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Decarbonization of Summer Cooling Energy Demands of Buildings Employing Absorption Systems in the Framework of Climate Change in Italy

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Abstract: Temperatures in the Mediterranean area have gradually risen in the last decades due to climate change, especially in the Italian Peninsula. This phenomenon has increased the cooling needs to ensure thermal comfort in buildings and, consequently, the use of refrigeration machines. Summer air conditioning is carried out mainly using compression machines powered by electricity supplied by the national network. All this contributes to the emission of climate-changing gases. To avoid this disadvantageous chain, compression machines could be replaced by absorption cooling systems powered by solar energy. The energy needs of the buildings in a time are directly proportional to the sum of positive differences between the outdoor air temperature and the indoor set point of the systems (equal to 26°C). The annual sum of hourly temperature differences defined above can be computed for each grid cell thanks to a numerical weather prediction model, namely the Weather Research and Forecasting model, that simulates the hourly temperatures on high-resolution computation grids and over fairly large extents. Maps of cooling consumption for buildings are thus produced. Choosing absorption solar energy-powered systems instead of vapor compression refrigeration systems leads to a drop in electrical energy consumption and therefore in emissions of greenhouse gases. In this work, different hypothetical scenarios of penetration of this technology have been considered. And the subsequent consumption of electricity withdrawn from the national grid has been estimated together with the reduction of greenhouse gas emissions.

Keywords: Climate change, Buildings cooling, summer energy needs, WRF, Maps, Mediterranean area.

1. INTRODUCTION

Climate change is a global phenomenon that must arouse interest in the scientific community, particularly for some areas of the planet [1]. The rise in maximum temperatures and the prolongation of heatwaves concern especially densely populated areas [2]. In these geographical areas, from an energy point of view, there will be a strong need for decisive responses able to modify the way companies have satisfied their needs so far.

In the civil sector, the energetic problem is complex [3]. On the one hand, energy consumption is necessary to ensure the well-being of the occupants of buildings throughout the day; on the other hand, it causes part of the emissions of climate-altering gases, responsible for climate change [4]. Precisely this leads to more vigorous use of energy resources in order to maintain indoor thermo-hygrometric well-being [5]. In practice, due to the current paradigms of energy production and consumption systems, the more modern societies pollute the planet, the more they are forced to pollute to maintain modern standards of quality of life [6, 7].

It, therefore, appears essential to identify eco-compatible solutions by converting the energy-intensive systems currently in use, while satisfying the energy requirements [8, 9].

In the context of global (and therefore local) warming, energy needs for summer air conditioning deserve particular attention [10]. The technology currently dominating the market is refrigeration production based on saturated vapor compression machines. These machines require electrical energy which is degraded into heat. The useful effect allows subtracting heat at low temperatures, thus cooling indoor environments [11].

Absorption refrigeration machines are a niche technology at the moment, but they could solve the problem of reducing climate-altering emissions by replacing the current refrigeration machines over time. This technology, driven by low-temperature heat (which could be of totally renewable origin, thanks to thermal solar panels) also offers the possibility of easier storage of its energy source, for use staggered over time [12].

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Among the geographical areas where overheating will lead to particularly hot summers, there is the Mediterranean basin [13]. The Italian peninsula, completely lapped by the sea on three sides, is a climatically varied territory that extends from north to south along different latitudes. Due to the high population density of some areas, a large building stock is present. It is not particularly efficient from an energy point of view (given its ancient construction) and has a considerable energy requirement [14, 15]. All this makes Italy a remarkable case study for this research.

1.1. Background

The scientific literature contains many studies aimed at predicting the energy consumption of future climate scenarios to assess interventions to mitigate energy needs in different areas of the planet. Sobhani *et al* [16] focused on the optimization of renewable energy for nZEB. Jiang *et al* [17] also analyzed climate change-related energy needs of residential buildings in Germany and consequent emissions. Roshan *et al* [18] presented a scientific work focused on a case study in Iran, while Rey-Hernàndez *et al* [19] considered the Lalladolid area in Spain. Eyre and Baruah [20] investigated uncertainties about future energy demand for the residential sector in the UK. Gonzalez *et al* [21] focused on the effects of climate change on energy consumption and thermal comfort in historic buildings. Pérez-Andreu *et al* [22] analyzed the energy needs for cooling in the Mediterranean area due to climate change. Zeng and Weng [23] studied the effects of climate change in the Los Angeles area (US) using GIS-based data and Berger *et al* [24] performed the same analysis for Vienna (Austria). Cao *et al* [25] examined technologies able to minimize the energy consumption of buildings on a global level, as well as Andric *et al* [26] who differentiated their investigations according to different types of climate. Larsen *et al* [27] focused on extreme climatic events and their energy effects in the European area, while Morakinyo *et al* [28] deal with the Hong Kong area.

These studies predicted energy consumption in the coming decades and found solutions suitable for containing energy needs in buildings. It is interesting to understand how mature and available technology such as absorption refrigeration machines can replace compression machines in the future, to minimize greenhouse gas emissions, complying with the European political roadmap up to 2050. Remarkable studies show the state of the art of these technologies for refrigeration production (Srikhirin *et al* [29], Kin and Ferreira [30], Talbi and Agnew [31], and Kaynakli and Kilic [32]). More specifically, some authors have investigated the integration of absorption refrigeration machines with systems for supplying the heat necessary for their functioning as a solar source (Ferreira and Kim [33], Desideri *et al* [34], Ullah *et al*. [35]), showing how to reduce greenhouse gas emissions.

