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Benchmarking cooling and heating energy demands considering climate change, population growth and cooling device uptake

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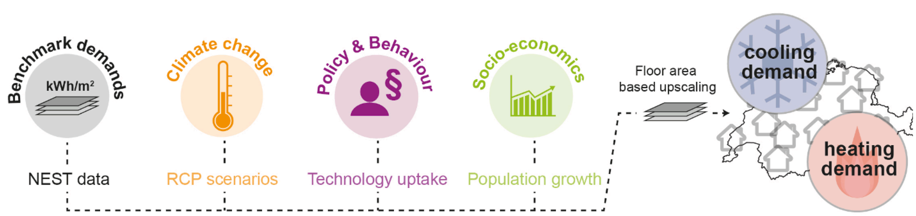
HIGHLIGHTS

- Population-weighted climate models to predict future thermal energy building demand.
- Countries in temperate climates are prone to an increase in cooling demands.
- Significantly more Swiss cooling energy is projected, but heating still dominates by mid century.
- Cooling device uptake has a critical influence on cooling energy demand.
- By 2050 up to 17.5 TWh cooling energy could be required in Switzerland.

GRAPHICAL ABSTRACT



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ABSTRACT

The planning of future energy policies and energy systems requires an understanding of the intricate relationships between climate change, technology uptake, population growth and building energy demand. Building cooling demand is expected to increase considerably in many parts of the world as the climate warms on average. In temperate climates, this increase is expected to be particularly large due to the increase in the number of days when cooling is required to maintain a comfortable indoor building temperature. We quantify the impact of climate change, cooling device uptake and population growth based on population-weighted climate models, population growth scenarios and measured thermal energy demand data for Switzerland. This study incorporates three climate development scenarios and we find for an extreme case, that up to 17.5 TWh cooling energy would be required by the middle of the 21st century compared to 3–5 TWh in more moderate cases. Heating energy demand is expected to decrease to around 20 TWh by mid-century, which is approximately one-third of the current Swiss building heating demand. The presented combined quantification of future cooling demands for Switzerland provides a set of benchmarked energy demands and highlights the critical role of air-conditioning technology uptake, which significantly contributes to future cooling demands. Pursuing alternative cooling strategies is therefore needed to limit cooling energy demand impacts on the future energy systems particularly in countries with temperate climates.

1. Introduction

Due to climate change, the demand for space cooling is expected to significantly increase globally in the next decades [1]. As reported for Europe, a small increase in mean temperature can result in a large increase in Cooling Degree Days (CDD) which could lead to an increased

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demand for cooling energy [2]. Total thermal building energy demand depends on a range of different drivers such as climate change, user behaviour, regulations, population growth, building properties and the diffusion and availability of technologies [3]. A warming climate could result in considerable cooling energy demand growth in regions with temperate climates, where cooling demands are currently low. The number of days requiring cooling to maintain comfortable indoor air temperatures could reach levels, where a growing fraction of people would want to install a cooling system. Resulting increases in cooling energy demand and an electrification of heating will have various impacts on the energy system such as affecting peak electricity demand and thus need to be considered when designing and planning future energy systems [4]. In literature, the spatio-temporal energy demand impacts of heat pumps is e.g. discussed for the UK [5]. Also, regional considerations such as cooling demand increases due to climate change in Los Angeles [6], London [7], Freiburg (Germany) [8], Athens [9] and Greece [10] are discussed in literature. A global context on the topic is provided by Isaac and Vuuren [11]. These studies provide a quantitative basis for such considerations since thermal building energy demands are simulated based on the three main drivers: climate change, population growth and cooling device uptake.

1.1. Cooling and heating building energy demand in Switzerland, Europe and globally

In literature, the development of Cooling- and Heating Degree Days (HDD) and possible impacts on space heating and cooling demands have been the focus of numerous studies. Aebischer, Henderson and Catenazzi focused on the impact of climate change on energy demand in the Swiss service sector [12]. The study of Christenson, Mand and Gyalistras focused on the correlation between a temperature increase and degree days and the possible impact on the building energy demand in Switzerland [13]. Berger and Worlitschek analyzed the impact of HDD on residential space cooling demands in Switzerland [14]. Furthermore, they analyzed the spatial impacts of 68 climate models on the HDD and CDD distribution in Switzerland [15]. Frank [16] estimates that the mean temperature rise of 4.4 °C in Switzerland until 2100 could increase office building energy demands between 223% and 1050%, while the heating demand decreases between 33 to 44% in the same period. Frank highlights the importance of night ventilation strategies and thermal inertia to reduce the future active cooling requirements of buildings [16]. European space cooling demands are analyzed by Werner who compares space cooling energy demands of several European countries and regions and estimates that a cooling energy demand for residential and service buildings of over 1000 TWh per year could be required if the demands of all EU-28 countries are summed (assuming a 100% saturation with cooling devices) [17]. Environmental impacts of room air-conditioners in Europe are investigated by Pout and Hitchin [18]. Belzer, Scott and Sands discuss the climate change impacts on the energy consumption of commercial buildings in the USA based on survey data up to the year 2030 [19]. Wang and Chen furthermore investigate the change in heating and cooling energy use in buildings in the USA [20].

