the cooling energy consumption of households. It is found that the Unit Energy Consumption for cooling, UEC, is a logarithmic function of the family income which increases rapidly for low income levels and slowly for high incomes. As proposed in Ref. [27], it may be calculated by the following formula:

$$\text{UEC} = \text{CDD}\times(0.865\times\ln(\text{Income})-6.04). \quad (2)$$

where CDD is the cooling degree days. which is a measure of deviation of the daily temperature from a base predefined temperature.

3.1.2. The relation between air conditioning penetration and electricity prices

Several studies calculated the elasticity of room air conditioners regarding the electricity prices and found that varies between −0,59 and −0,12.

Using the appropriate data from the USA, an analysis presented in Ref. [23], has estimated that the elasticities of the air conditioning demand regarding the electricity prices are between −0,22 and −0,35 for room air conditioners, while are found to be very small and insignificant for central systems [23]. The same authors [28], using a slightly different methodology calculated that the elasticity of room air conditioners demand regarding the electricity prices are close to −0,34, while the corresponding elasticity for central air conditioners is −0,07. This means that the impact of electricity prices on the purchases of central air conditioners is very limited. An analysis of the historical data concerning the purchases of room air conditioning in the USA during the period 1960–1980 [6], has found that elasticities concerning the electricity prices follow a decreasing trend. In particular, elasticities were −0,59, −0,2 and −0,12 in 1960, 1970 and 1980 respectively.

3.1.3. The relation between air conditioning penetration and equipment prices

The price of air conditioning equipment has a very strong impact on sales. Lower prices boost the air conditioning market and increase units demand. The high penetration of air conditioning in the USA during the years 1987–2005 is mainly attributed to lower equipment prices. In fact, during this period, the average price of room air conditioners in the USA was reduced by 49%, while central systems become 14–49% less expensive [28]. The elasticity of the air conditioning penetration regarding the equipment prices, in the USA market, is assessed in Ref. [28] for the period 2007–2015 and is found to be close to −0,24 for the central air conditioning and −0,11 to −0,12 for the room air conditioners. Using data of a different period in the USA market, it is calculated that the elasticity regarding the AC unit prices are −0,34 for the room air conditioners and −0,178 for the central systems [23].

3.2. Climatic factors affecting the demand for cooling and the penetration of air conditioning

The local climate and mainly the ambient temperature, humidity and solar radiation determine at large the cooling load of buildings and the demand for air conditioning. The Cooling Degree Days, is a quite simple and easy to assess parameter used by many researchers, to evaluate the impact of local climate on air conditioning demand and penetration.

Correlation of the cooling related energy consumption data from the USA, against the corresponding values of the cooling degree days has shown an almost linear relation [29]

$$Q = 0,0193\,\mathrm{CDD} - 2913\,\mathrm{Kwh/m^2} \quad (3)$$

which indicates that climatic zones with less than 150 cooling degree days should present an almost zero cooling energy consumption. Eq. (3), is based on data collected from several zones of the USA presenting air conditioning saturation levels between 38% to 97% [29]. Given the dynamic nature of the market and the continuous change of the pentration levels, the use of Eq. (3), may be avoided.

In parallel, the Cooling Degree Days, CDD, are used in most of the models as the proper variable to characterize the relation between climate and the air conditioning market. For countries with a significant penetration of air conditioning, like the United States, a correlation between the air conditioning saturation levels and the corresponding cooling degree days has been found and the following formula is proposed [8,29,30]:

$$\mathrm{Saturation} = A - B \times e^{-C*\mathrm{CDD}} \quad (4)$$

where according to [30] A = 0,944, B = 1.17 and C = 0.00298, while in Ref. [8], it is proposed to use: A = 1, B = 0,949 and C = 0.00187.

The above relation shows that the saturation levels of air conditioning rise steeply from zero to about 90% at 1100 cooling degree days [29]. It is evident that the specific saturation levels calculated by the above equation are valid only for the USA market. Predictions for Europe, based on the above equation are almost 7–8 times higher than the current saturation levels, as the current penetration of air conditioning is considerably lower than in the United States [29].

The specific impact of local climate on the diffusion of air conditioners is usually evaluated through the estimation of the elasticity parameter related to the cooling degree days. Using historical market data from the USA, it is calculated that the cooling degree days elasticity for central and room air conditioners are very high and equal to 0,989 and 1,07 respectively [31]. This is the highest elasticity value among all parameters affecting the air conditioning market and signifies the extreme importance of the local climate on the air conditioning market penetration.

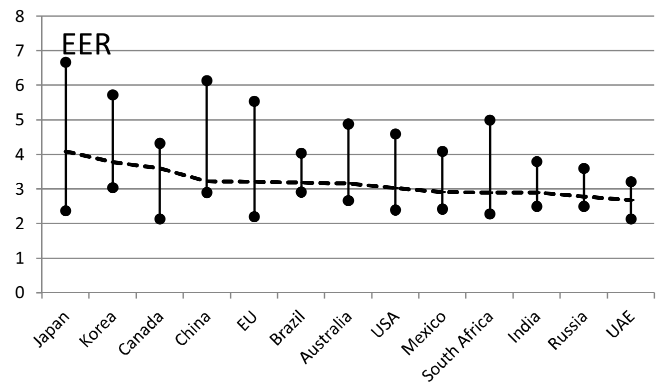

Fig. 3. Maximum, minimum and average EER of room air conditioning, (split units), in different countries, (Data from Refs. [11,16,32]).

3.3. Technological factors affecting the penetration of air conditioning – the impact of energy efficiency

High energy efficient air conditioners decrease significantly the energy consumption of households. The efficiency of the air conditioner in a country depends highly on the national energy standards and regulations, the market conditions and the available family income. Significant variations regarding the efficiency of air conditioning exist between the various countries. Fig. 3, presents the minimum, average and maximum EER of split unit room air conditioners in selected countries [11,16,32]. Strict standards on air conditioners efficiency boost the air conditioners market towards the adoption of higher efficiency systems. In Europe, where the energy efficiency labeling for air conditioners is introduced since 2002, the percentage of room units with variable speed drive increased from 4% to 50%, the share of reverse cycle models increased from 50% in 2002 to 90%, and the average EER increased from 2,5 in 2002 to 3,3. Higher energy efficiencies of the air conditioning equipment statistically are associated with an increase of the market demand for cooling (due to the associated reduction usage cost) and decrease the corresponding energy consumption During the period of the high air conditioning penetration in the

USA, (1987–2005), increased energy efficiencies were associated with a higher the penetration of air conditioning in the country. During this period, the average energy efficiency, increased by 23%, and 27% for the room and the central air conditioners respectively [23]. Analysis of the technical and market data from USA given in Ref. [23], has shown that the elasticity of the energy efficiency regarding the air conditioning sales is high especially for the central air conditioning systems. In particular, during the period 2005–2015, the estimated energy efficiency elasticities for the central systems varied between 0,53 and 0,97, while the corresponding elasticities for the room air conditions were between 0,16 and 0,27 [23].

4. Future trends of the main drivers defining the demand for cooling

It is widely accepted that the cooling energy consumption of buildings as well as the market growth of cooling related equipment, will increase significantly in the future years. Specific demographic, economic, technological and climate reasons like the expected serious increase of the earth's population, the local and global climate change, and the increase of the family income, are among others, the main drivers of the expected growth. Several studies have been performed aiming to investigate and identify the levels of the future cooling energy consumption and also the potential evolution of the relevant economic parameters associated with the expected market development [14,27,33–35]. Existing investigations focus either on specific geographic zones of the planet or attempt to provide global figures for the whole world. Prediction models are of varying complexity and accuracy and may rely simply on demographic or climatic parameters and inputs, or a combination of both, or may employ a full set of data including demographic, climatic, economic, technological and social input parameters.

The future cooling energy consumption of buildings, Ec, may be calculated by the following general expression [36]:

$$\mathrm{Ec} = \mathrm{A} \times \mathrm{S} \times \mathrm{I} \tag{5}$$

where A is the Activity expressing the driver of the energy demand for a specific service or sector, S is the structure that determine the energy demand while I is the Energy Intensity expressing to the amount of the required energy per unit of activity.

For residential Buildings the above equation may be written as [27]:

$$\begin{aligned}\mathrm{Ecr} &= \mathrm{Population}/(\mathrm{Average\ Household\ Size}) \times \mathrm{Penetration} \\ &\quad \times \mathrm{UEC}/\mathrm{Efficiency\ improvement}\end{aligned} \tag{6}$$

where UEC is the average cooling energy consumption used for cooling per household using air conditioning calculated by Eq. (2). Ecr is in kWh. Also, Efficiency Improvement counts for the potential increase of the efficiency compared to the current values and is higher than one.

Considering that:

$$\mathrm{Penetration} = \mathrm{Availability} \times \mathrm{ClimaticMaximumSaturation} \tag{7}$$

where the Availability and the Climatic Maximum Saturation can be calculated by the Eqs. (3) and (4) respectively. Using the above expressions in Eq. (6), it is obtained that the future energy consumption for cooling of the residential sector can be calculated as a function of five main parameters and in particular: the local population size, the size of households, the cooling degree days, the Gross Domestic Product per capita, and the expected efficiency improvements:

$$\begin{aligned}\mathrm{Ecr} &= \mathrm{POP}/(\mathrm{AHS}) \times (0,944 - 1,17 \times e^{-0.00298 * \mathrm{CDD}}) \times (\mathrm{CDD} \\ &\quad \times (0,865 \times \ln(\mathrm{GDP}) - 6,04)/\mathrm{EI}/(1 + e^{4152} \times e^{-0,237 \mathrm{x} \mathrm{GDP}/1000})\end{aligned} \tag{8}$$

where POP is the population size, AHS the average housing size, GDP the Gross Domestic Product per Capita, and EI the efficiency improvement.

A more simplified expression to calculate the future energy consumption for the cooling of the residential and the tertiary sectors are given in Ref. [37]. The proposed expressions are:

For the Residential sector:

$$\mathrm{Ecr} = \mathrm{NH} \times \mathrm{NPH} \times \mathrm{FAP} \times \mathrm{EPM(r)} \tag{9}$$

For the tertiary sector:

$$\mathrm{Ect} = \mathrm{GDP} \times \mathrm{FAGDP} \times \mathrm{EPM(t)} \tag{10}$$

where NH is the number of households, NPH is the number of persons living in each household, FAP is the floor area per person, FAGDP is the floor area per GDP and EPM(r) and EPM(t) are the cooling energy used per square meter by the residential and tertiary buildings respectively.

In the following sections, the expected evolution of the above five parameters determining the future cooling energy consumption is analyzed.

4.1. Climate change and increase of the cooling degree days

Global and local climate change increase ambient temperature and the corresponding number of cooling degree days. The magnitude of the temperature increase is predicted through a number of climatic scenarios proposed mainly by the IPCC [38]. Based on the specific assumptions of each climatic scenario and the expected increase of the local ambient temperature, the foreseeable increase of the cooling degree days is calculated. Several studies have estimated the future value of the cooling degree days for various zones of the planet. Warren et al. [39], calculated the future value of the cooling degree days, base 18C, for twelve major regions of the planet and for five distinctive scenarios of temperature increase. In particular, the CDD are calculated considering that the ambient temperature may increase from 0,0 to 1,0 K, 1,0 to 2,0 K, 2,0 to 3,0 K, 3,0 to 4,0 K and 4,0 to 5,0 K. The current as well as the predicted future cooling degree days for the twelve regions and the five scenarios of temperature increase are given in Fig. 4. As shown, the regions suffering the highest proportional increase of the cooling degree days are those presenting currently a low value of CDD, like Russia and Central Asia, Europe and North America, while the lowest proportional increase is expected in regions presenting a high value of CDD like South Asia, West Africa and West Africa.