There is an advantage in using absorption machines rather than power compression machines with electricity produced by photovoltaic panels. That is, the absorbing surfaces of the latter for the production of the electricity are greater than the absorbing surfaces necessary for the production of heat at low temperature with thermal solar panels. Furthermore, the costs of installation and maintenance of the latter are much lower than those of photovoltaics. Thanks to the possibility of easily storing thermal energy, the production and consumption of energy can be staggered over time. Even electricity can be stored thanks to the storage battery but with much higher costs and significantly shorter equipment lifetimes.

1.2. The Technology of Absorption Machines Powered by Solar Energy

Absorption systems represent the most promising option among solar cooling technologies. 82% of solar-powered cooling systems are absorption chillers which appear to be a smart solution as the demand for energy for cooling buildings occurs at the same time as the peaks of solar radiation.

Such systems are based on the affinity of two substances: lithium bromide (LiBr, absorbent) and water (H_2O, refrigerant). A typical single-effect absorption cycle is shown in Figure **1**, where the connections with a solar collector and the end-user are highlighted.

The refrigeration production necessary for the summer air conditioning of the buildings served by the system is supplied by an absorption machine. This provides the refrigeration of the heat-carrying fluid of the building's hydronic system using the thermo-physical properties of an absorbent-refrigerant solution. The heat coming from a solar panel is transferred to the generator "G" of the refrigeration unit. Thanks to this energy supply, it is possible to obtain chilled water from the evaporator "E" at temperatures compatible with the cooling of domestic environments, releasing

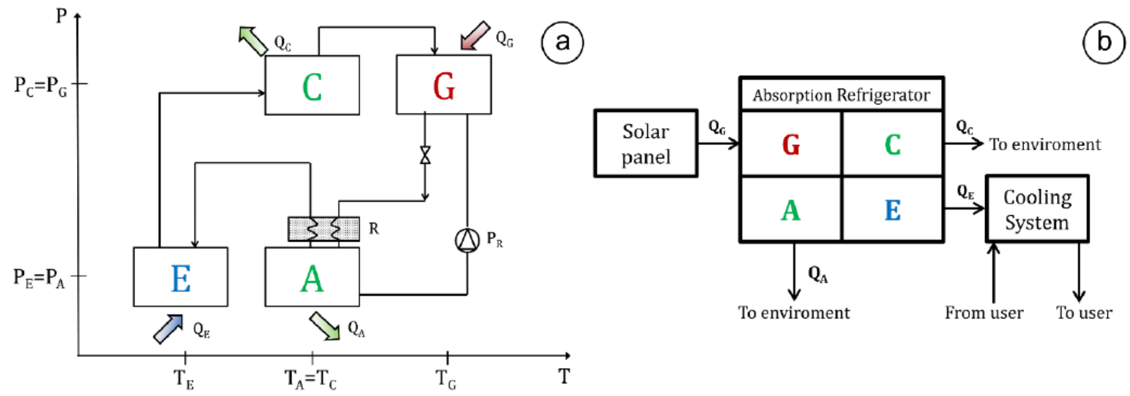

Figure 1: Diagram of an absorption machine powered by thermal solar panels.

degraded heat at room temperature in the condenser "C" and the absorber "A". At low pressure and temperature, the refrigerant is absorbed and the solution obtained is pumped to the generator where, at higher temperature and pressure, the refrigerant is separated. The vapor refrigerant is sent to the condenser while the solution richer in absorbent is returned to the absorber.

The coefficient of performance of an absorption refrigeration machine, ie the ratio between the heat output to the evaporator and the total energy supplied to the machine, is defined as [12, 36–39]:

$$COP = \frac{Q_E}{Q_G + L_{PS}} \quad \text{(Eq. 1)}$$

where:

$$Q_E = r(T_E) + c_{PR}(T_E - T_C) \quad \text{(Eq. 2)}$$

$$Q_G = r(T_G) + s(x_G, T_G) - [m(1-\alpha) + \alpha] \cdot c_{PS}(T_A - T_G) \quad \text{(Eq. 3)}$$

$$L_{Ps} = \frac{m \cdot \gamma_s (P_A - P_G)}{\eta_p} \quad \text{(Eq. 4)}$$

For its operation, the system requires the heat coming from the solar pond and the electricity to power the circulation pumps of the fluids used in the various parts of the system. This little energy amount is assumed to be negligible in this work.

A hydronic system powered by chilled water from the evaporator of the refrigeration machine distributes the "cold" inside the building, ensuring air conditioning during the hot periods of the year [40]. Currently, only a few manufacturers offer small-scale absorption chillers on the market. This is why there is a need to promote this technology (based on H_2O/LiBr solutions) to develop and market machines with a nominal cooling capacity of around 5 kW and a COP of at least 0.6, usable in domestic users capable of replacing compression systems.

1.3. Purpose of the Work

The energy needs of buildings are directly proportional to the difference between the outdoor air temperature and the internal set point of the conditioning systems (equal to 26°C) [36]. The annual sum of such hourly temperature differences can be computed for each grid cell using numerical weather forecasting models that simulate hourly temperatures on high-resolution grids (covering large geographical areas) and on long periods. In this way, maps of annual consumption for cooling buildings are created.