While space heating is a well-investigated field of research for countries with cold winters such as Switzerland, the data situation for space cooling is more scarce [14]. Countries with regions of comparable climates and CDD to Switzerland such as parts of the USA or Canada have already reached a high saturation of cooling devices and therefore correlations between the number of CDD and the uptake of cooling devices was investigated [11,21,22]. For Switzerland, there are only few installed cooling devices in residential buildings, which make up the vast majority of overall building area. Furthermore, the evolution of future cooling demands is unclear. As of today, no comprehensive national-scale future benchmarking of cooling and heating energy demands is available for Switzerland. This work presents such a quantification with help of representative population-weighted climate scenarios data and measured heating and cooling demand data from a state-of-the-art building demonstrator which consists of several office and residential building units [23]. This data and analysis allows the benchmarking of future space heating and cooling demands whilst accounting for climate change, spatial population distribution, cooling device uptake and population growth. This analysis provides the basis to develop best strategies on how to supply future energy demands via energy-efficient strategies such as passive cooling, district cooling and climate-adapted architectural measures [24,25]. Whereas our findings are most relevant for European regions with a temperate climate, our presented methodology is easily transferable to other regions or countries.

Several literature values are relevant for this investigation concerning the current Swiss building stock and thermal building demand: The average Swiss heating energy demands for residential buildings are reported to be 101 kWh/m^2 in 2018 [26]. The SIA 2024:2015 norm lists current average heating energy demands for multi-family homes to be slightly higher at 113 kWh/m^2 [27]. The current heating demands for offices are reported to be 82 kWh/m^2 [27]. On average, this result in cooling energy demands of 8 kWh/m^2 for small offices and less than 2 kWh/m^2 for residential buildings, since the fraction of buildings with installed cooling devices is particularly low in the residential sector and also a large fraction of offices are not equipped with active cooling devices [27]. Another source reports electricity demands for 100 offices in Switzerland at just above 20 kWh/m^2 [21]. Resulting cooling energy demand depends on the cooling device efficiency, which was not reported in the cited study. Considering a coefficient of performance (COP) of a heat pump of approximatively 4 would correspond to a cooling energy demand of approximately 80 kWh/m^2 for the cited 100 offices [28].

The renovation and renewal rate of the Swiss building stock will have a crucial influence on total future building energy demands. The Swiss Federal Office of Energy (SFOE) targets 20 kWh/m^2 heating energy demand for new buildings and estimates the average demand for 2050 at 40–45 kWh/m^2 for residential buildings in its “Business As Usual” (BAU) scenario [29]. If the “New Energy Policy” (NEP) scenario of the same study was followed, the aim of on average 20 kWh/m^2 heating energy demand would be reached. This would mean that the current heating energy demand (2020) must be significantly reduced, i.e. by a factor of 5 by 2050. Furthermore, it is reported that the total cooling energy demand of all sectors is expected to increase to up to 30 kWh/m^2.

1.2. The critical role of cooling technology uptake

The uptake of cooling devices is a key driver of cooling energy demand. Unfortunately, data on the fraction of buildings of the different sectors equipped with cooling devices are scarce in most countries. For service buildings, we assume that around 50% of the floor area is currently being cooled in Switzerland and we assume that currently only a small fraction of residential buildings are equipped with cooling devices [12]. However, as demonstrated in the literature and as discussed in this work, a small change in CDD and the increasing number of heatwave occurrences could have a critical impact on the number of cooling devices being installed. On a global scale, the total number of cooling devices is expected to drastically grow from around 300 million devices in 2020 to over 1 billion devices by 2050, which results in significant impacts on energy demand and energy systems [1,30]. Most OECD countries such as Japan, South Korea, Canada and the USA already have reached a high saturation of cooling devices, while other countries such as China have a high growth rate due to climate change and increasing income [30]. The uptake and spatial unfolding of emerging technologies over time is a dynamic process and is increasingly being studied in the energy domain [2,21,30–33]. Research clearly shows that the geographic distribution of cooling devices and the number of installed devices is determined by culture, policy, income, prices or climatic factors [9–11,21,22]. For this study, the device uptake curves of Canada and the USA are an important reference, as they likely mark the upper boundary for Switzerland [21,31].

1.3. Objective and manuscript structure

The objective of this paper is to benchmark future thermal building energy demands with the main focus on cooling, taking into account climate change, population growth and cooling device uptake. Since data on cooling demand and the installation of cooling devices in Switzerland is scarce, this work allows researchers and policymakers to better understand the effect of different drivers on thermal building energy demands and to investigate the potential impact on the future energy system.

The remaining of this manuscript is structured as follows: Section 2 provides the calculation methods for population-weighted temperatures, introduces underlying climate models and provides the calculation of mean temperatures and indicator days along with the correlation between measured ambient temperatures and thermal building energy demands. Section 3 presents and discusses the results. We then conclude with final recommendations.

2. Methods

2.1. Climate data

We use historic weather data (2010–2019) by MeteoSwiss from roughly 150 weather stations distributed across Switzerland [34]. Future climate data are taken from the CH2018 dataset, which constitutes a recent joint climate simulation effort by the Swiss National Centre for Climate Services and is based on EURO-CORTEX models [35]. An ensemble of 68 different climate projections based on global and regional climate models is provided in the CH2018 dataset for three emission scenarios from the Representative Concentration Pathway (RCP). The RCP scenarios (RCP 2.6, RCP 4.5 RCP 8.5) reflect the expected increase of solar radiation in $\frac{W}{m^2}$ until 2100. This increase in irradiation is directly correlated to the development of the worldwide CO_2 emissions and the accumulation of thereof in the atmosphere since CO_2 interferes with infrared wavelengths. For example, the RCP 2.6 scenario corresponds to an increase in solar irradiation of 2.6 $\frac{W}{m^2}$, 4.5 $\frac{W}{m^2}$ for the RCP 4.5 scenario and 8.5 $\frac{W}{m^2}$ for the RCP 8.5 scenario respectively with a baseline global solar irradiance of approximatively 1120 $\frac{W}{m^2}$ [36]. The RCP 2.6 scenario is expected to be followed if the worldwide CO_2 emissions are drastically reduced. The RCP 4.5 scenario assumes that CO_2 emissions further increase towards 2050 until they are stabilized. The RCP 8.5 scenario assumes that no specific measures are taken to reduce future emissions. To derive localized climate projections, the future climate projections are provided as bias-corrected with help of station-localized observations based on the quantile mapping approach [35].