In absolute terms, an increase of the ambient temperature from 0,0 to 1,0 K is expected to rise the global average cooling degree days by 13,7%, or 182 CDD. The higher absolute increase of the cooling degree days is calculated for West Africa, 270 CDD, followed by West Asia, 238 CDD. For a temperature increase between 1,0 to 2,0 K, the average rise of the cooling degree days is close to 33,2% or 439 CDD. The highest absolute increase is foreseen for West Africa, 683 CDD, followed by South and East Africa. When the temperature increase is between 2,0 to 3,0 K, 3,0 to 4,0 and 4,0 to 5,0 then the average increase of the cooling degree days is 55%, 76% and 99% while the absolute increase of the cooling degree days is 727, 1005 and 1306 respectively. In all scenarios West Africa presents the highest absolute increase of the cooling degree days followed by Central America and South and East Africa.

Calculation of the possible increase of the Cooling Degree Days, base 22 °C and not 18,1 °C as usually used, for 58 major European cities, against the corresponding cooling degree days for the period 1961–1990 is reported in Ref. [40]. Estimations are performed for the period 2021–2050 and 2071–2100 using the A1b scenario of the IPPC. The specific scenario foresees an average surface temperature increase close to 1,6 K in 2050 and 2,8 K in 2100 compared

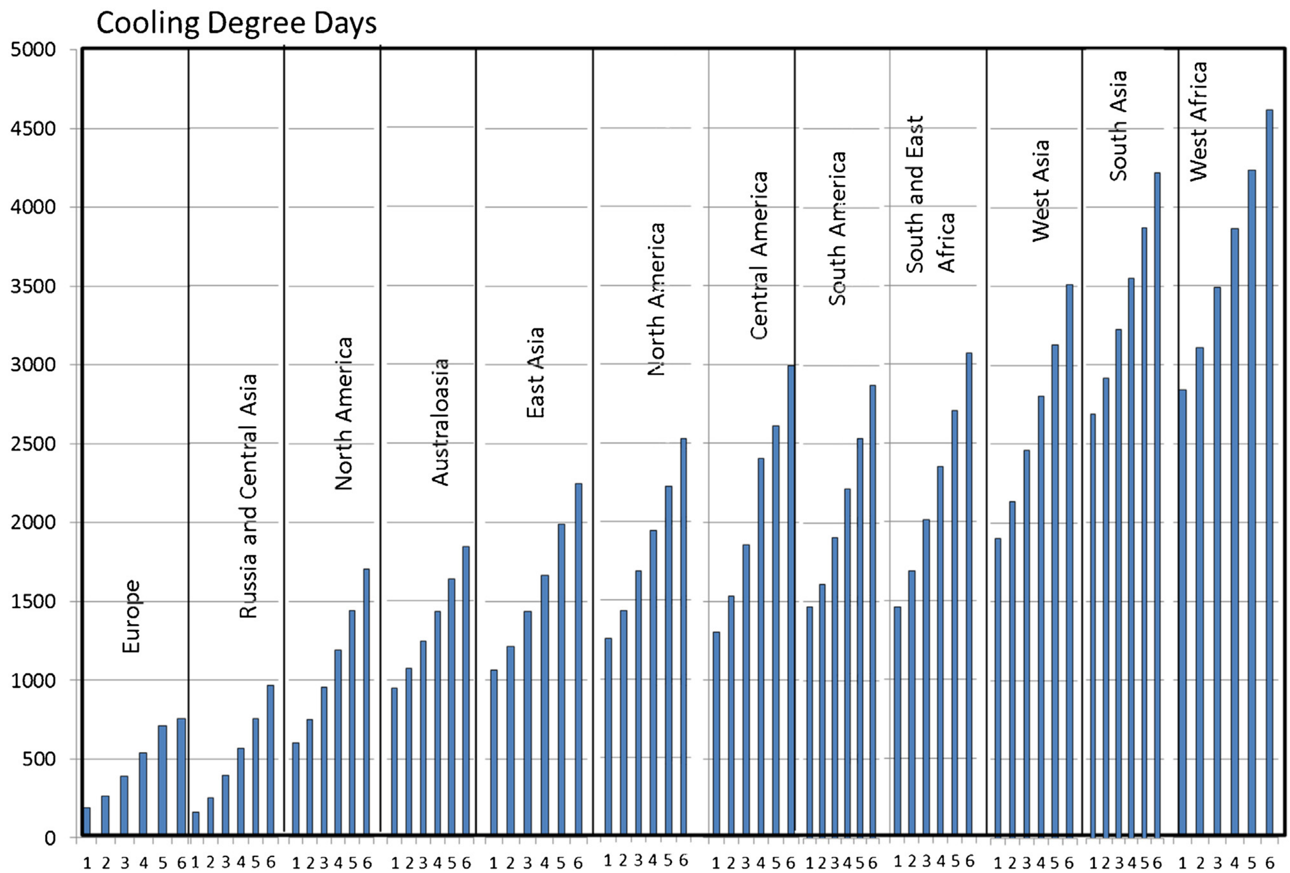

Fig. 4. Current and Future Cooling Degree Days for the Major Areas of the Planet and for different climatic scenarios, ((1) Baseline, (2) Increase between 0 and 1 K, (3) Increase between 1 and 2 K, (4) Increase between 2 and 3 K, (5) Increase between 3 and 4 K, and 6. Increase between 4 and 5 K). Data are adapted from Warren et al. [39].

to 2000. The current as well as the calculated values of the cooling degree days are given in Fig. 5. The average CDD value for the reference period was close to 123, against 186 given in Ref. [39] but for a temperature base of 18C. When, both values are calculated for the same temperature base, they found to be in good agreement. The average predicted cooling degree days for the period 2021–2050, are close to 306 and present an increase near to 146% compared to the reference case. In the period 2071–2100, the corresponding increase is close to 200% and the average cooling degree days are around to 372. The calculated increase rate is in good agreement with the corresponding figures given in Ref. [39], for the considered levels of temperature increase. The highest absolute rise reports for the Mediterranean cities where the cooling degree days increase range varies between 250–1200 in 2021–2050 and corresponds to a rise around to 134%. The corresponding increase in 2071–2100 ranges between 320–1470, an increase close to 173%, compared to the reference period. A significant increase of the cooling degree days, for the period 2021–2050, is also reported for the Mediterranean area in Refs. [41–43]. In Ref. [41], the potential increase of the cooling degree days for a temperature rise close to 2 K, is calculated for a temperature base of 25C. It is found that cooling degree days may increase between 50–250, compared to the reference period 1960–1990. The highest increase is calculated in the South Iberian area, North Italy, Balkans, Greece and Southern Turkey. In Ref. [42], six climate models have been used to calculate the cooling degree days, (base 25 °C), in the Mediterranean area in the period 2021–2050. The calculated increase was significantly lower than the one predicted in Ref. [41], and ranged between 50–180 cooling degree days, compared to the reference period, (1960–1990). Finally, in Ref. [43], the cooling degree days in the Eastern Mediterranean, (base 18 °C), are calculated for 2030 by considering several climate policy scenarios. It is reported that cooling degree days may increase up to 25,3% reaching values between 643–718 CDD.

The potential increase of the cooling degree days, (base 24 °C), in China, for the period 2006–2100 using a high, midrange and a low emission scenario, is reported in Ref. [44]. It is found that under the high emissions scenario, cooling degree days may increase following a trend close to 155 CDD/decade presenting in 2100 an increase close to 240% compared to 2005, and an average value close to 2400 cooling degree days. Under the midrange scenario, the increasing trend is reduced to 46,3 CDD/decade while the estimated increase for 2100 is close to 140% compared to 2005.

Several research works have been performed to estimate the potential increase of the cooling degree days in the United States [45–48]. Using the high emission climate scenario RCP8,5, the cooling degree days for the period 2080–2099, (base 18,3 °C), are calculated in Ref. [29], for 25 major American cities, (Fig. 6). It is found that cooling degree days may increase between 1,1 to 7,5 times compared to 1981–2010, with an average for the 25 cities close to 2,3 times. The higher proportional increase is expected in San Francesco and Seattle city and the lower one in Miami and Phoenix. The higher absolute increase of the cooling degree days is expected in the warmer zones of the country currently experiencing a high value of cooling degree days.

Knowledge of the cooling degree days is necessary to estimate the present and future cooling consumption of buildings in a specific region. Given that the evolution of energy consumption

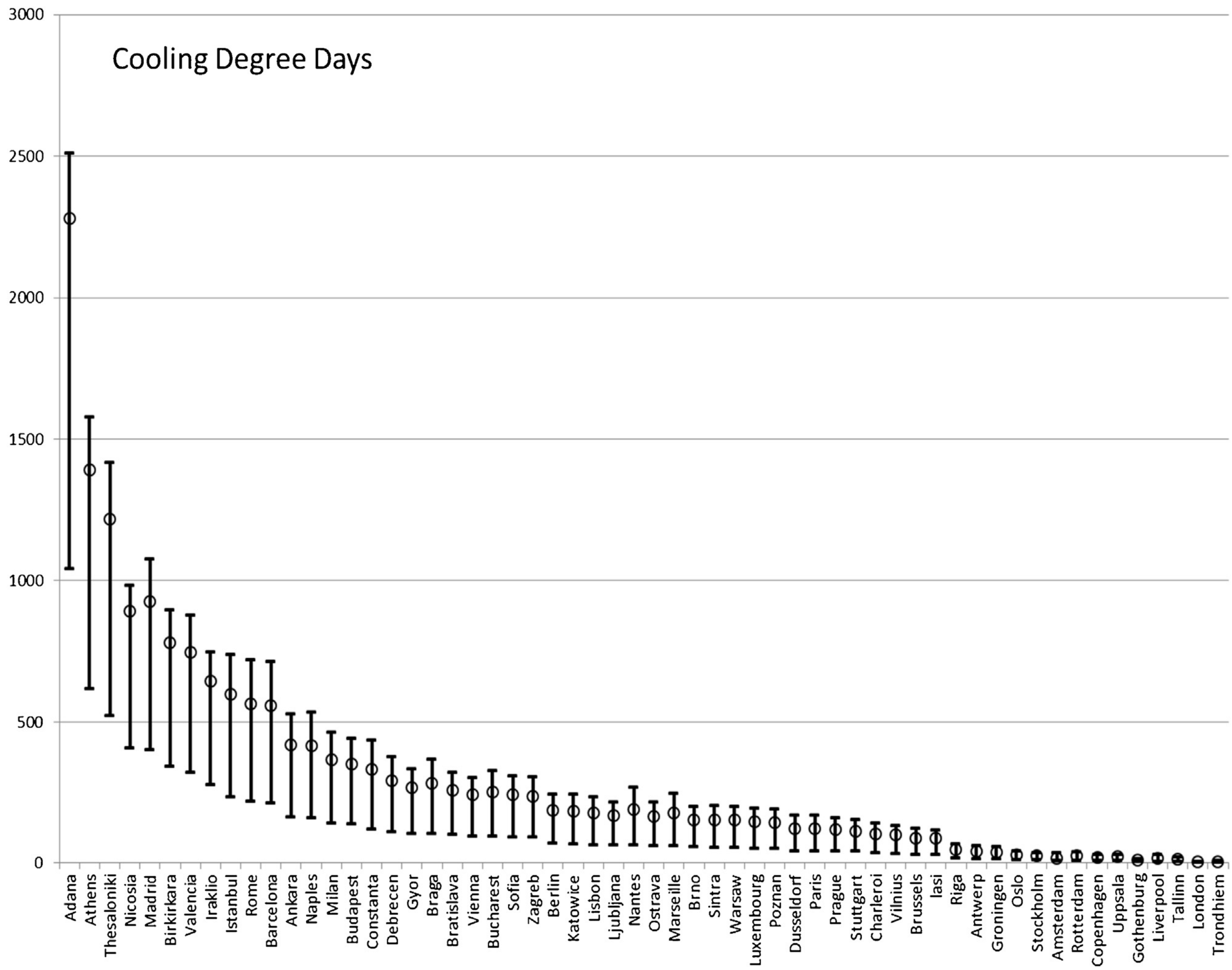

Fig. 5. Current, and Predicted Cooling Degree Days, (base 22 °C), for 58 European Cities. The lower part of the high-low bars represents the current value, circles represent the CDD value of the period 2012–2050 and the upper part the corresponding CDD value for 20171-2100, Data are from Ref. [40].