This work is aimed at demonstrating a possible approach to reduce electricity consumption and greenhouse gas emissions by replacing the functioning compression machines with absorption systems powered by solar energy.

2. METHODOLOGY

The need for summer cooling of buildings will evolve in Italy as a function of climate change in the coming decades [5]. Based on current emission data from the Italian national electricity system [41], for compression refrigeration systems this evolution will affect the electricity consumption and the concomitant greenhouse gas emissions with a negative impact on the climate. The basic idea of the present work is the investigation of hypothetical solutions to interrupt this harmful chain for the benefit of people and the environment. The system analyzed depends also on environmental and energy policies and the future is by its nature uncertain. Therefore this approach implies some hypotheses: i) the market penetration of the (more eco-friendly) absorption machines to replace the compression ones; ii) the change in future carbon dioxide emissions relative to the national energy mix for the production of electricity.

2.1. Study Area

Italy is a peninsula in southern Europe located between the 47th and 36th parallel and surrounded on three sides by the Mediterranean Sea [42]. It is positioned in the central part of the temperate zone of the northern hemisphere and presents a temperate Mediterranean climate, with sensible differences linked to the heterogeneity of the territory [43]. Figure **2** shows the orographic map of Italy on the left and the variety of Köppen-Geiger climate classes (also listed in Table **1**) on the right [44].

The average annual values of temperature in Italy can be summarized as follows:

- minimum values: -8.8°C in the North, -2.8°C in the Center, 0.6°C in the South and a national average around -4.0°C;
- averages values: 11.6°C in the North, 14.5°C in the Center, 15.7°C in the South and a national average around 14.0°C;
- maximum values: 31.6°C in the North, 32.9°C in the Center, 34.8°C in the South and a national average around 33.1°C.

The global solar radiation at the ground has a range between 4,370 MJ/m^2 per year in the north of Italy (near Bolzano) and more than 6,040 MJ/m^2 per year in far south Italy (near Syracuse) [45].

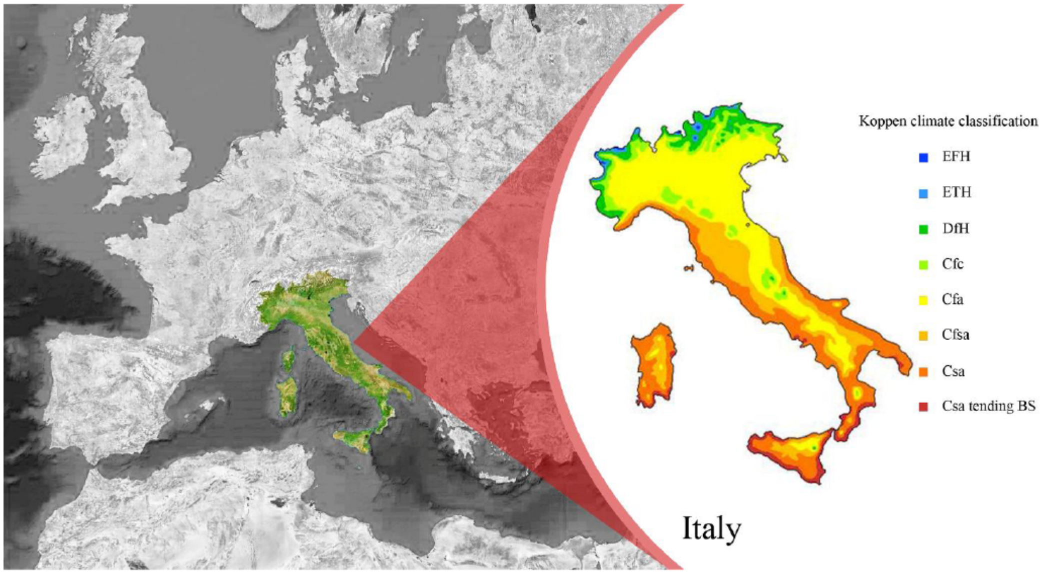

Figure 2: Orographic map (on the left) and Köppen-Geiger climatic zones (on the right) of Italy.

Table 1: Köppen-Geiger Climate Classes in Italy

Classificazione	Tipo di Clima	Localizzazione Geografica in Italia
Csa tending to BS	Subtropical temperate	Southern coastal areas
Csa	Warm temperate	Low-altitude areas in the center and south
Cfsa	Transitional temperate	Low-altitude areas in the north
Cfa	Temperate with warm summer	Low slopes of the Po Valley
Cfc	Cool temperate	Pre-Alpine and Apennine areas
DfH	Cold temperate	Alpine arch and high Apennine areas
ETH	The cold of the tundra	Alpine arch at high altitudes
EFH	Permanent snows	Alpine peaks

2.2. Use of Weather Research and Forecasting (WRF) Model

The Weather Research and Forecasting (WRF) model is a next-generation mesoscale numerical weather prediction system [46]. Since its initial development at the end of the 90s, it has had a notable diffusion in many research fields with several different applications in addition to pure atmospheric research: for example, coupling with chemistry and transport models for air quality simulation (*e.g.*, Falasca and Curci [47]) or with building energy simulation tools (*e.g.*, Ciancio *et al* [48]), idealized simulations of local winds (*e.g.*, Catalano and Moeng [49]; Falasca *et al* [50]). For more details, the reader is referred to the technical notes (Skamarock *et al* [51]) and the user's manual.