2.2. Population-weighting of temperature

Population-weighted temperature data have been used in energy simulations to capture the effect of urbanization in calculating heating or cooling demands [15,37]. Energy simulations are highly sensitive to the choice of weather station and therefore a high resolution of weather stations is necessary to capture the variability of spatially explicit weather effects [38,39]. To account for urbanization and to capture spatially explicit weather effects, we apply a population weighting factor to temperature measurements for weather stations (less than 1800 m) based on the population distribution according to the Swiss building cadastre [40]. The national hourly population-weighted temperature (T_w^h) of Switzerland is calculated according to Eq. (1):

$$T_w^h = \sum_{i=1}^{n} w_i * T_i^h, w_i = \frac{p_i}{\sum_{i=1}^{n} p_i} \tag{1}$$

Whereby the local weather-station based temperature T_i^h is weighted by a population weighting factor (w) given by the fraction of the population p_i to the total number of inhabitants of Switzerland ($\sum_{i=1}^{n} p_i$). We find that weighting by population leads in overall to about 1 °C higher temperatures. For example, the mean area-weighted temperature in Switzerland was ~9 °C in 2018 compared to the population-weighted mean temperature of ~10 °C. This is to be expected as the majority of people are living in lower, warmer altitudes and due to urban heat island effects. The population distribution by altitude is plotted in Fig. 2.

The MeteoSwiss temperature data is all ground-based and favourably to be used if a high density of ground-based weather stations is available. Alternatively, satellite-based data could be used for regions with a less dense grid of ground stations. In the **Supporting Information (SI) Note 1**, our population-weighted temperatures derived from ground station weather data are compared to satellite-based temperatures (MERRA-2) downloaded from the renewables.ninja platform. This analysis reveals that careful attention needs to be given to the used temperature data source, as ground-based or satellite-based measurements might considerably differ [41]. The comparison is relevant as a reference and for follow-up studies based on the MERRA-2 temperature datasets.

2.2.1. Population-weighting of historic climate data

To prepare population-weighted historic climate data, we first create a grid spanning Switzerland with a resolution of 5 km. Based on population data taken from the Swiss building cadastral data [40], we aggregate the population living within each grid-cell. In a next step, hourly temperature data (measured 2 m above ground) from the Federal Office of Meteorology and Climatology are processed for around 150 weather stations for the historic timespan between 2010 and 2019 [42]. Fig. 1 shows the population grid centroids and the respectively assigned weather stations. The assignment of the grid-cells carrying the population information to the closest weather station is indicated by the Thiessen polygons. To calculate the population-weighted temperature, the measured temperature for each weather station is multiplied by a weighting factor based on the population fraction of Switzerland.

Building energy simulations are sensitive to the choice of weather stations and a high resolution of weather stations is necessary to capture the variability of spatially explicit weather effects [38,39]. A spatially explicit weather effect could, for example, be the weather difference on a mountain ridge (e.g. Jungfraujoch station at 3550 m above sea level) compared to a village in a valley in the same grid cell. Therefore, weather stations above 1800 m above sea level are ignored in the analysis and the population closest to those stations are assigned to the next closest weather station. The weather station density in Switzerland still is favourable even after ignoring stations above 1800 m. We note that about 80% of the population is assigned to weather stations situated below 800 m. Furthermore, all main agglomeration centres of Switzerland fall into altitudes at around 500–600 m and only about 10% of the population is distributed at altitudes above 1000 m (Fig. 2).

2.2.2. Population-weighting of future climate data

We use climate scenario data from the CH2018 dataset, which constitutes a recent joint climate simulation effort by the Swiss National Center for Climate Services and which are based on the EURO-CORTEX models [35]. However, as no hourly temperature data is provided, we extract daily minimum and maximum temperatures and apply morphing techniques to convert all temperature scenarios to hourly resolution following Belcher et al. [43]. The weighting of the CH2018 temperature data with the population is performed with the identical methodological approach as outlined in the previous section, except that the set of weather stations is used from the respective CH2018 dataset. Changes to the future population patterns are ignored for the temperature weighting.