depends also to the total number of the local inhabitants, population weighted cooling degree days may be used. In this case, population weighted cooling degree days are calculated as [46]:

$$CDD_i = \frac{\sum_j CDD_{i,j} P_{i,j}}{\sum_j P_{i,j}} \quad (11)$$

where Pi,j is the population in the specific region. Several articles have estimated the population weighted future cooling degree days for USA [46,49,50]. A total of 18 scenarios considering two different concentration pathways, three climate models and three population scenarios are used to calculate the population weighted cooling degree until 2100 [46]. It is reported that under the emission scenario considering a CO_2 concentration close to 550 ppmv CO_2 at the end of the 21st century, populated weighted cooling degree days in China will increase between 20 and 35% compared to 2000, while when the CO_2 concentration is close to 850 ppmv, the corresponding increase of the population weighted cooling degree days is expected to be between 65 and 87%. In parallel, the calculated corresponding increase of the population weighted cooling degree days may vary between 0,0% and 107% for the two CO_2 concentration scenarios.

4.2. *Future trends of population size*

The world population is increasing constantly. While according to the United Nation forecasts, the total world population in 2000, was close to 6126 million [51], a significant increase up to the end of the century is predicted, (Table 1). Based on the predictions of lower, middle and high population scenarios, the total population may vary between 8179–8821 million by 2030 and 8710–10721 million in 2050. This corresponds to an increase up to 44% and 76% for 2030 and 2050 respectively compared to 2000. Forecasts for 2100 involve a high degree of uncertainty and the potential increases of the population vary between 19–171% compared to 2000. Most of the new population is expected in developing countries of Asia and Africa, where at 2030, almost the 51,8% and the 34,3% of the additional world population is expected to live, while at 2050, the corresponding share is 46% and 41% respectively. A very low increase or even decrease is expected of the developed nations. In Europe the size of the population in 2030 may vary between −2% to 4,4%, while in North America an increase between 21 and 31% is expected. Forecasts for the European population in 2050, fluctuate between a decrease up to 12,2% and an increase of 7,2%, while in North America it is expected that the population will increase between 24–52%.

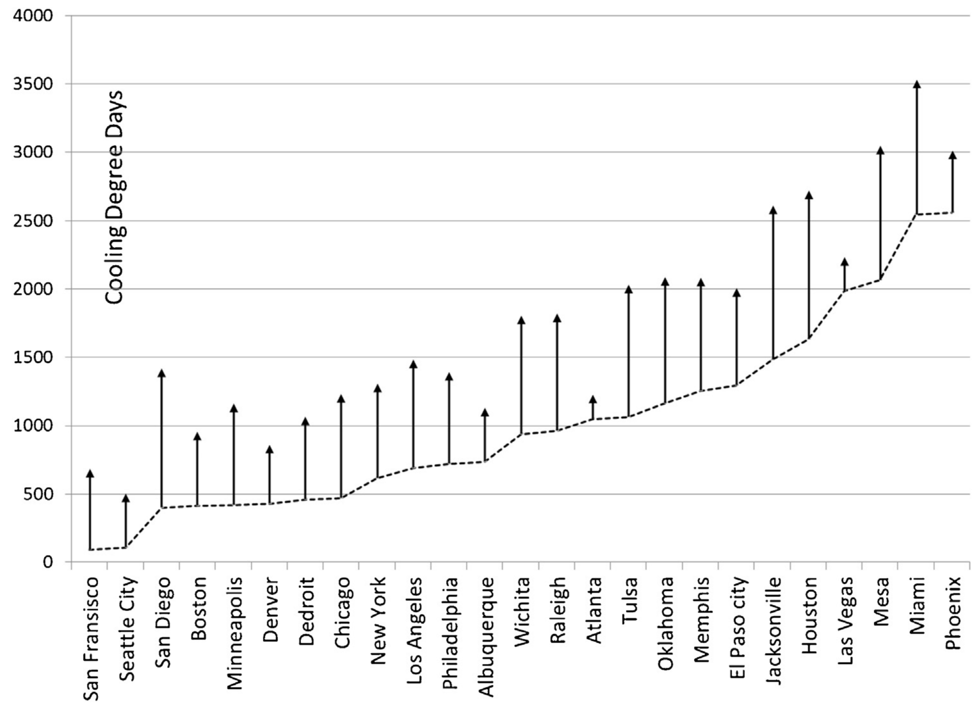

Fig. 6. Cooling Degree Days, (18,3 °C base), for selected USA cities. Data for 1981–2010, (line), and calculated values for 2080–2099 under the high emission scenario, RCP8,5. Data are from Ref. [45].

Table 1
Current and Future Projected Population in the major geographic regions, Source [51], Values in millions.

Year	Scenario	Europe	Asia	Africa	Latin America and the Caribbean	Oceania	North America	World
2000		726,5	3719	811,1	526,9	31,1	313,7	6164,3
2030	Middle	733,9	4922,8	1679,3	721,1	47,4	396,3	8500,7
	High	759,1	5112,8	1739,6	750,8	49,1	410,4	8821,8
	Low	708,8	4732,7	1619,0	691,3	45,6	382,1	8179,0
2050	Middle	706,8	5266,8	2477,5	784,2	56,6	433,1	9725,1
	High	779,1	5873,2	2730,7	878,9	62,3	476,9	10801,0
	Low	637,7	4698,2	2235,6	696,2	51,1	391,2	8710,0
2100	Middle	645,6	4888,6	4386,5	721,2	71,1	500,1	11,313,2
	High	960,1	7546,0	6130,8	1123,1	100,2	716,8	16577,0
	Low	415,8	3001,7	3048,7	439,4	49,2	339,1	7293,8

4.3. Future trends in gross domestic product

The future economic development of the world depends on the socioeconomic pathways that define and control the drivers of the global growth. Forecast of the world and the regional future economic output is essential for the prediction of the future emission scenarios and the corresponding definition of the necessary mitigation and adaptation policies. Several global scenarios aiming to predict the future energy consumption and the corresponding emissions are based on forecasts of the future gross economic output, GDP, and its distribution in the world [52–63]. Economic estimations are performed considering various Shared Socioeconomic Pathways, (SSPs), that involve a combination of different socioeconomic developments and policies in the world and the main geographic regions. In fact, the assumptions of the considered SSPs define highly the projected GDP value. Fig. 7, presents in a comparative way the forecasts of 19 models regarding the expected GDP per capita in 2050. As shown, based on the specific assumptions of the various scenarios, the expected average GDP per capita in 2050, may vary between 7200–26,400 US dollars of 1990. The important vagueness of the predictions is associated with the uncertainty about the future population size and the corresponding productivity rate. Lower GDP values are predicted by those scenarios assuming a serious population increase and a relatively low growth rate.

Independently of the vagueness of the GDP forecasts, it is agreed that serious GDP differences will continue to exist between the main geographic zones of the Earth. Fig. 8, presents the variety of the GDP per capita for 2050, between the 16 main geographic and economic zones of the planet. Forecasts and data are taken from the MIT emission scenario [52]. As shown, the predicted average world GDP per capita for 2050, is close to 9175 US$ of 1990, while the maximum GDP is in the USA with 55500 US$ and the lowest in Africa with just 1190 US$ of 1990. The predicted average GDP/capita for the developed countries and in particular USA, Canada, Japan, Europe and Oceania is close to 42600 US$ while the corresponding value for the rest of the world is 6520 US$, almost 85% lower.

4.4. Trends on the housing size

The total floor area of residential and commercial buildings is increasing continuously. While the total floor area of the residential buildings in the world, was in 2010 between 140–190 billion square meters, various forecasts [64–68], predict an increase between 180–290 billion square meters in 2030 and 190 and 370 billion square meters in 2050, (Table 2). The figures correspond to a world

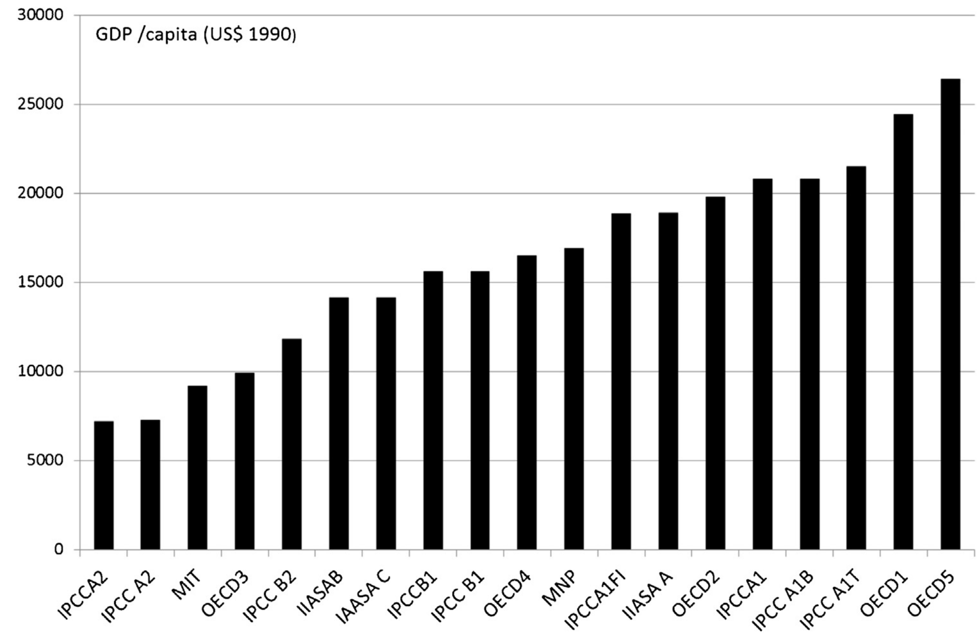

Fig. 7. Predicted global GDP per capita in 2050 by the various emission scenarios, (In US$1990).