In the present study, the numerical setup is based on two domains linked through the one-way nesting technique: i) the first domain covers Europe with a horizontal resolution equal to 36 km; ii) the second domain (the nested one) covers Italy with a horizontal resolution equal to 12 km. The vertical grid consists of 33 levels and is common to the two domains. Figure **3** shows the borders of the two domains and the topography of domain d02 over Italy.

The physics configuration (*i.e.*, the parameterizations of short and longwave radiation, microphysics, planetary boundary layer, etc.) has been already applied and tested in previous works, such as Falasca *et al* [52] and Falasca *et al* [53]. It is depicted in Table **1**.

Initial and boundary conditions are provided by two different databases: i) Global Forecasting System (GFS) operational analyses of the National Center for Environmental Prediction (NCEP) for simulations of past years; ii) NCAR CESM Global bias-corrected CMIP5 Output for simulations of future years.

Two cases are considered in this work considering two climate scenarios for the future developed by the Intergovernmental Panel on Climate Change (IPCC), namely RCP4.5 and RCP8.5 [54].

Table 1: Physics Configuration of the WRF Simulations

Category	Scheme
Microphysics:	WSM6
Longwave radiation:	RRTMG scheme
Shortwave radiation:	RRTMG scheme
Surface layer:	Revised MM5 Monin-Obukhov
Land Surface:	Unified Noah land-surface model
Planetary Boundary Layer:	Bougeault and Lacarrere

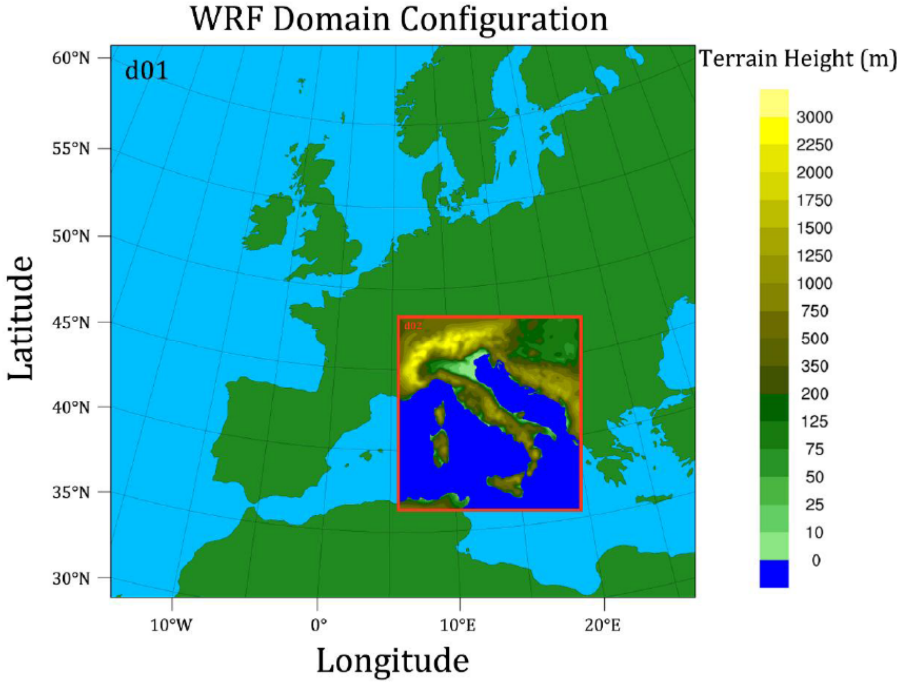

Figure 3: WRF domains and topography of domain over Italy.

2.3. $\sum\Delta T_c^+$ Calculation for a Cooling Period

The legislation currently in force prescribes a method for the computation of buildings' energy consumption for cooling based on the proportionality between the energy consumption and a common factor. Such a factor consists in the sum of the positive values of the temperature differences between the external environment and the set point of the summer air conditioning systems. Therefore, the energy consumption of a building during the cooling period is directly proportional to this simple factor defined as in Eq. 5:

$$\Delta T_c^+ = \sum_{h=1}^{n}(T_{out} - 26°C)_h^+ \qquad \text{(Eq. 5)}$$

where T_{out} represents the hourly outdoor ambient temperature and the "plus" sign as an exponent indicates that the summation includes only the positive values of differences. Similarly, the letter "*h*" as a subscript indicates that the summation includes hourly values of temperatures and deltas.

This quantity (Eq. 5) provides also information on the severity and duration of climatic events occurring in a geographical area in the considered period. Furthermore, it is independent of the geometric and thermo-physical characteristics of the buildings.

In Italy, the cooling season covers the May-October period for a total of 4,416 hours. In this study, the hourly values of ambient temperature are computed by the meteorological model WRF at a horizontal spatial resolution of 12 km as described in the previous section.

2.4. Summer Cooling Systems in the Italian Residential Sector

Residential buildings in Italy amount to almost 30.5 million and almost 20% are not permanently occupied and/or empty. There are 17.7 million systems for summer cooling (considering the installed condensing units). The energy consumed annually for cooling buildings is equal to 4.83 TWh.