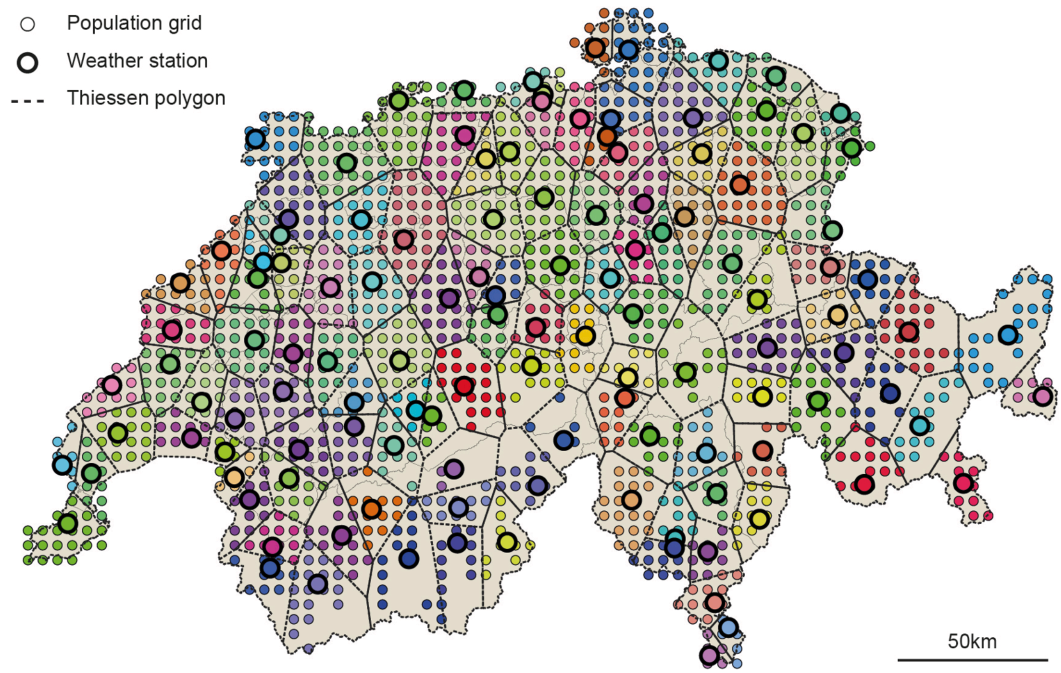

Fig. 1. The Swiss population is distributed on a grid with 5 km resolution and then assigned and aggregated to the closest weather station, which serves as the weight for calculating national population-weighted hourly temperatures. The Thiessen polygons depict how population grids centroids are assigned to the weather stations, which is also indicated by the same colouring. All population grid centroids within each Thiessen polygon are assigned to one weather station.

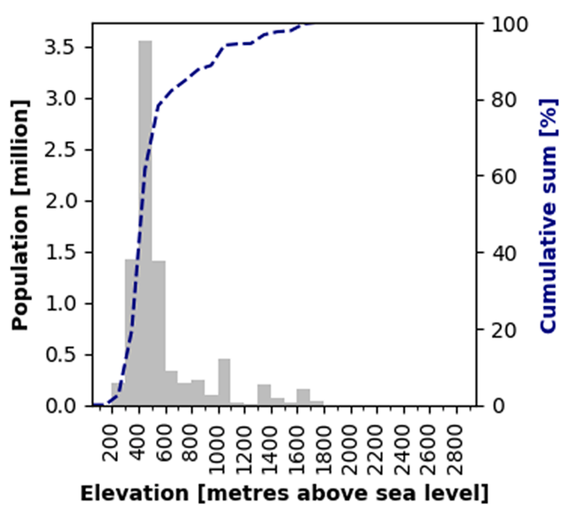

Fig. 2. Population distribution as a function of elevation. About 80% of the population are assigned to weather stations situated below 800 m above sea level.

2.3. Indicator day extraction from climate models

Climate indicators such as Heating Degree Days (HDD) and Cooling Degree Days (CDD) are commonly used to correlate climate to thermal building energy demands [14,15,37]. Population-weighted temperatures from the 68 CH2018 climate models along with historic temperature data (2010–2019) were used to calculate mean temperatures and climate indicators such as CDD and HDD based on hourly resolved temperatures. In a further step, the results are aggregated by RCP scenario (12 models for RCP 2.6, 25 models for RCP 4.5 and 31 models for RCP 8.5). In a further aggregation step, the yearly mean values for temperature, HDD and CDD are calculated based on hourly temperatures and consecutively further aggregated to decades. The base temperature for the calculation of the HDD is 12 °C and for CDD 18.3 °C (See Equations 2–3). These threshold temperatures are commonly used values for Switzerland [14,15]. The aimed indoor temperature (T_{in}) is set at 20 °C. If the outside temperature is equal or below 12 °C, a HDD is given by the difference between $T_{in} = 20°C$ and the hourly mean outdoor temperatures (T_i) that are equal or below the base temperature $T_{HDD} = 12$ °C. The HDD are summed up over the day and divided by 24 (Equation (2)). To obtain the yearly amount of HDD, the daily HDD are consecutively summed up over the standardized 365 days of the year (8760 h). An analysis of the temperature measurements of selected weather stations throughout Switzerland and the extracted indicator days such as CDD, HDD, tropical nights and hot days is provided in **SI Note 2**. We find, that the mean temperature could increase up to around 2 °C, the number of HDD could decrease from around 3300 to 2700 and the hot days (daily maximal temperature rises above 30 °C) could increase from the historic mean of five (2010–2019) to over 15 after 2050 in the RCP 8.5 scenario. Similarly, the number of tropical nights (over 20 °C) could increase from historically only a few to over 10 beyond 2050 in the RCP 8.5 scenario.

$$if\ T_i \leqslant 12^{\circ}C : HDD\ [^{\circ}C] = \frac{\sum_{i=1}^{24} T_{in}[^{\circ}C] T_i[^{\circ}C]}{24} \quad (2)$$

$$if\ T_i > 18.3\ ^{\circ}C : \quad CDD\ [^{\circ}C] = \frac{\sum_{i=1}^{24} T_i[^{\circ}C] - \ T_{CDD}[^{\circ}C]}{24} \quad (3)$$