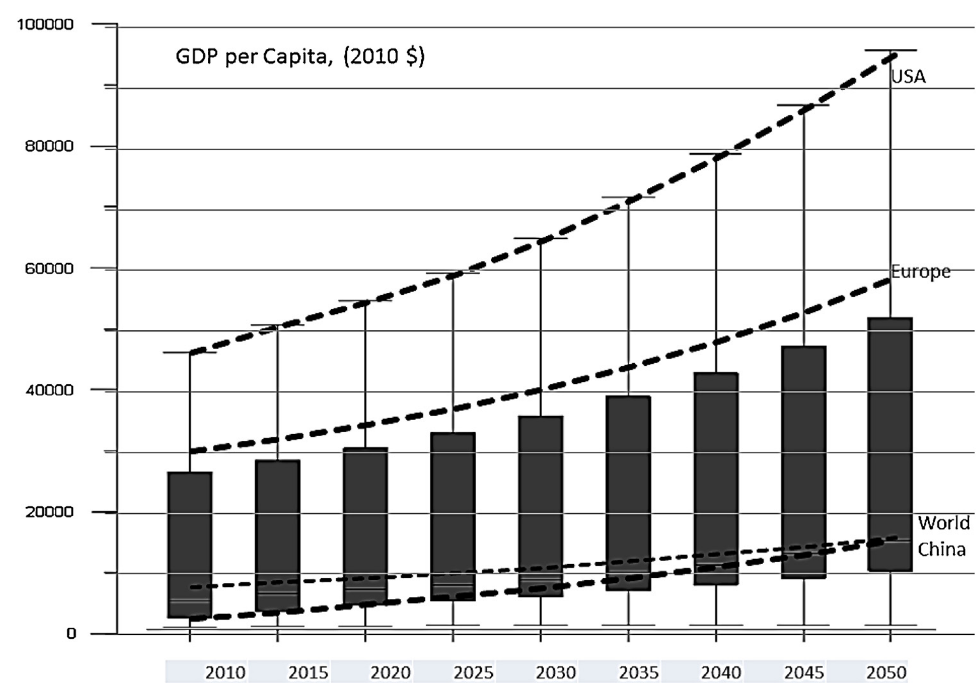

Fig. 8. Predicted Growth of the GDP per Capita between 2010 and 2050 for all major areas of the world, (in US$ 2010), Data from Ref. [52]. Each boxplot comprises all data from all major zones of the world.

average of 20,7–24 m^2 per person in 2010, increasing to 25–30 m^2 in 2030 and 28,5 to 37 m^2 per person in 2050 [64,65]. The highest increase rate of the residential floor area is expected in South Asia, the North Africa and Middle East zone. The expected increase of the total residential area between 2005 and 2050 is close to 508% and 481% respectively. A decrease rate of about 18%, is expected in Oceania and Western Europe, 3%, also between 2005 and 2050.

In parallel, while the total floor area of the commercial buildings in 2010 was between 21–24 billion square meters, it is expected to increase between 25–30 billion in 2030 and 28,5 to 37 billion in 2050 [64,65]. The average floor area of commercial buildings in 2010 was close to 5 m^2/person, and it is expected to increase up to 5,5 and 6 m^2/person in 2030 and 2050 respectively [65]. The highest increase rate of the commercial floor area between 2005 and 2050 [63], is expected in North Africa and Middle East area, (549%), the Central and Eastern Europe, (483%), and South Asia, (471%). The smaller increase is expected in North America, (51%).

Increase of the total floor area for both the residential and commercial buildings is mainly attributed to three specific reasons: (a) the expected rise of the global population that increases the number of households, (b) the significant decrease of the size of households, (persons/household) and (c) the obvious relation between the occupied floor area and the income, GDP. In fact, according to [64,65], while the average household size in the world was in 2010, close

Table 2
Major Current and Future statistical data and economic drivers for the residential and commercial buildings in the world.

	2010, (billion m^2)	2030, (billion m^2)	2050, (billion m^2)	Source
Total Floor Area of Residential Buildings	164	266	354	[65]
	141	211	274	[37]
	170	180	190	[66], low scenario
	170	195	230	[66], middle scenario
	170	220	340	[66], high scenario
	190	290	370	[67], high scenario
	190	240	270	[67], low scenario
			253,2	[68]
Average m^2 per person residential buildings	24	30	37	[65]
	20,7	25	28,5	[37]
Persons per household	3,6	2,9	2,7	[65]
	3,6	3,3	2,3	[37]
Residential Floor Area/capita or per dwelling vs GDP/capita	Floor Area/dwelling = (GDP/capita – 419,66)/166,38			[66]
	Floor Area/capita = 6,33 Ln (GDP/capita) – 28,95			[27]
Total Floor Area Commercial Buildings	35	46	57	[65]
	49,8	74,5	93,7	[37]
	45	70	120	[67], high scenario
	45	50	80	[67], low scenario
			99,1	[68]
Total Floor area commercial buildings per person, (m^2)	5	5,5	6	[65]
Commercial Floor Area per GDP	9,9 E-4	8,40E-04	6,00E-04	[37]
Commercial Floor Area per person vs GDP/person	Floor Area/person = 0,0005 × GDP/person – 0,004847			[67]

to 3,6 persons, it is expected to decrease between 2,9 and 3,3 persons in 2030 and 2,3 to 2,7 persons in 2050, (Table 2). In parallel, analysis of statistical data for the major geographic zones of the planet and the whole world, shows a statistically significant relation between the occupied floor area and the corresponding GDP for both the residential and commercial buildings [27,66,67]. Specific relations, tabulated in Table 2, have been proposed to estimate the potential increase of the occupied building space as a function the GDP [27,66,67]. The relation proposed in Ref. [27] is based on data from UN habitat program, Eurostat and IEA, while the corresponding relation proposed in Ref. [66], uses data from Europe and some IEA countries together with corresponding statistics from China and India. According to the relation proposed to [27], the average floor area per person for a GNP close to 60000 US$/capita is close to 40 m^2, and it is reduced to 28 m^2/capita and 22 m^2/capita for GNP's of 10000 and 5000 US$ per person. The specific predictions are quite close to the average values given in Ref. [65].

4.5. Future trends in energy efficiency

Scientific and industrial research has succeeded to improve the efficiency of most of the air conditioning systems. In particular, the performance of the split type air conditioners in the EU, American, Asian and Australian markets has improved by 3% per year during the last 15 years [69]. Especially for the room air conditioners, possible improvements are focused on the design of more efficient heat exchangers, compressors, inverters, expansion valves, reduction of the crankcase heating, and the reduction of the standby load. It is estimated [70], that the use of advanced heat exchangers may improve the efficiency of the room air conditioners between 9–28%, the development and use of more efficient compressors between 6–19%, the use of proper inverters between 20–25%, the use of thermostatic and electronic expansion valves between 5–9%, and the reduced crankcase heating power between 10 and 11%. Technical improvements of similar nature are also foreseen and projected for the commercial cooling systems and the heat pumps [71]. The main energy efficiency drivers for commercial cooling systems and heat pumps relies on the use of more efficient heat exchangers and compressors, the use of advanced fan motors and the implementation of proper control systems [53]. Several technical and economic analyses have shown that most of the projected technological improvements are cost effective [72], while it is expected that the delivered energy cost of cooling until 2050 will decrease between 50–65% [73].

Forecasts of the performance of the residential and commercial air conditioning systems estimate an import increase in the future. Analysis of the expected efficiency of the cooling systems in USA, predict an increase of the average COP performance of the installed stock from the current value of 2,8 to 3,5 in 2050 and 4,4 in 2090 [74]. A detailed analysis of the projected performance of the main residential and commercial end uses air conditioning equipment up to 2040, is given in Ref. [75]. The projected performance for most of the cooling systems is summarized in Table 3. For the residential systems, a very significant increase of the EER is foreseen for the ground source heat pumps while the expected improvements for the residential air conditioning and air source heat pumps are considerable but not spectacular. In particular, the best EER for the available ground source heat pumps in 2040 is expected to be close to 46 compared to 28 in 2013. In parallel, the highest EER of the residential heat pumps will increase from 22 in 2013 to 25 in 2040, and the best EER of the residential air conditioning systems will rise from 11,5 in 2013 to 12,9 in 2040. For the commercial rooftop air conditioning systems, the highest EER of the ground source heat pumps is expected to increase from 20,6 in 2013 to 26 in 2040. As it concerns the commercial chillers, a quite small increase of the performance is expected for the centrifugal, screw and scroll chillers, while a quite significant rise of the performance is expected for the gas fired absorption chillers.

New national labelling schemes, standards and improved legislation on the minimum performance of air conditioners contribute highly to increase the average performance of the air conditioners and decrease the world cooling energy consumption. In China, more strict energy performance standards for room air conditioners are applied since 2010. Class A split units with CC < 14,000 should present an EER superior to 3,3 while in the previous labelling scheme it was 3.1. As a result of the technological developments and the strict legislative and labelling framework, the efficiency of the worst room air conditioner has improved from 2,3 in 2005 to 2,9 in 2010 [76]. In Europe, since 2013, a new more efficient Energy labelling scheme for air conditioners applies. The new labelling scheme is based on the seasonal EER and considers the efficiency of the systems under part load conditions. For the highest class of room air conditioners A+++, the minimum SEER, (seasonal EER), requirement should be higher than 8,5 while the lower class G,

Table 3
Current and Future Performance of Various Residential and Commercial Cooling Technologies, Data from Ref. [75].

Air Conditioning Type		2013		2020		2030		2040	
		Typical	High	Typical	High	Typical	High	Typical	High
Residential Air Conditioning	EER	10,8	11,5	10,9	11,9	10,9	12,9	11,1	12,9
Residential Air Source Heat Pumps	SEER	14	22	14,5	23	15,5	24	16	25
Residential Ground Source Heat Pumps	EER	14,2	28	17,1	36	21	42	24	46
Residential Gas Heat Pumps	COP	0,6		0,7		0,7		0,7	
Commercial Chillers									
Gas Fired Absorption	COP	1,1		1,2		1,3		1,4	
Gas Fired Engine Driven	COP	1,7		1,8		1,8		1,8	
Centrifugal	COP,(F.L)	6,1	7,8	6,5	8,0	6,8	8,2	7,0	8,4
Reciprocating	COP,(F.L)	2,81	3,52	3,06	3,52	3,06	3,52	3,06	3,52
Screw	COP,(F.L)	2,84	3,46	3,10	3,55	3,20	3,66	3,26	3,74
Scroll	COP,(F.L)	3,02	3,17	3,08	3,23	3,17	3,29	3,23	3.32
Commercial Roof Top									
Air Conditioners	EER	11,2	13,9	11,5	13,9	11,5	13,9	11,5	13,9
Gas Fired Engine Driven	COP	1,1		1,1		1,1		1,1	
Heat Pumps	EER	11,0	12,0	11,0	12,0	11,0	12,0	11,0	12,0
Ground Source Heat Pumps	EER	17,1	20,6	18,0	22,0	20	24	22	26

requires SEER less than 2,6. In the previous labelling scheme the performance of the highest rank label was close to 3,2. In Korea, new requirements regarding the minimum energy performance, MEP, of the room air conditioners apply. The minimum performance of the small split units has increased to 3,37 while the previous value was 2,86.

5. Existing impact of global and local climate change on the cooling energy consumption of buildings

Several studies have attempted to quantify the existing impact of the global and local climate change on the cooling energy demand of buildings. Studies are classified into two major categories. Those aiming to evaluate the existing cooling energy penalty because of the global warming observed the last 50 years and, second studies aiming to address and to calculate the cooling energy penalty imposed by the urban heat island. Evaluation of the cooling penalty induced by the global climate change is based on a long series of past and current climatic data used as inputs in building energy simulation models to evaluate the cooling energy needs of specific type of buildings. Detailed calculations of the cooling energy penalty are performed in 18 cities around the world and are reported in details at Ref. [77]. All studies have concentrated on the multiyear energy impact of the global climate change in small and large offices as well as on residential buildings. The cooling energy consumption for at least a period of 40 years is evaluated using detailed simulation techniques or by a simple comparison of the corresponding cooling degree days. In average, it is found that in the period between 1970 and 2010, the cooling load of the considered buildings has increased on average by almost 23%. Details on the specific results obtained in each considered city are given in Ref. [77].