The average annual number of installations (substitutions or first installations) in existing buildings is equal to 1.040.00 (72.6% in residential and 27.4% in non-residential buildings). The ratio between new installations and replacements of existing appliances is approximately 1 to 9. The fluctuation over the years was 53%. Therefore, the summer cooling systems installed annually amount to approximately 755,000 units in the residential sector, with an average annual variability of 400,000 units. Additionally, new installations in residential buildings amount to approximately 84,000 units ("Hypothesis B") with an average excursion for minimum and maximum of 44,400 units (40,000 units = "Hypothesis A"; 128,000 = "Hypothesis C"). It is assumed that the growing energy needs due to climatic variations are balanced by the installation of new units.

The energetic analysis carried out in this study is based on the following assumptions: i) the annual statistical data listed above will be constant in the future, ii) policies promoting the abatement of climate-altering emissions will be implemented, iii) absorption machines powered by solar thermal panels can achieve a market penetration of 50% (worst scenario)

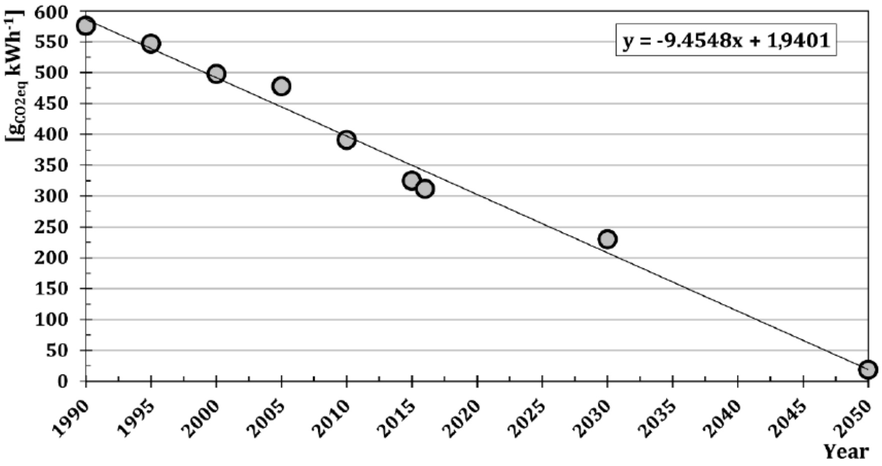

Figure 4: Evolution of emissions (g_{CO2}) per kWh of electricity produced by the Italian national energy mix: past trend and future forecast.

to 100% (best scenario) compared to the total number of plants installed annually.

As regards the Italian energy mix, it changed in recent decades with a consequent reduction of the climate-changing emissions per unit of electricity produced. Figure **4** shows the trend obtained by linearly interpolating the data available from 1990 to 2016 and considering the estimated data for 2030 according to the INECP scenario (equal to 230 gCO2eq kWh^{-1}). As can be seen, emissions tend to zero by 2050, in line with the European Community target.

3. RESULTS AND DISCUSSIONS

3.1. Maps on Italy

The maps of the quantity $\sum\Delta T_c^+$ for Italy during the hot season have been realized using the gridded values of the ambient temperature simulated by the WRF meteorological model. Figure **5** shows the map for 2019, while Figure **6** and Figure **7** show the map for 2050 according to the RCP4.5 and RCP85 IPCC scenarios, respectively.

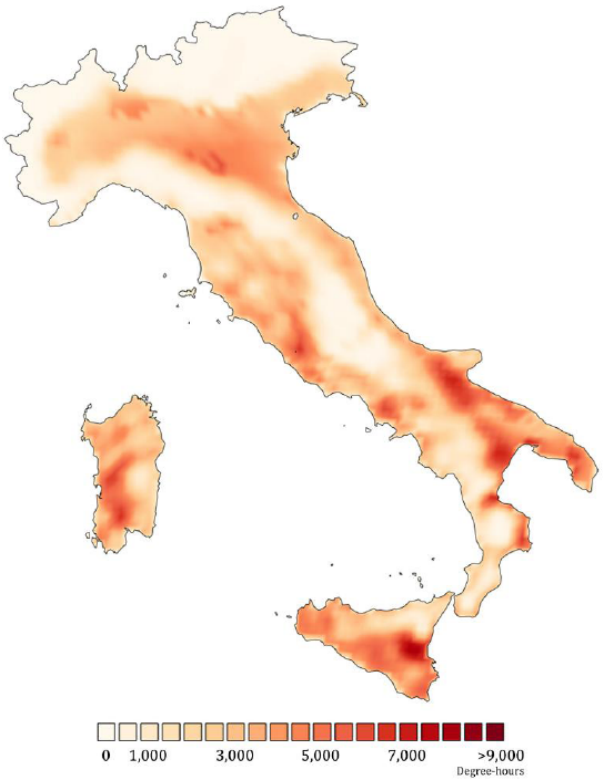

Figure 5: map of $\sum\Delta T_c^+$ for Italy for 2019.