2.4. Bottom-up heating and cooling energy demand

Heating and cooling demands are obtained from the NEST building demonstrator in Dübendorf, Switzerland. NEST is a modular research and innovation building at Empa to accelerate the innovation in the construction sector [23]. It consists of office and residential building units and is equipped with various sensors to record the thermal energy demands. The building consists of a central backbone and three open platforms where individual building units are installed. Three office and residential building units were analysed towards their hourly area-specific heating and cooling energy demands as a function of the external temperature measured in Dübendorf (MeteoSwiss weather station). The area weighted average setpoint temperature for office units is 22.4 °C and 23.4 °C for residential units. The energy demands for space heating and cooling were aggregated for residential and office units and correlated with the hourly mean outside temperature. The hourly resolution is further aggregated to a daily average to reduce noise which originates from the different. We find that the space air conditioning energy demands are well described by a linear correlation (Equation (4)). The established correlations are further discussed in the result and discussion section and are shown in Fig. 4.

$$E\left[\frac{kWh}{m^2}\right] = a^*T_i\ [^\circ C] + b \tag{4}$$

The values of the parameters a and b in the above linear equation are provided in **SI Note 2.**

2.5. Population growth and floor area statistics

Population growth is one of the main drivers towards higher (cooling) energy demands if all other factors remain constant. In 2019, the Swiss population was around 8.6 million inhabitants. The population is expected to grow until at least 2050 with growth rates following three different paths (we call them conservative, moderate and populous) according to the Swiss Federal Statistical Office [44]. The moderate scenario expects 10.4 million inhabitants by 2050, the low scenario 9.5 million and the populous scenario 11.4 million people.

For the calculation of total projected cooling energy demands, the sector and capita specific floor area is required. Current average residential floor areas are approximatively 46 m^2 per capita (average from multi family houses and single family houses), while office space is estimated at 7.4 m^2 and similarly service building space at 4.9 m^2 [45,46]. Therefore, residential floor area constitutes around 75% of the building floor area requiring space cooling. The thermal building energy demand of Switzerland was projected based on these framing conditions.

3. Results and discussion

3.1. How climate change affects cooling and heating demands

Climate change influences the ambient temperature and therefore will be driving changes in the demand for space heating and cooling in Switzerland in the coming decades. In the following, the influence of climate change on the number of Cooling Degree Days (CDD) is discussed. Three climate scenarios are investigated and plotted (RCP 2.6, 4.5, 8.5) for the years 2010–2059 (Fig. 3). Additionally, measured data for the period 2010 to 2019 is provided for comparison in the same plot. The calculation is based on aggregated hourly resolved and population-weighted temperature data based on 68 climate models as discussed in Section 2.2. The development of Heating Degree Days (HDD), Hot days (HD), Tropical nights (TN) and the population-weighted yearly mean temperature is investigated and the results are shown in **SI Note 2.** An increase in the population-weighted yearly mean temperature is expected for all climate scenarios compared to the historic 2010–2019 period, where the yearly mean temperature was around 10 °C. In the RCP 8.5 scenario, a temperature increase of up to 2 °C is expected until 2059. In the same period, the HDD could drop from around 3300 recorded in the past decade down to just above 2500 by 2059 in the most extreme scenario investigated. In the past decade, five hot days with maximum temperatures above 30 °C were measured in Switzerland. In the RCP 8.5 scenario, this number could rise to well above 15 by mid-century. The number of tropical nights (minimal temperature of the day always above 20 °C) is expected to increase even more from only occasional events in the past decade to a mean value above 10 [35].

For CDD, we note that the collected historic mean temperatures (population-weighted) between 2010 and 2019 show a larger variability compared to the climate model predictions. The extreme year of 2018 (>300 CDD) already reflects what an average year around 2050 could look like if the actual climate path lies between the RCP 4.5 and RCP 8.5 scenario. Generally, CDD are expected to increase in every climate scenario until around 2050 where a decline in CDD is expected for the RCP 2.6 and RCP 4.5 scenario. The CDD would further increase if the RCP 8.5 scenario was followed and could almost double compared to the historic decade (2010 to 2019). Furthermore, the number of HDD is