Studies aiming to evaluate the impact of the urban heat island and the local urban climate change on the cooling energy consumption of individual buildings, are based on estimations of the specific energy consumption performed using proper climatic data collected from urban and rural stations in a place. Analysis of 13 studies aiming to evaluate the cooling penalty of residential and office buildings as induced by the urban heat island [77], shown that the increase of the summer load of the urban buildings is on average 13% higher than the corresponding load of similar rural buildings. The cooling penalty is more significant in geographic areas with an average summer temperature above 27 °C, while its almost insignificant in heating dominated areas. Finally, it is found that a logarithmic relation exists between the cooling penalty per degree of urban heat island intensity and the reference cooling demand of the buildings as calculated for the undisturbed rural zones [77]. More details and information are given in Ref. [77].

The impact of urban overheating on the global energy consumption of cities is estimated in four studies performed in Beijing, Athens and Tokyo Japan [77]. Analysis of the specific results, shown that in average the Global Energy Penalty per unit of city Surface, (GEPS), is close to 2,4, (±1,5), kWh/m^2, the Global Energy Penalty per unit of city Surface and per degree of the UHI intensity, GEPSI, is 0.74 (±0.67) kWh/m2/K, the global energy penalty per person, GEPP, is 237 (±130) kWh/p and the global energy penalty per person and per degree of the UHI intensity, GEPPI, is 70 (±45) kWh/p/K [77].

6. Forecasting the impact of the global climate change on the future cooling energy consumption of individual commercial buildings

Several studies have attempted to evaluate the potential energy impact of the global climate change on the cooling energy consumption of various building types. Given the high cooling demand of the commercial buildings, most of the studies have focused on the estimation of the potential impact of climate change on the cooling demand of typical office buildings [78–90]. In order to assess and evaluate the existing knowledge on the topic, 144 case studies published in Refs. [78–90], have been analyzed. All studies have calculated the potential increase of the cooling demand of offices because of the global climate change. The considered case studies are located in 40 different cities in Europe, America, Asia and Australia. Each examined article has considered one or more office buildings of different characteristics under one or more climatic scenarios. The calculations of the currentand future cooling demand were performed in a range of initial and final assessment periods and in various set point temperatures. The initial or reference time period varied between 1990 and 2010, while the final assessment was mainly performed for 2030, 2050 and 2100 or for a non-determined period. Indoor set points temperatures ranged between 21–26 °C.

The overall analysis has focused to four main parameters: (a) The undisturbed current cooling demand of each considered building, Q, which is the reference cooling consumption of the building at time zero and without to account the future impact of climate change (b) the assumed average temperature increase because of the climate change, ΔT, during the final assessment period, (c) the

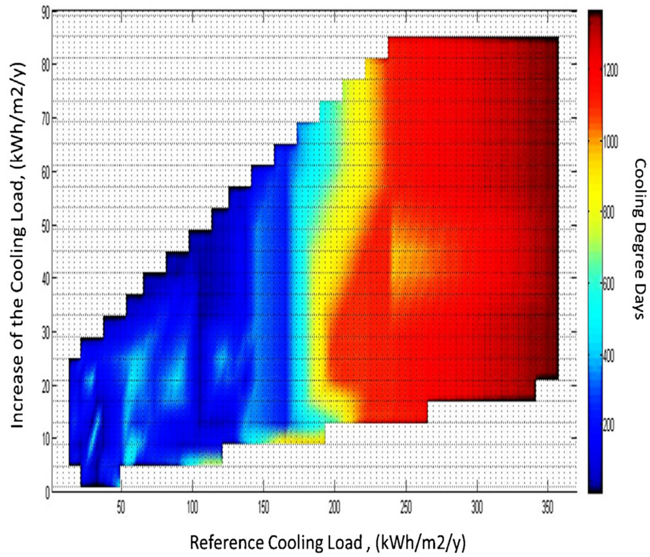

Fig. 9. A 3D representation of the used current cooling energy consumption of office buildings, (kWh/m2/y), the expected increase of the cooling energy consumption, (kWh/m2/y), and the currentcooling degree days for each of the considered locations.

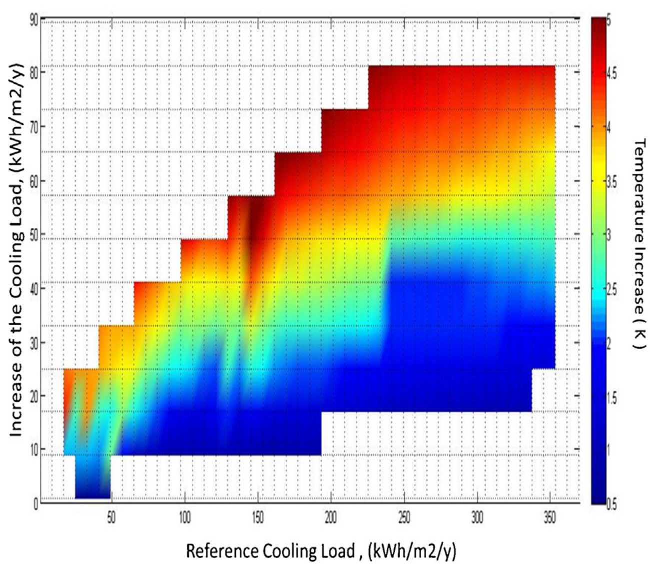

Fig. 10. A 3D representation of the used current cooling energy consumption of office buildings, (kWh/m2/y), the expected increase of the cooling energy consumption, (kWh/m2/y), and the corresponding considered increase of the ambient temperature for each of the considered locations.

reference cooling degree days at the considered location at time zero calculated at a temperature base equal to the assumed set point temperature, DD, and d) the calculated increase of the cooling demand during the final assessment period caused by the climate change, ΔQ.

The reference cooling load, for all the examined cases, varied between 12–360 thermal kWh/m^2/y, as a function of the local climate, the set point temperature and the building characteristics. The reference cooling degree days varied between 8–1366, while the considered temperature increase ranged between 0,4 to 5 K. Finally, the calculated increase of the cooling demand ranged between 1–86 kWh/m^2/y. Fig. 9 and 10 present the relation and the variability between the four considered parameters. It is obvious that the lower the cooling degree days, the lower the reference cooling demand and the lower the calculated increase of the cooling consumption. High reference cooling demands correspond to high cooling degree days while for the same reference consumption and degree days the calculated increase of the demand varies significantly as a function of the considered climate change scenario. The absolute impact of the temperature increase becomes more significant for increasing reference cooling demands of buildings located mainly in cooling dominated geographic zones.

The overall analysis has shown that there is a strong non linear correlation between the reference cooling demand, Q, and the calculated absolute increase of the cooling consumption per degree of temperature rise, (Fig. 11). The size of the circles in Fig. 11, presents the percentage increase of the reference cooling load. On the average, for reference cooling demands close to 50 kWh/m^2/y, the calculated average increase of the cooling consumption per degree of temperature rise, $\Delta Q/\Delta T$, is close to 6 kWh/m^2/y/K, and is twice as much when the reference load is increasing three folds, 150 kWh/m^2/y. A further increase of the $\Delta Q/\Delta T$ value, close to 17 kWh/m^2/y/K, is calculated for much higher cooling demands close to 300 kWh/m2/y. As expected, the relative impact of the potential temperature increase is considerably lower for high cooling degree days values. This is more evident when the reference cooling demand, Q, is plotted against the relative increase of the cooling consumption per degree of temperature rise, $\Delta Q/Q/\Delta T$, Fig. 12. As clearly shown, the higher the reference cooling demand the lower the relative increase of the cooling consumption per degree of temperature rise.

7. Forecasting the future cooling energy consumption of the building sector

Prediction of the future cooling energy consumption is necessary to forecast the future electricity needs and the additional power demand. A considerable number of models and methodologies have been proposed and used to predict the future cooling energy demand in the major geographic zones of the planet for both the residential and the commercial sectors [8,14,15,27,34,49,91–96]. Most of the models are based on the estimation (a) of the future ownership of appliances taking into account the rise of the local GDP and the expected population increase, (b) the baseline cooling energy consumption, (c) the potential impact of the climate change and (d) the expected increase of the efficiency of the air conditioning systems and of the whole buildings [8,27,14,91,92,93,96]. Other models are considering part of the above inputs and are mainly focused on the increase of the population and the impact of the climate change [15,34,49]. Most of the models are focusing on specific geographic zones of the planet while few models attempt to predict the future cooling consumption for all continents and the whole world. Predictions are referring to different time periods, however, most of the models are focusing in 2050 and 2100.

The existing predictions of the residential cooling energy demand for the major geographic zones and for the years 2030, 2050 and 2100 are shown in Fig. 13 [8,27,14,91,92,93,96]. Only data predicted from models considering all the four parameters mentioned previously, are considered. Because of the substantial uncertainty regarding the evolution of the future air conditioning market and the local economic and climatic parameters, significant discrepancies and serious differences are identified between the various models. However, it is evident that a very significant and continuous increase of the future residential cooling demand is expected for the coming years. While in 2030, the highest demand in expected in USA and Europe, Asia seems to be the more significant consumer in 2050 and 2100. The highest absolute increase of the cooling demand is expected in Asiatic countries and in particular in India and China mainly because of the rapid expected

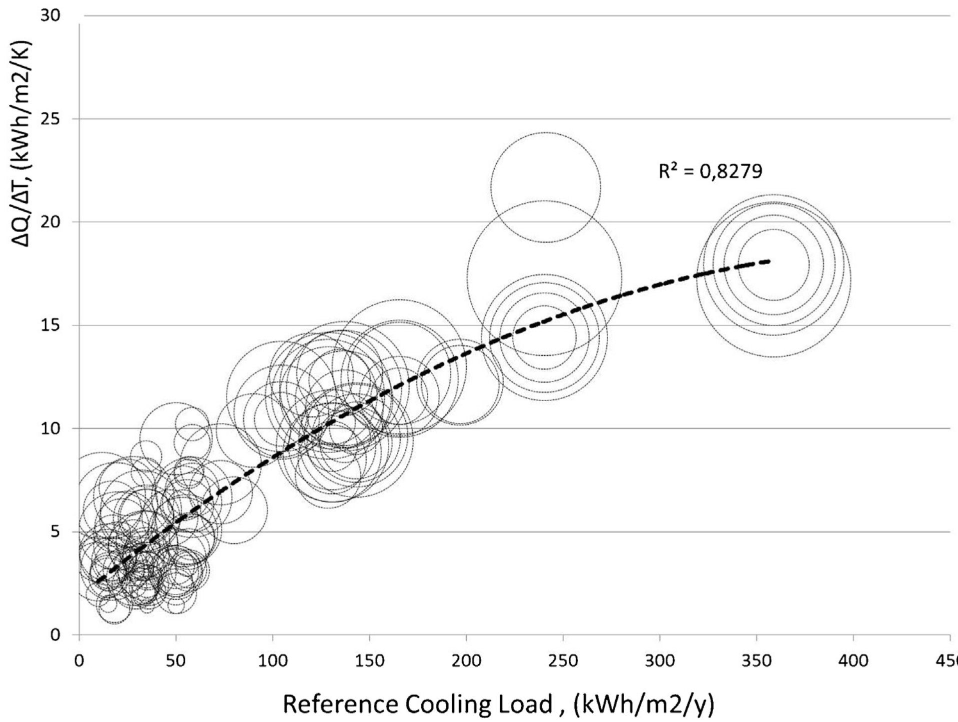

Fig. 11. The relation between the Reference Cooling Energy for the considered office buildings and of the increase of the cooling energy demand per degree of ambient temperature, (ΔQ/ΔT). The size of the circles, presents the percentage increase of the reference cooling load.