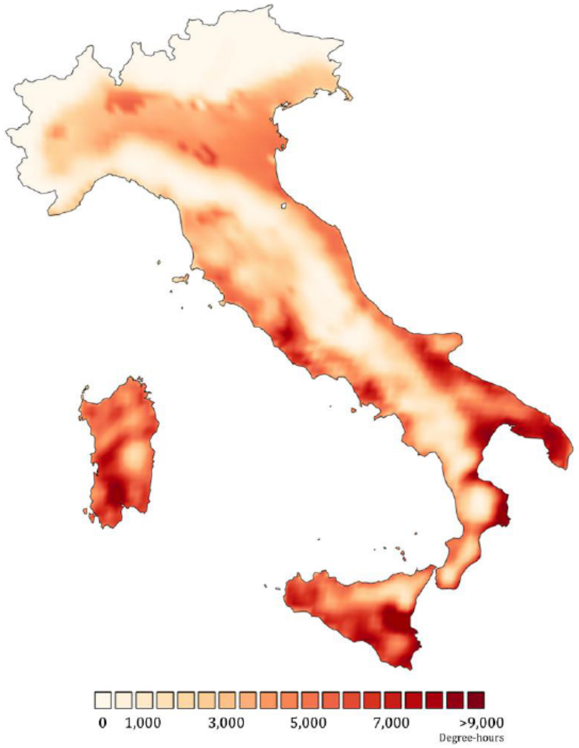

Figure 6: map of $\sum\Delta T_c^+$ for Italy in 2050 according to the IPCC scenario RCP4.5.

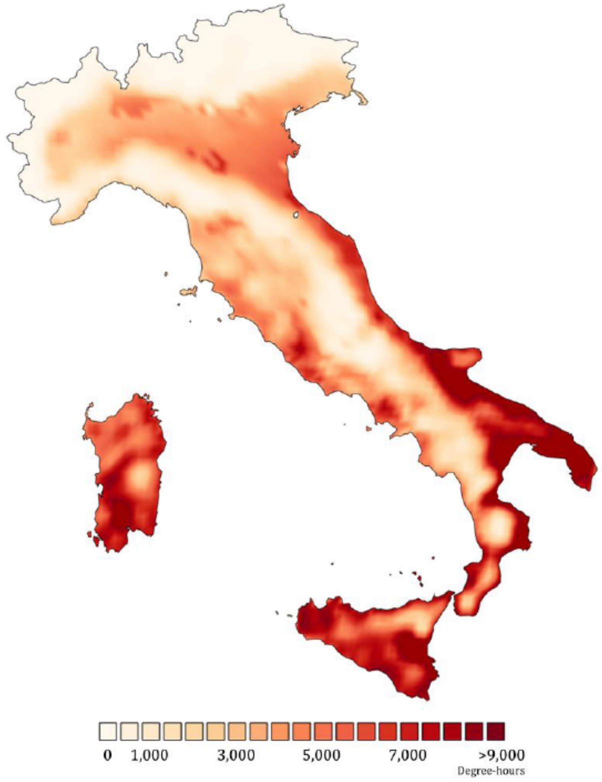

Figure 7: map of $\sum\Delta T_c^+$ for Italy in 2050 according to the IPCC scenario RCP8.5.

The increase in the local value of $\sum\Delta T_c^+$ from 2019 to 2050 is due to the increase in ambient temperature in large portions of the Italian territory and is visible thanks to the accentuation of the red areas on the maps. The $\sum\Delta T_c^+$ increase is represented in Figure **8** through the average value of all the calculation nodes in Italy. The steeper slope of the line corresponding to the severe RCP8.5 scenario leads to a $\sum\Delta T_c^+$ value in 2050 approximately 20% higher than that predicted in the RCP4.5 case.

In more detail, $\sum\Delta T_c^+$ will grow from 2050 to 2080 by about 60% and 33% according to the RCP8.5 and the RCP4.5 scenario, respectively (Figure **9**).

3.2. Energetic Analysis

The energy demand for cooling residential buildings increases in the time span from 2019 to 2050 proportionally to the growth of ∑ΔTc+ displayed in Figure **9**.

Figure **10** shows the increases in the amount of energy withdrawn from the national network (in TWh) in 2050 compared to 2019 for summer cooling in the Italian residential sector. Based on the current average installation rate of the new cooling equipment, three different percentages of penetration of the solar-powered absorption machines are assumed: 50%, 75%, and 100% of the total amount. These increases in electricity are controlled. It is noted that despite this, the market penetration of this technology cannot counteract the increase in energy demand linked to climate change. Even if the energy consumption is reduced in the three cases, the market penetration of this technology is unable to balance the increase in energy demand linked to climate change.

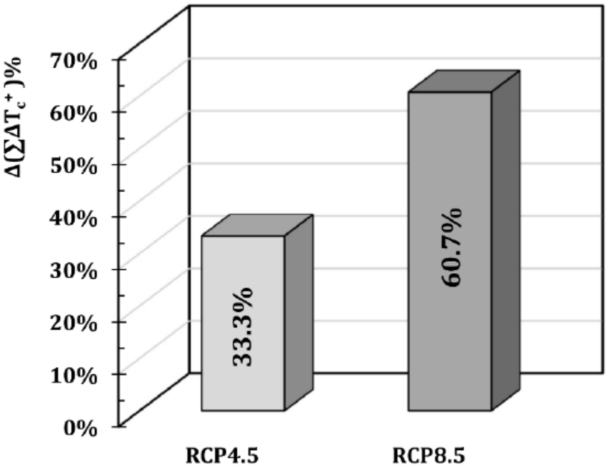

Figure 9: Percentage increase in the value of ∑ΔTc + from 2019 to 2050 according to the RCP4.5 and RCP8.5 scenarios.