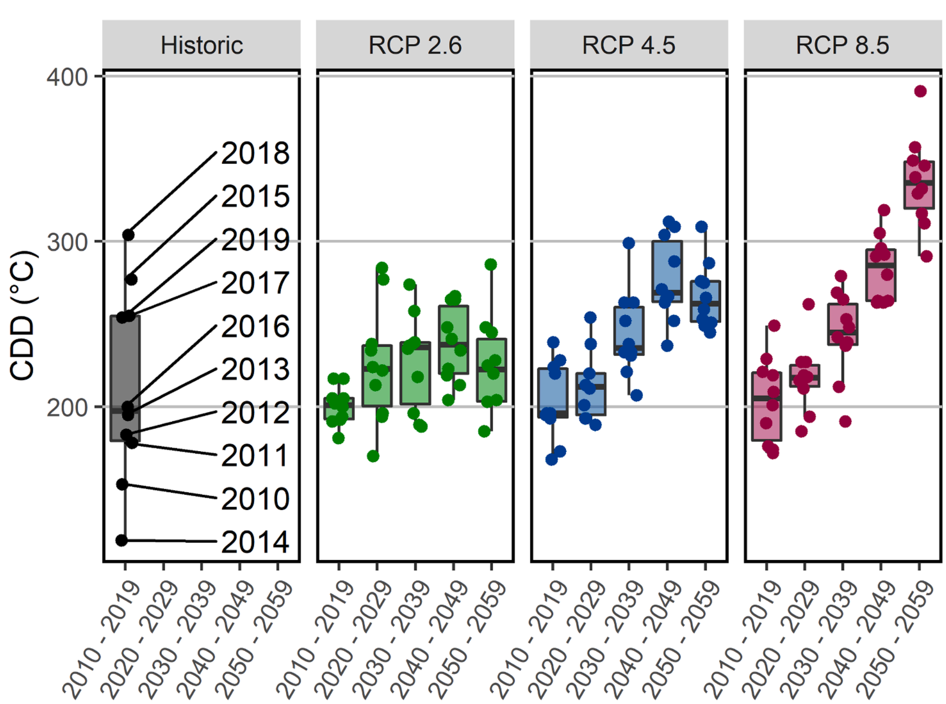

Fig. 3. Future annual mean Cooling Degree Days (CDD) calculated for three different climate scenarios (RCP 2.6, RCP 4.5, RCP 8.5) and historic data for the year 2010–2019 based on population-weighted temperatures. Yearly mean values are aggregated to decades to highlight the trends rather than differences among individual years. In the past decade, we calculated on average around 200 CDD. The CDD are expected to increase in every model until 2050 and will not further increase on average in the RCP 2.6 and RCP 4.5 scenario after 2050.

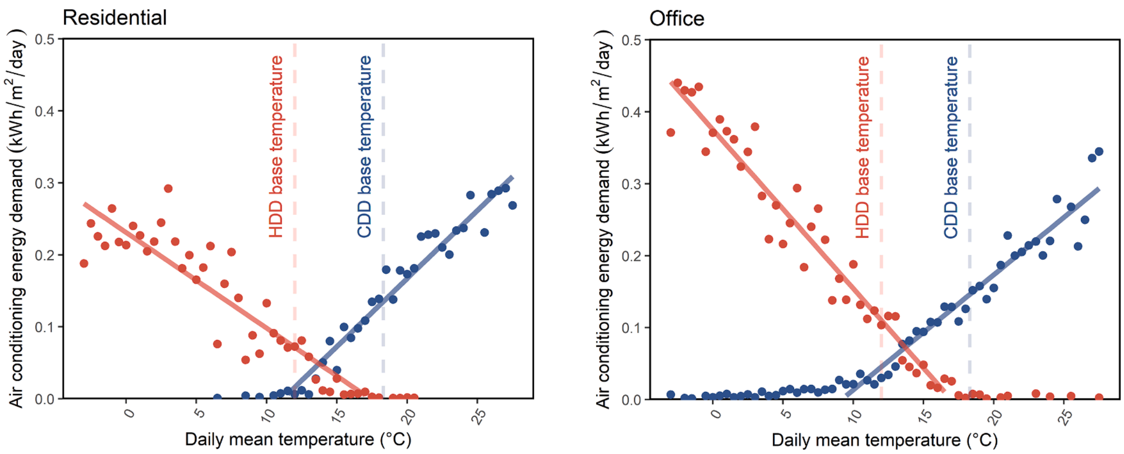

Fig. 4. Correlation between daily mean ambient air temperatures (MeteoSwiss weather station in Dübendorf) based on hourly measurements with heating (red) and cooling (blue) energy demands for (left) residential and (right) office building units of the NEST building. The measured and daily aggregated data are fitted with a linear line.

expected to decrease while the number of HD and TN is increasing.

A comparison of the climate indicators described above is plotted for the historic 2010–2019 period for different selected regions across Switzerland. One comparison to highlight is between Zurich Kloten (agglomeration) and Zurich city, which shows significant differences in the number of measured tropical nights, presumably due to urban heat island effects. Also, the number of CDD and hot days is higher in Zurich city compared to the agglomeration. Furthermore, there are significant variations among other regions of Switzerland, which is expected. However, such local effects and national differences are well integrated to the calculation of national mean temperatures by using population-weighted data. The results of the local comparison are plotted in **SI Note 2.** Based on the expected CDD development, the cooling device uptake can be estimated for future climate scenarios in Switzerland as discussed in Section 3.6. The population-weighted daily mean temperature for the different climate scenarios is correlated with ambient temperature specific space heating and cooling demands, allowing a national benchmarking of demands as discussed in Section 3.3.

3.2. Relating space air conditioning energy demands to ambient air temperatures

Future space heating and cooling energy demands can be calculated with the climate scenarios discussed in Section 3.2, if a correlation between the ambient temperature and the building space heating and cooling demands is known. We have established a correlation for residential and office building units (area-specific) based on hourly data from NEST and meteorological data from a close-by MeteoSwiss weather station (Dübendorf). The heating and cooling energy demand correlations, which were aggregated to daily means, are shown in Fig. 4.

The correlations for the NEST building have a crossing point at around 14 °C. This crossing point results presumably from a demand for heating and cooling during the same day which we have observed in office units and to a lower extent also in residential units. For example, rooms are heated in the colder morning hours and cooled during warmer afternoon hours with higher occupation (offices), solar irradiation and generally higher internal gains (e.g. cooking, computers, meetings). Particularly the transition months April, May, September and October are prone to having cooling and heating in the same day. Hourly resolved thermal demand data is aggregated by months and building type (office, residential) to analyse the demand profiles as shown in **SI Note 3.** While we can explain the observed demand profiles, we argue that there is still potential to reduce the active cooling demand e.g. via passive cooling strategies. Analysis of the demand profiles enables such future optimizations in the NEST building.

Fig. 4 also shows, that below 16–17 °C, a substantial and gradually increasing heating demand was measured in both office and residential units. Heating demands were thereby measured already above the commonly used base temperature for HDD (12 °C). Measured cooling demand starts at daily mean temperatures above around 9–12 °C, which is clearly below the commonly used base temperature for CDD of 18.3 °C and most likely due to increased cooling demands during afternoon hours in transition months.