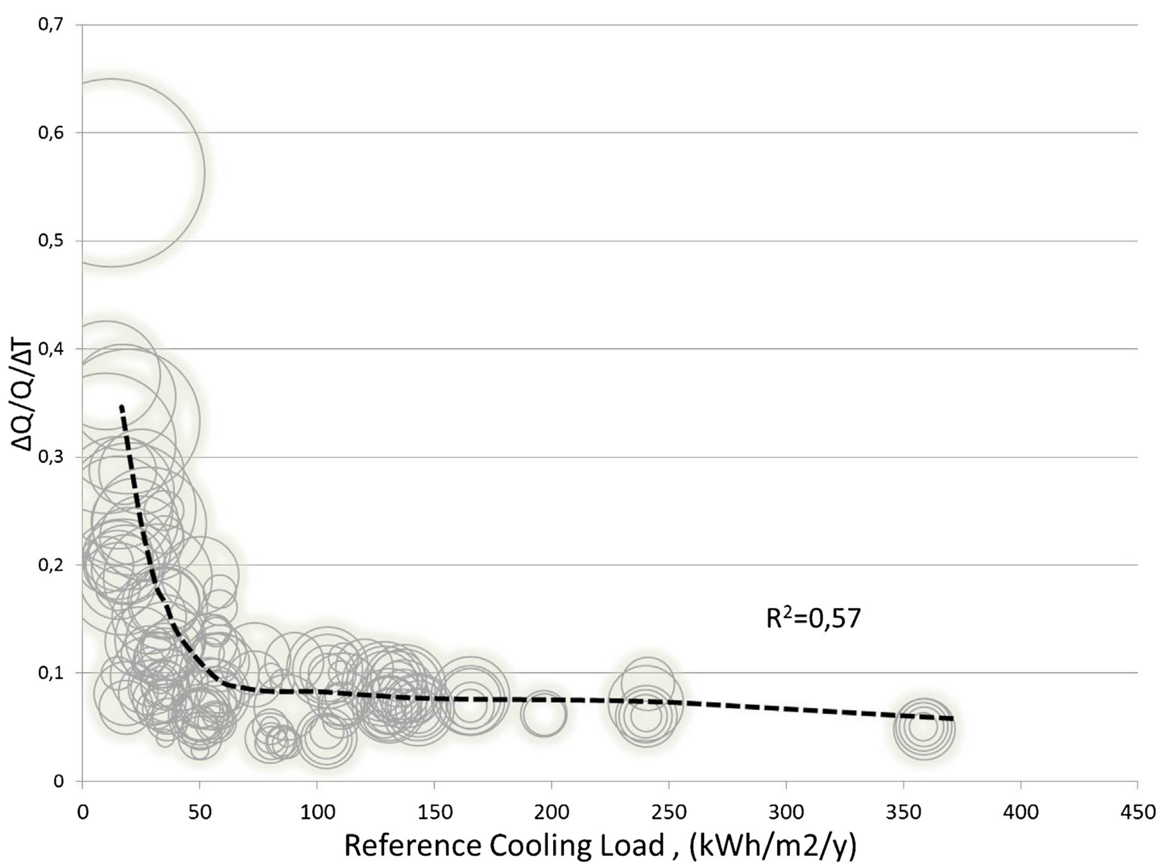

Fig. 12. Relation between the Reference Cooling Energy for the considered office buildings and of the ratio of the cooling energy increase and the reference cooling demand per degree of ambient temperature, (ΔQ/Q/ΔT). The size of the circles, presents the percentage increase of the reference cooling load.

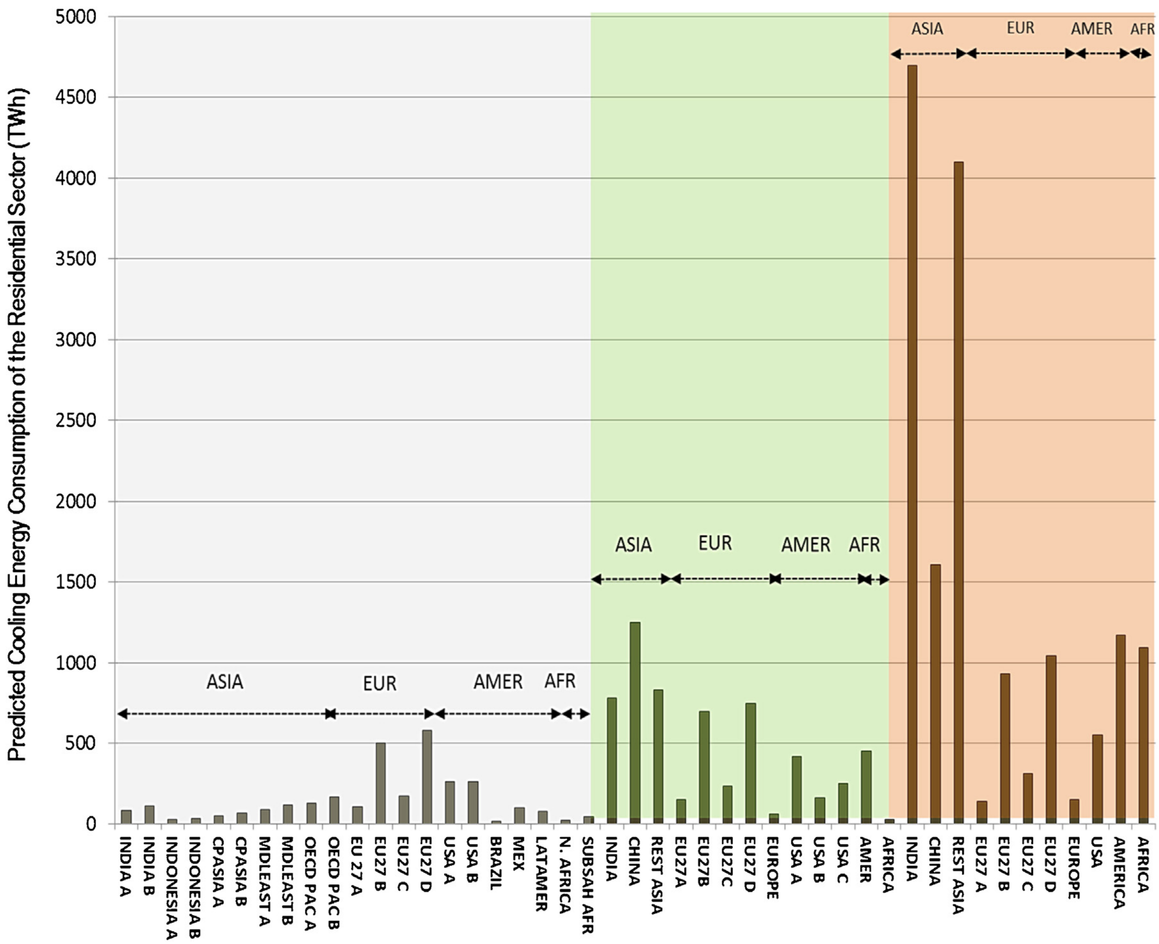

Fig. 13. Predicted Future Residential Cooling Energy Consumption by the various existing models. The blue Zone(left part of the figure) is for 2030, the green, (middle part of the figure) for 2050 and the red (right part), for 2100. Data are from Refs. [8,27,14,91,92,95,96]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

penetration of air conditioning, the increase of the population and the important impact of the global climate change. In India, predictions from Refs. [8,27], show that the residential cooling consumption may reach 110 TWh in 2030, 780 TWh in 2050 and 4700 in 2100. In China, the residential energy demand may reach 1250 TWh in 2050 and 1610 in 2100, while for the rest of the Asian Countries the consumption may increase up to 4100 TWh by 2100. From the European countries, existing predictions given in Refs. [14,27,92] present a very significant variation mainly because of the considerable differences in the assumptions regarding the future penetration of the air conditioners and the expected increase of the ambient temperature. The existing forecasts for Europe and for 2050 vary between 60 TWh [27], 151–233 TWh [19] and 700–750 TWh [92]. For 2100, predictions vary between 150 TWh [27], 140–315 [19], and 930–1050 [92]. For the commercial sector, data published in Ref. [14], predicts for 2030 a total cooling demand between 930 and 1050 TWh, for 2050 a consumption between 1050 and 1500 TWh while for 2100 the predicted consumption vary between 1400–2850 TWh. For USA, predictions of the residential demand given in Refs. [27,95,96], forecast a cooling demand close to 260 TWh, while in 2050 and 2100 it may increase up to 420 and 555 TWh respectively [27]. For the commercial sector, it is foreseen that the cooling demand in 2050 may range between 270–563 TWh [96]. For the rest of the American continent, the residential cooling demand in 2050 and 2100 is expected to be close to 450 and 1170 TWh respectively [27]. Finally, a tremendous increase of the residential cooling energy consumption is expected in Africa between 2050 and 2100. While the predicted cooling consumption in 2050 is close to 30 TWh, it is foreseen to increase up to 1100 TWh in 2100 [27].

8. Forecasting the future cooling energy consumption of commercial buildings

The future energy consumption of the commercial buildings, Ect(t), can be determined as a function of the foreseen total floor area, FA, of the commercial buildings, their specific energy consumption per square meter, EPM(t), the possible energy impact of the climate change, f(CDD), the future increase of penetration of the air conditioning, f(ACavlblty), the estimated increase of the efficiency of the air conditioners, f(ACeff), and also of the global energy performance of the building, f(BldgPerf).

$$\mathrm{Ect}(t) = \mathrm{FA} \times \mathrm{EPM}(t) \times f(\mathrm{CDD}) \times f(\mathrm{ACavlblty}) \times f(\mathrm{ACeff}) \times f(\mathrm{BldgPerf}) \quad (12)$$

Using the existing forecasts regarding the evolution of the main parameters of the commercial buildings, three scenarios are developed to predict the future cooling energy consumption of the commercial buildings in the world for 2050. The specific setups refer to a High Development, an Average and a Low Development Scenarios. The basic assumptions and inputs for each scenario are given in Table 4.

The Low Development Scenario considers that by 2050 the total world floor area of the commercial buildings will be close to 80 billion square meters. This value corresponds to the low prediction boundary given in Ref. [67]. The current average cooling energy

Table 4
Inputs and Assumptions for the three scenarios forecasting the cooling energy consumption of the commercial sector in 2050.

Scenarios	Floor Area, (m2)	EPM, (kWh/m$^{2)}$	F(CDD)	F(ACavlblty)	F(ACeff)	F(bldgperf)	References
Low Development Scenario	8,00E + 10	13	1,14	1,1	0,96	0,9	[20,39,67,97]
Average Development Scenario	9,90E + 10	14	1,32	1,2	0,88	0,8	[37,39,20,97]
High Development Scenario	1,20E + 11	15	1,55	1,3	0,8	0,7	[39,67,20,97]

consumption of the commercial buildings is calculated by dividing the total cooling energy consumption of the commercial buildings given in Ref. [20], with the current floor area of the commercial buildings, 43,2 billion square meters, proposed in Ref. [97], which is the highest reported value in the literature. This corresponds to an current cooling energy consumption close to 13 kWh/m^2/y. The possible increase of the cooling energy consumption because of the global climate change is considered as a linear function of the increase rate of the cooling degree days. This is an assumption considered by most of the existing forecast scenarios [39,41,43], and it is very close to the reality. For the present scenario, it was considered that the temperature increase in 2050 will not exceed 1 K. Using the predictions on the average world future degree days, given in Ref. [39], it is calculated that f(CDD) = 1137, which corresponds to an average increase of the cooling demand by 13,7%.