Balancing the increase in energy demand for cooling through the introduction of this technology entails the cessation of the emissions of climate-altering gases into the atmosphere. Indeed, they are linked to the withdrawal of electricity from the national grid and are based on the hypothesis of current specific CO2 emissions. This implies an increase in the number of machines installed annually compared to scenario B for 2019: i) in the best case, by 108% (equal to 190,500 units installed annually) assuming 100% of new installations with absorption technology and climate scenario RCP 4.5; ii) at worst, by 392% (equal to 693,000 units installed annually) assuming 50% of new

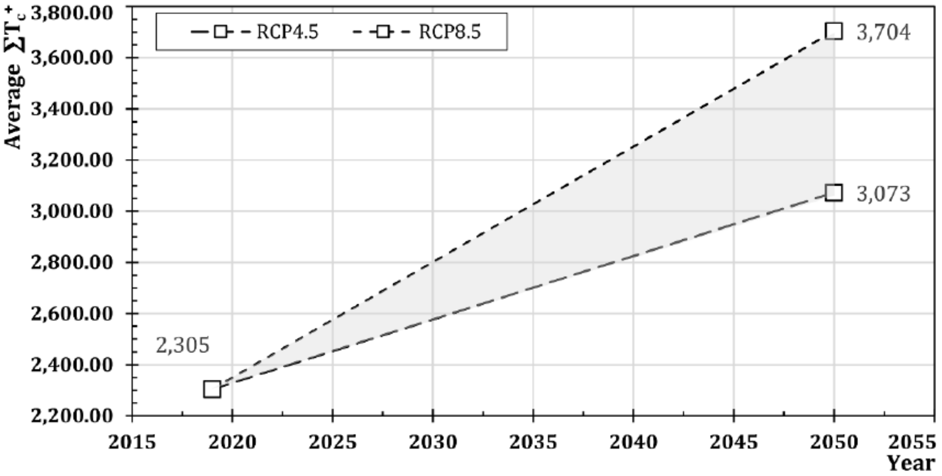

Figure 8: Increase of the $\sum\Delta T_c^+$ averaged over Italy, from 2019 to 2050 and according to the two scenarios RCP4.5 and RCP8.5.

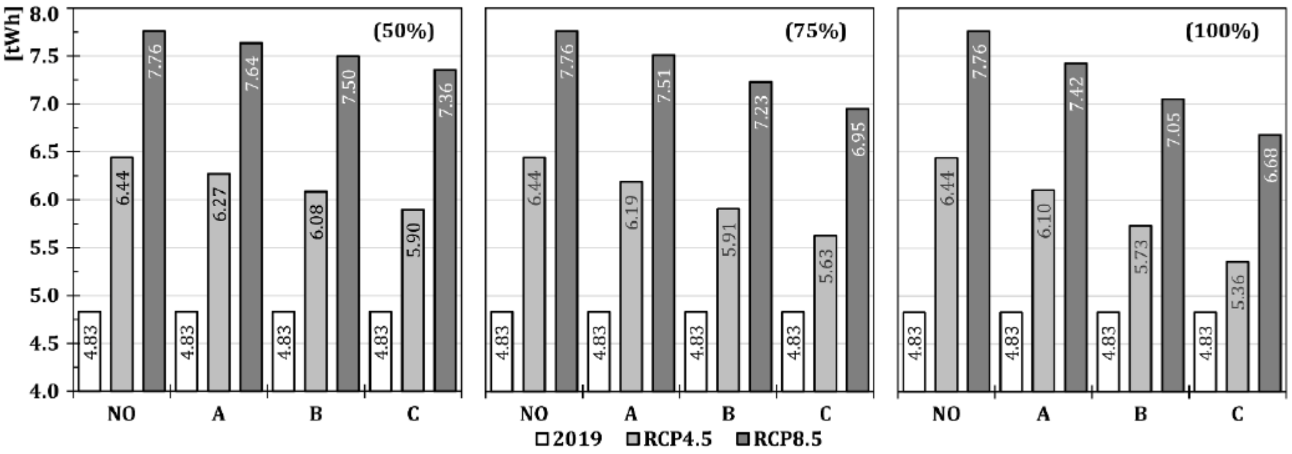

Figure10: Trend in energy requests for cooling residential users in Italy as a function of the climatic scene in 2050. Different amounts of units placed on the market (hypotheses A, B, and C) and different penetration rates of absorption technology powered by solar energy (50%, 75%. 100% of the total) are considered.

installations with absorption technology and RCP 8.5 climatic scenario.

Emissions of greenhouse gases will increase in proportion to the energy demand in the hypothesis of a constant specific emission rate: i) by 33.33% according to the RCP 4.5 scenario and ii) by 60.71% according to the RCP8.5 scenario. If the hypotheses discussed so far are implemented, CO2 emissions will follow the data reported in Table **2** by 2050. The climate-altering gases introduced into the atmosphere will increase by controlled percentages, despite the greater energy input necessary for summer air conditioning due to climate overheating. However, the European goal of decarbonizing these needs would be far from being achieved.