The deviation of actual heating and cooling energy demands to the HDD and CDD base temperatures shows, that these threshold values have to be interpreted with the necessary care since they are not indicating real-world threshold temperatures in every case. The here presented real-world data based correlation allows therefore a more accurate extrapolation of space heating and cooling demands compared to a calculation solely based on the number of HDD and CDD. Together with the ambient temperature development in the different climate scenarios and the established correlations, future space heating and cooling energy demands can be benchmarked as discussed in Section 3.4.

3.3. Future national area-specific space heating and cooling demands

Future area-specific space heating and cooling energy demands were calculated based on population-weighted climate scenarios and real-world heating and cooling demand correlated with the ambient temperature. The expected area-specific annual thermal building energy demands for office and residential buildings for the three investigated RCP scenarios are shown in Fig. 5.

Generally, a decrease in the floor area-specific space heating demand is expected due to climate change, while the demand for cooling is increasing. In the RCP 2.6 and 4.5 scenarios, the climate is expected to stabilize around 2050. Hence, the heating and cooling energy demands per floor area in those scenarios will stabilize as well or even slightly decrease. If the RCP 8.5 scenario is followed, the cooling energy demand would continuously increase throughout 2050 and therefore could overcome the decreasing heating demand at some point in the future. In summary, a clear trend towards higher cooling energy demands and lower heating energy demands for all future investigated climate scenarios is visible.

Since future energy demand calculations in this study are based on specific values for heating and cooling demands of NEST building units, it is crucial to set these values into relation to values from the current Swiss building stock before the national demands are calculated based on the presented results. A comprehensive overview on reported thermal energy demands of Swiss buildings was provided in the

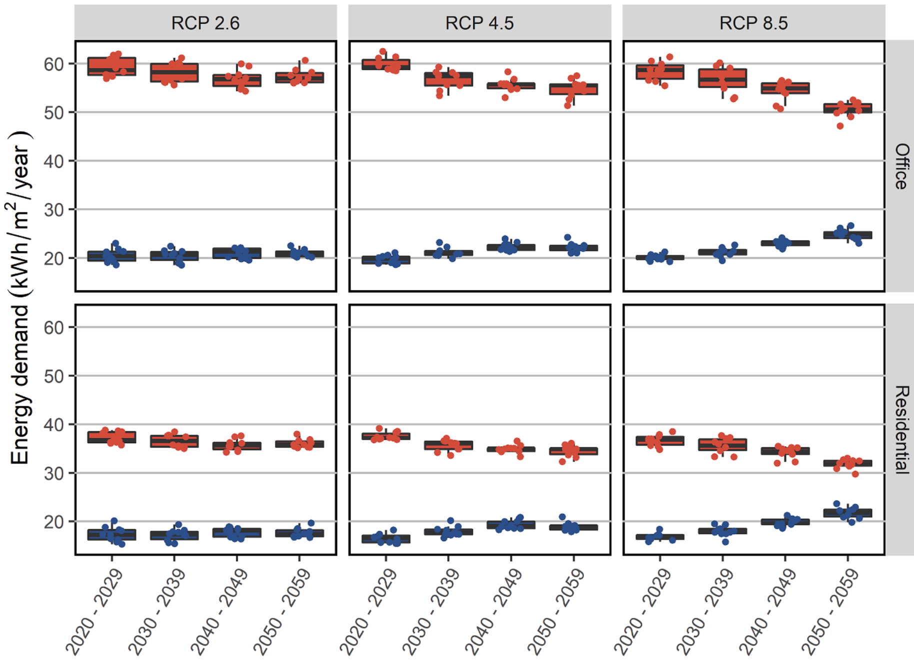

Fig. 5. Future space heating and cooling energy demands per m^2 for Switzerland based on population-weighted climate scenarios correlated with the energy demand of highly efficient Swiss buildings as a function of temperature of measured data for residential and office building units. Heating energy demands are generally decreasing while cooling energy demands increase and become substantially more significant in the future. Demands for heating still remain dominant across all scenarios over the analysed period until 2059.

introduction. In Section 3.5, the results of this study are compared to reported values from literature.

3.4. Comparison of NEST space heating and cooling demands to the Swiss building stock

The energy demand of the NEST building represents modern residential and office buildings in Switzerland, if compared to literature values. In the following, we discuss how representative the NEST building is for the current and future Swiss building stock.

The annual energy demand for residential building units of the NEST building was 38 kWh/m^2 for heating and 18 kWh/m^2 for cooling in the year 2019. Office building units showed a heating energy demand of 60 kWh/m^2 and a cooling energy demand of 21 kWh/m^2. For heating energy demands, it was found, that the current heating energy demand for the NEST building is significantly smaller compared to the average Swiss building stock which was reported to be between 101 kWh/m^2 and 113 kWh/m^2 for residential buildings in the year 2018, while the measured demand in the NEST building was 38 kWh/m^2 [26,27]. However, the NEST building would approximatively represent the average Swiss residential building stock around 2050 in the BAU scenario [29]. If significant policy measures are taken (NEP scenario), the NEST building has a heating energy demand above average by the year 2050, while the cooling energy demand would remain below the expected 30 kWh/m^2 [29]. For offices, the difference is smaller if the 60 kWh/m^2 heating energy demand of the NEST offices is compared to the reported approximate 80 kWh/m^2 reported for offices [27,28]. In summary, the heating energy demand of NEST is approximatively 60% lower compared to the current Swiss average for residential buildings and 25% lower for office buildings. The cooling energy demand for residential buildings cannot be compared due to lack of data. Cooling is however estimated to be approximately four times more efficient in NEST office units compared to reported values for average Swiss offices.