The future penetration of the air conditioning in the commercial buildings is a rather «gray» area. Currentdata show an average penetration of about 80% in the USA, almost 100% in Japan and close to 30% in Europe [98]. Data on the penetration of the air conditioning in the commercial buildings in the rest of the world are very limited. In China, the penetration of the air conditioning in the commercial sector until 2000, was close to 20% while it is foreseen to increase near to 55% by 2020 [99]. In parallel, it is reported that in the recent years the penetration of air conditioning in the commercial buildings in the USA remains flat while in China the penetration rate is quite high [99]. Given the above data, the present scenario is based on the assumption of the average world penetration of air conditioning in the commercial buildings will be close to 55%. Such an assumption is reasonably pessimistic, given the current penetration levels and the growth rates in both developed and developing countries. The average increase of the penetration f(ACavlblty) is calculated as the weighted average penetration in the world, taking into account the foreseen floor area of the commercial buildings in the major geographical zones in the world predicted in Ref. [100]. The calculated value of the f(ACavlblty) was close to 1,1, which means an increase of the penetration rate close to 10%.

The potential increase of the performance of air conditioners used in commercial buildings is calculated using the efficiency forecasts given in Ref. [75]. For the present scenario it is taken f(ACeff) = 0,96. Finally, the scenario considers that the average global efficiency of the commercial buildings in the world will improve by 10% mainly because of the applied higher energy performance standards, the increased efficiency of the envelope technologies and the applied adaptation technologies, despite the considerable increase of the installed electronic equipment [58–60,101–103] Thus, it is considered that f(bldgperf) = 0,9.

The average development scenario considered that the total floor area of the commercial buildings in 2050 will increase close to 99 billion square meters. This value is proposed in Ref. [37] and is an average between the high and low forecasts given in Ref. [67]. The current cooling energy demand is calculated equal to 14 kWh/m^2/y, using the same methodology as in the low scenario, but considering that the actual floor area of the commercial buildings is slightly lower, 39,2 billion square meters, as proposed in Ref. [20]. As it concerns the potential impact of the climate change, it is assumed that the average temperature increase in 2050 will be between 1–2 K. Using the corresponding predicted cooling degree days in Ref. [39], it is calculated that f(CDD) = 1.32. In terms of the potential penetration of the air conditioning in the commercial sector, it was considered that the average penetration rate in the world will be close to 60%. Using the same methodology as in the previous scenario, it is calculated that f(ACavlblty) = 1,2. Finally, according to the predictions given in Ref. [75], it is taken that f(ACeff) = 0,88, while the potential decrease because of the global improvement of the energy performance of the commercial buildings is considered close to 20% and thus f(bldgperf) = 0,8.

The high development scenario considers that the total floor area of the commercial buildings in 2050 will increase up to 120 billion square meters. This is the highest value proposed in Ref. [67]. The current cooling energy consumption of the commercial buildings is calculated as in the previous scenarios considering that the current floor area of the commercial buildings is considerably lower, 37 billion square meters [104]. This resulted in a value of EPM close to 15 kWh/m^2/y. As it concerns the possible impact of the climate change, it is assumed that the potential temperature increase will be between 2 and 3 K, and using the CDD values predicted in Ref. [39], it is calculated than f(CDD) = 1,55. The penetration rate of the air conditioning is assumed close to 70% that resulted in a value of f(ACavlblty) = 1,3. The scenario considered a relatively high potential increase of the efficiency of the air conditioners for commercial buildings, f(ACeff) = 0,8 and a considerable improvement of the total building performance: f(bldgperf) = 0,7.

The predicted levels of the cooling energy consumption of the three considered scenarios for 2050, are given in Fig. 14. The projected consumption for the low, average and high development scenarios are: 1,13 PWH, 1,55 PWH and 2,03 PWH respectively. Predictions correspond to an increase of the cooling energy demand of the commercial buildings, compared to the current consumption, close to 200%, 275% and 360% respectively. Given the substantial uncertainty in all the considered inputs, a sensitivity analysis has been performed to identify the variability of the predictions regarding each input parameter. For each of the three scenarios, the cooling energy consumption has been calculated considering the low, average and higher value of each input while keeping all other parameters constant. The obtained results are plotted in Fig. 14. The highest variability, almost 50%, is because of the uncertainty on the total floor area of the commercial buildings, followed by the variability due to the climate change, 36%, and the potential increase of the global energy performance of the commercial buildings, 30%. The lower calculated variability values are associated with the uncertainty on the potential penetration of the air conditioning, 18% and the possible increase of the efficiency of the commercial air conditioners, 8%. The highest cooling energy consumption is calculated for the higher development scenario when the lowest global energy performance of buildings is considered, while the minimum cooling energy consumption corresponds to the low development scenario when the maximum global energy performance is assumed. The ratio between the higher and the lower value is close to 2,97. In conclusion, the cooling energy consumption of the commercial buildings in 2050 will vary between 0,9 to 2,61 PWH with a most probable average value close to 1,55 PWH.

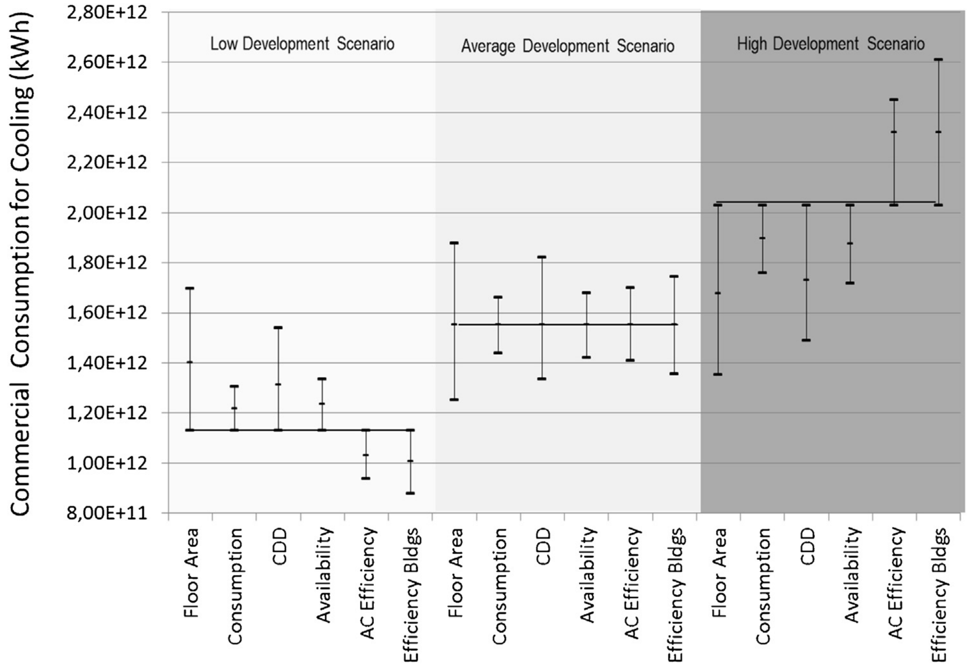

Fig. 14. Predicted Cooling Energy Consumption of the Commercial Buildings in the World, for 2050. Results of the Low, Average and High Development Scenarios and variability as a function of the main parameters and drivers.

9. Forecasting the future energy consumption of the residential buildings

The future cooling energy consumption of the residential buildings, Ecr, can be estimated as a function of the world population, POP, the residential floor area per person, FAP, the current cooling energy consumption per square meter of the residential buildings, EPM(r), the possible energy impact of the climate change, f(CDD), the future increase of penetration of the air conditioning in the residential sector, f(ACavlblty), the estimated increase of the efficiency of the air conditioners, f(ACeff), and also of the global energy performance of the residential buildings, f(BldgPerf).

$$\begin{aligned} \mathrm{Ect(r)} &= \mathrm{POP} \times \mathrm{FAP} \times \mathrm{EPM(r)} \times \mathrm{f(CDD)} \\ &\quad \times \mathrm{f(ACavlblty)} \times \mathrm{f(ACeff)} \times \mathrm{f(BldgPerf)}, \end{aligned} \tag{13}$$

As in the case of commercial buildings, three scenarios have been developed to assess the cooling energy consumption in 2050. The basic assumptions of the Low, Average and High development scenarios for the residential buildings are given in Table 5.

The Low Development Scenario considers that the world population in 2050 will be close to 8,71 billion people. This is the lowest proposed value in the literature and is used by the IPCC [51], for the so called B2 scenario. The residential floor area per capita in 2050 is taken equal to 28,5 m^2/person as proposed in Ref. [54]. This is also one of the lowest values in the existing literature. The current cooling energy consumption per square meter is calculated by dividing the total cooling energy consumption of the residential buildings given in Ref. [20], with the current floor area of the residential buildings, 190 billion square meters, proposed in Ref. [67], which is the highest reported value in the literature. It is calculated that EPM(r) = 3,67 kWh/m^2. The impact of the climate change on the cooling residential consumption is considered the same way as for the commercial buildings. For the low development scenario, it is assumed that the temperature increase by 2050 will not exceed 1 K, while using the predicted cooling degree days from Ref. [39], it is taken that f(CDD) = 1,14. To calculate the future penetration of air conditioning in the residential sector, the methodology proposed in Ref. [8] and explained previously is adopted. The potential availability levels of air conditioning are calculated as a function of the GDP as proposed in the Eq. (1). For the low development scenario, the GDP is taken equal to 11800 US $(1995), as proposed by the IPCC low development scenario [39]. Then, the current and 2050 availability levels for are calculated from Eq. (1), and it is obtained that f(ACavlblty) = 2,37. The potential increase of the efficiency of the residential air conditioners is calculated using the data given in Ref. [75], and is taken f(ACeff) = 0,96. Finally, the potential increase of the total building energy performance is taken into account the same way as for the commercial buildings and it is assumed that f(bldgperf) = 0,9.

For the average development scenario, the population in 2050 is taken equal to 15,6 billion people, as proposed by the B1 IPCC scenario [51]. The floor area per capita is considered equal to 30 m^2/person as proposed in Ref. [65]. The cooling energy consumption per square meter, EPM(r) is taken equal to 4,1 kWh/m^2/y. This value resulted, as in the low development scenario considering that the total residential floor area is 170 billion square meters as proposed in Ref. [66]. The potential temperature increase was assumed between 1–2 K, and it is taken that f(CDD) = 1,32. The average world GDP was taken equal to 15,600 US$(1995) as proposed by the PCC [39] and the parameter f(ACavlblty) was calculated using Eq. (1), equal to 4,75. The increase of the efficiency of the air residential air conditioners was taken according to suggested values in Ref. [75], f(ACeff) = 0,88. Finally, the possible increase of the total performance of the residential building stock is taken equal to the one considered for the commercial buildings, f(bldgperf) = 0,8.

Finally, for the High Development scenario, the total world population in 2050 was taken equal to 10,8 billion as proposed by the A1 scenario of the IPCC [51]. The residential floor area per capita was taken equal to 37 as proposed in Ref. [65]. The cooling energy consumption per square meter, EPM(r) is calculated equal to 5,0 kWh/m^2/y, in a similar way as in the previous scenarios but considering that the total residential floor area is 141

Table 5
Inputs and Assumptions for the three scenarios forecasting the cooling energy consumption of the residential sector in 2050.

Scenarios	Population	Floor Area per person, (m^2)	EPM, (kWh/m^2)	F(CDD)	F(ACavlblty)	F(ACeff)	F(bldgperf)	References
Low Development Scenario	8,71E+09	28,5	3,7	1,14	2,37	0,96	0,9	[51,54,39,58,8,75]
Average Development Scenario	9,73E+09	30	4,1	1,32	4,75	0,88	0,8	[51,65,39,58,8,75]
High Development Scenario	1,08E+10	37	5,0	1,55	8,62	0,82	0,7	[51,65,39,58,8,5,75].

billion square meters as proposed in Ref. [37]. The impact of the climate change is taken into account considering that f(CDD) = 1,55 which is based on the assumption that the average ambient temperature will increase between 2–3 K by 2050. The average world GDP used to calculate the AC penetration was taken equal to 20800 US$(1995), which is the upper bound proposed by IPCC [39]. Such an assumption resulted in a value of f(ACavlblty) = 8,62 which indicates that the average penetration of the air conditioning by 2050 will increase almost 8,62 times compared to the current penetration. Finally, the considered increase of the residential air conditioners was the highest possible suggested in Ref. [75], f(ACeff) = 0,82, while it was considered that the global energy performance of the residential buildings will improve by 30% until 2050, and thus f(bldgperf) = 0,7.