In the present analysis, the variability of the specific emission rate of the national electricity grid has been taken into account, from the current values to values proper of the decarbonization that the EU intends to achieve by 2050 (hypothesized in Figure **3**). The percentage of anhydride carbon dioxide introduced for this purpose in the year 2050 has been predicted and compared to that introduced in 2019 according to hypotheses A, B, and C and in the hypotheses of acquisition of the machine absorption in the market (Figure **11**).

As can be seen from Figure **11**, incentivizing the penetration of very high percentages of cooling systems based on solar-powered absorption technology would contribute significantly to the almost total decarbonization of Italian energy needs in 2050. This behavior plies to both climatic scenarios and is more pronounced in the case of the more optimistic RCP4.5 scenario.

CONCLUSIONS

Climate change will unavoidably lead to a higher demand for energy to meet the summer air conditioning needs of buildings. Consequently, the emissions of climate-changing gases linked to the functioning of

Table 2: Percentage Variation in Greenhouse Gases in 2050 Compared to 2019

Greenhouse gas Emissions [%]							
Climate Scenario		**2050 RCP4.5 – 2019**			**2050 RCP8.5 - 2019**		
Replacement rate		**50%**	**75%**	**100%**	**50%**	**75%**	**100%**
Hypothesis	A	29,83%	58,08%	28,08%	55,46%	26,33%	53,71%
	B	25,98%	55,20%	22,30%	49,68%	18,62%	46,00%
	C	22,12%	52,31%	16,52%	43,90%	10,91%	38,29%

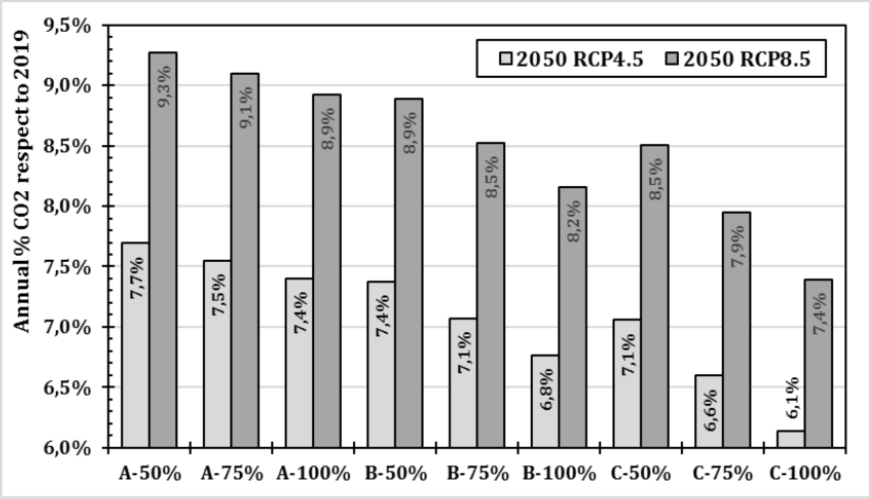

Figure 11: Carbon dioxide emissions as a function of the climatic scenario at 2050 (RCP4.5 or RCP8.5), depending on the number of units placed on the market (hypothesis A, B, and C) and the penetration rate of the absorption technology solar powered energy (50%, 75%. 100% of the total).

cooling electricity-powered systems will grow, especially in densely populated regions such as the Mediterranean area.

This work starts from an evaluation of the current market of new systems installed annually and is based on different penetration hypotheses for absorption refrigeration machines powered by solar energy. The effects of future climate change (in 2050, according to two different scenarios) on the summer energy needs of buildings are quantified by mapping a suitable index on the entire Italian territory. Then, a possible approach is outlined to reduce the release of climate-changing gases into the atmosphere following the European decarbonization objectives, and at the same time satisfy the growing future energy demand in Italy.

This objective appears achievable, but only: i) by encouraging the marketing and heavy market penetration of small machines (to better adapt them to residential needs) that exploit this technology; ii) by reducing the specific emissions of carbon dioxide per unit of electricity produced by the national energy mix.

The evolution of the costs of solar-powered systems over a long time (such that considered here) is difficult to predict. The reduction of costs as these technologies invade the market could make them economically very competitive thanks to large-scale automated production. It must also be considered that such systems have been on the market for a long time and are now technologically mature. To finish, when comparing this alternative technology with the currently prevailing one, it should take into account also the "environmental" costs related to the use of less environmental friendly technologies.

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NOMENCLATURE

COP	Coefficient of performance
c_{PR}	specific heat at a constant pressure of the refrigerant
c_{PS}	specific heat at a constant pressure of the solution
L_{PS}	specific work of the pump
m	mass of the refrigerant
P_A	absorber pressure
P_G	generator pressure
Q_E	heat exchanged to the evaporator

Q_G	heat exchanged to the generator
r	latent heat
s	heat of solution
T_A	absorber temperature
T_C	condenser temperature
T_E	evaporator temperature
T_G	generator temperature
x_G	ratio of the mass of the absorbent to the mass of solution to the generator
α	efficiency of the heat recovery unit
γ_S	specific volume of the solution
η_P	pump efficiency

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