The calculated levels of the future cooling energy consumption of the residential buildings are plotted in Fig. 15. The predicted levels of Ect (r) are 2,15 PWH/year, 5,27 PWH/year and 15,4 PWH/year for the Low, Average and High Development scenarios respectively, and correspond to an average increase of the residential cooling demand by 320%, 750% and 2270% compared to the 2010 consumption levels. Given the important uncertainty of the considered input parameters, a sensitivity analysis has been performed in a similar way as for the commercial buildings. It is evident that the highest uncertainty is associated with the future penetration levels of air conditioning in the residential sector. The huge fuzziness about the future GNP causes also another significant uncertainty. The calculated variability of the cooling demand is close to 360% when the low and the high penetration levels are considered. The calculated variability for all other considered inputs is quite low and varies between 24–35%.

As in the case of the commercial buildings, the higher residential cooling energy consumption is calculated for the high development scenario when the lowest global energy performance of buildings is considered, while the minimum residential cooling energy consumption corresponds to the low development scenario when the maximum global energy performance is considered. The ratio between the higher and the lower value is 11,8. In conclusion, the cooling energy consumption of the residential buildings in 2050 is predicted to vary between 1,67 to 19,8 PWH with a most probable average value close to 5,3 PWH.

The calculated average cooling consumption of the residential sector, (5,27 PWH), is slightly higher than the predictions of the reference scenario, (4,2 PWH), presented in Ref. [27]. The range of the predictions in Ref. [8], varies between 2,6 PWH to almost 6,0 PWH. The difference is mainly due to the much lower cooling energy consumption assumed in Ref. [27] for the starting year, 2010 and the relatively low assumed values for the cooling degree days. In fact, the estimated in Ref. [27], cooling energy consumption in 2010 was close to 0,45 PWH, while the assumed value in the present study is close to 0,7 PWH and is based on the available consumption data from Refs. [20,21]. In parallel, the predicted by the present study, residential cooling energy consumption is considerably lower than the corresponding values given in Ref. [92]. According to [92], the global world residential cooling energy consumption in 2050 will vary between 7 PWH without to consider the impact of the climate change to 11,7 PWH when climate change is taken into account. The specific predictions considered a higher AC penetration level than in the present average scenario and ranges between the predictions of the average and high development of the present study. A comparative presentation of the range of predictions given in Ref. [92] and in the present study is given in Fig. 16.

The predicted total average cooling consumption in 2050, for both the residential and commercial sector is close to 6,8 PWH out of which 1,7 PWH or 32% is due to the global climate change. These values are considerably higher than the predictions given in Ref. [91] for the whole world in 2050. In fact, predictions in Ref. [91], refer to a global cooling consumption between 3,4 PWH without taking into account the climate change, and 4,2 PWH considering a temperature increase of 5,7 K. Differences are mainly due to the low assumed initial consumption for cooling in Ref. [91]. The average predicted cooling energy consumption for 2020 in Ref. [91], is close to 1,1 PWH, which is already lower than the registered cooling consumption in 2010, (1,2 PWH).

10. Recommendations and conclusions

Local and global Climate Change, increase of the world's population and potential economic growth result in a significant increase of the energy demand for cooling. While, in 2010, the global cooling consumption of the residential sector represented almost 4,4% of the total heating and cooling needs of buildings, it is expected to increase up to 35% in 2050 and 61% in 2100 [27]. In parallel, although the heating energy demand of the residential sector is expected to remain constant or slightly decrease in the future, the total heating and cooling consumption of buildings may increase up to 67% in 2050 and 166% in 2100 compared to the 2010 levels [27] intensifying the global energy and environmental problems.

Higher energy consumption for cooling is strongly associated with a very significant increase of the peak electricity demand that oblige utilities to build additional power plants to satisfy the extra needs for electricity. Significant future investments to increase the power capacity may raise the cost of electricity and put on strength the health and the quality of life of the low income and vulnerable population [105–108].

To face the problem of the future growth of the cooling energy needs and of the associated increase of climatic vulnerability, three major clusters of policy actions may be identified and proposed:

a) Actions Aiming to Mitigate the Global and Local Climate Change. Decrease of the greenhouse gas emissions and counterbalance of the urban heat island may significantly limit the amplitude of the temperature increase and the strength of the energy impact of the climatic change. Policies aiming to reduce the sources and enhance the sinks of temperature anomaly, like the use of clean fuels and mainly of renewable sources for power generation, higher energy efficiency, rationalization of the energy demand, intelligent and efficient use of energy, smart and resilient technologies for cities, green energy distribution systems, in association with urban mitigation technologies like cool and green materials and reduction of the anthropogenic heat, could seriously reduce the future demand for cooling [109,110] and protect the vulnerable population during the extreme climatic events. Research on the development of advanced geoengineering technologies to counteract the global and local climate

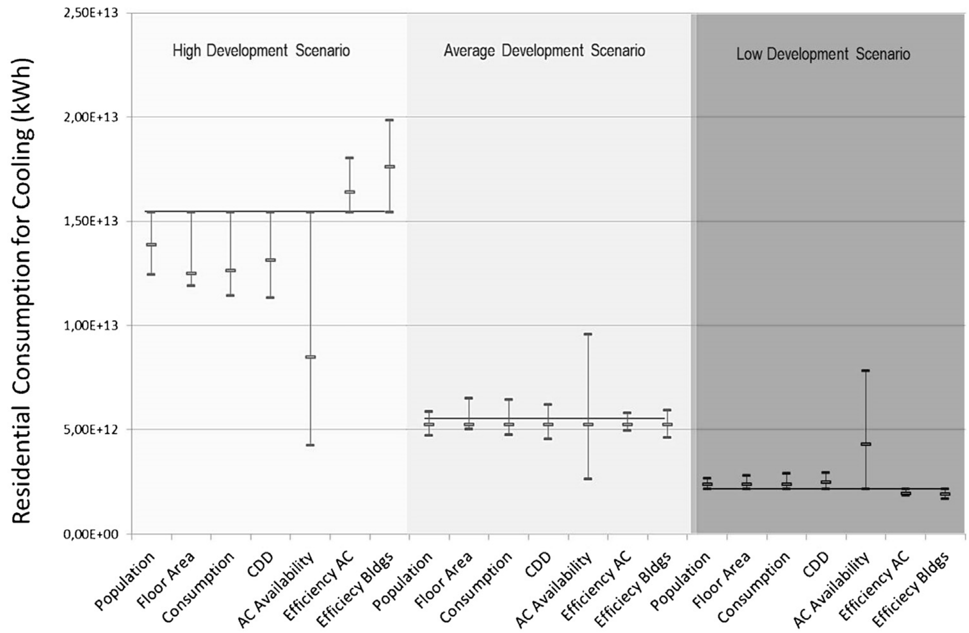

Fig. 15. Predicted Cooling Energy Consumption of the Residential Buildings in the World, for 2050. Results of the Low, Average and High Development Scenarios and variability as a function of the main parameters and drivers.

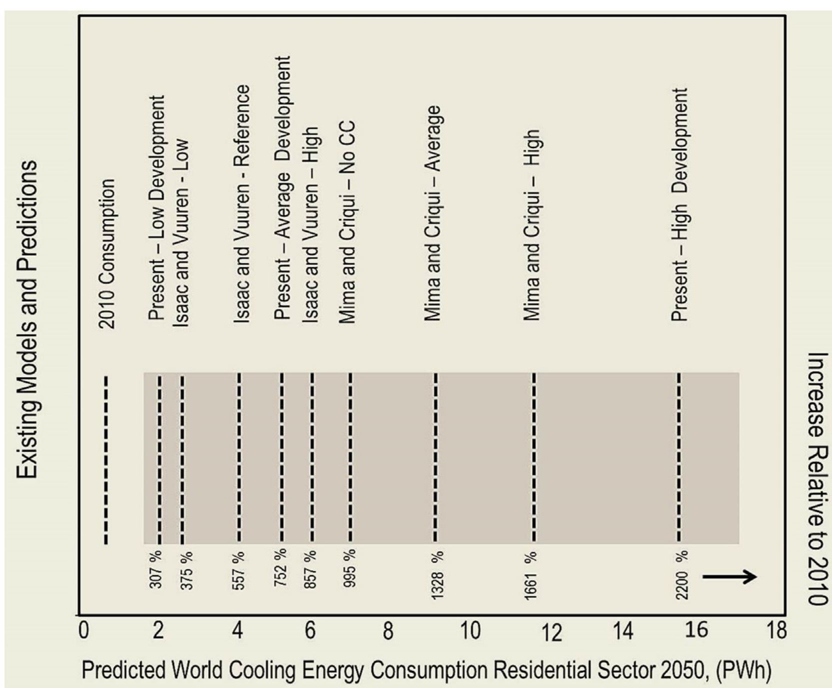

Fig. 16. Predicted Values of the World Cooling Energy Consumption of the Residential Sector in 2050.

change and on the development of high efficiency energy supply and management systems, techniques and materials for cities and settlements is a high priority and should be intensified.

b) Actions aiming to adapt the Building Sector and improve its Energy Performance. Buildings have to be adapted to the climatic anomaly by reducing their thermal loss to the ambient environment, be better protected from the ambient heat and manage efficiently internal heat loads. Use of advanced materials for the building shell, smart control systems, efficient lighting and service equipment, solar and renewable technologies and advanced ventilation technologies contributes to reduce considerably and even minimize the energy demand of buildings for heating and cooling purposes. Although the energy consumption of the new buildings is considerably low, energy retrofitting of the existing building stock is the main priority for the future. A rich spectrum of the available building energy efficiency technologies presents a reasonable cost and when employed may minimize the energy consumption of individual buildings. However, a massive energy rehabilitation of the existing building stock requires a further reduction of the cost of the energy efficient building technologies. Given the current technological status, the necessary investments to reduce drastically the global building energy consumption in the world, requires tremendous investments. Only in Europe, the necessary investments to achieve an almost 80% reduction of the building energy needs by 2050 are between 16 and 24 trillion Euros [101]. In parallel, the unprecedented urbanization and the increase of the population asks for the construction of billions of new buildings, mainly in less developed, quite poor zones of the planet that unfortunately suffer the more the consequences of the climate change. It is very crucial all these new buildings present significantly lower energy consumption through the use of reduced cost energy efficiency technologies.

c) Actions aiming to Improve the Efficiency of Mechanical Air Conditioning and Alternative Cooling Technologies.
Although, the efficiency of the mechanical air conditioning systems has improved impressively, it is not sufficient to counterbalance the tremendous increase of the future cooling demand. Breakthrough cutting edge technologies has to be developed through intensive scientific and industrial research. In parallel, the performance of the alternative cooling dissipation technologies associated with the use of low temperature environmental sinks has to improve further in order to provide low cost and reliable coverage of a fraction of the cooling needs.

Humanity faces a global energy and environmental challenge. In the future, the needs will be to reduce indoor temperatures, provide comfort and protect the vulnerable population; such needs may alter considerably the existing energy balance and affect a very high part of the world's population. It is evident that significant technological, policy and social initiatives are immediately needed to face the upcoming cooling challenges and protect our future.

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