At which point in time the NEST building will be representative of the Swiss building stock for either heating or cooling is difficult to predict, since it depends on many factors such as e.g. political decisions or the renovation rate of buildings. Nevertheless, the measured NEST data are a basis to extrapolate total building energy demands to the future based on different scenarios as discussed in Section 3.8.

3.5. Climate change-driven uptake of cooling devices

While we assume that the vast majority of buildings in Switzerland are equipped with space heating technologies, presumably only a small fraction of residential buildings are equipped with space cooling devices. To explore the sensitivity and the impact of different penetration rates of cooling devices, we define a low, moderate and high cooling device uptake scenario following a logistic curve (Fig. 6) based on literature values from other countries such as Canada and the USA. The referred literature was discussed in the introduction.

The different building sectors (residential, office, service) are expected to respond differently to the general trend of increasing CDD (from currently ~200 CDD to up to 400 CDD by 2050 depending on the RCP scenario). Literature suggests that the response of the service and commercial sector is relatively inelastic to CDD. We assume a linear increase of the cooled floor area in the service sector from 50% in 2020 to 90% in 2050 which remains at this level afterwards [2,32]. Offices are expected to follow the high uptake curve and residential buildings are estimated to follow a low, middle or high uptake scenario. The GDP in Switzerland is comparably high and a GDP limited uptake of cooling devices as discussed in the literature is not likely. The low uptake scenario for Switzerland is thus higher than the prediction of Dittmann, Rivière and Stabat for EU 28 countries [32]. The high uptake scenario corresponds approximatively to the case of Canada, which has a comparable number of CDD and an uptake of 42% with an assumed saturation of the number of devices required by the population [31,33]. The high scenario in this study is lower compared to the USA case (Henderson/Sailor and Pavlova), which is considered as the upper extreme case and not likely for Switzerland [21,22]. In the following, four cooling device uptake scenarios will be considered for the calculation of the total space cooling demand in Switzerland: Low, Middle, High and Full. The full scenario for residential buildings corresponds to an uptake of 100% and marks the upper limit and is intended as a hypothetical value for comparison. Since the floor area for residential buildings per capita is significantly higher (approximatively 3 times) compared to office and service buildings combined, the impact of cooling devices in the residential sector has a higher impact on the total energy demand.

As shown in Fig. 6**,** the middle uptake scenario with an increase from 200 to 400 CDD would result in tripling cooling devices from around

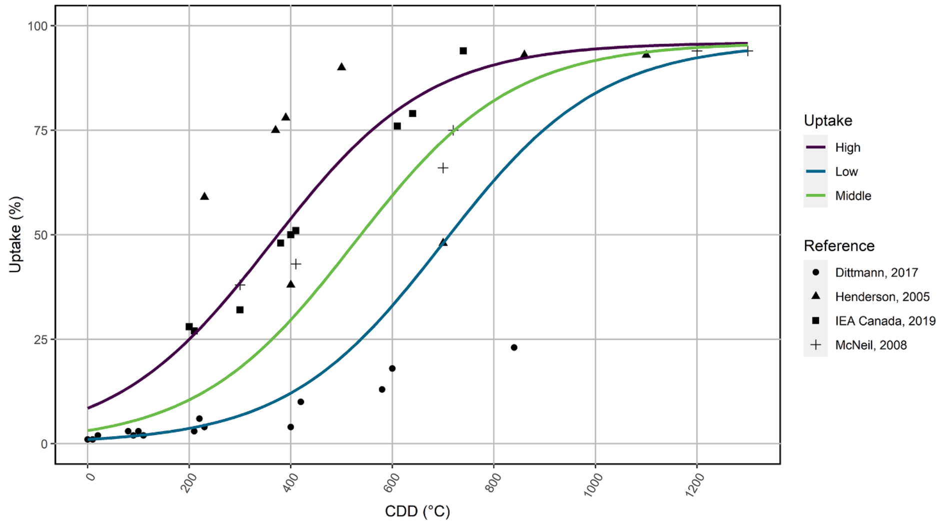

Fig. 6. Three (low, middle, high) cooling device uptake scenarios as a function of annual Cooling Degree Days (CDD) assuming an uptake following a logistic growth. Literature values are plotted as references[21,31–33]. By 2050, CDD values for Switzerland are expected to be in the range of 200–400. Depending on the climate scenario, the simulated uptake could vary between a few percentages to over 50%.

10% cooled floor area in 2020 to 30% after 2050. Following the high scenario, the cooled floor area of residential and office buildings would increase from 25% to around 55%.

3.6. Simulation of future cooling energy demands

Changes in floor area, population size or the uptake of cooling devices are key drivers of total cooling energy demand. The same holds true for heating except for the uptake of devices, where complete saturation with heating devices was assumed.

For calculating the cooling energy demand, a cooled floor area per capita of 46 m^2 for residential buildings, 7 m^2 for offices and 4.5 m^2 for service buildings is assumed. The floor area per capita for the three sectors was assumed to remain constant over time resulting in a linear influence of population growth on energy demand.

Fig. 7 shows the calculated national cooling energy demand development over time with three climate scenarios for office, residential and service buildings considering a moderate population growth, a middle uptake for residential, a high uptake for office buildings and a linear uptake for service buildings. The corresponding figure for heating can be found in **SI Note 4**. The total demand for cooling in the residential sector varies from around 1 TWh to up to 3 TWh. The total impact of office buildings is relatively small, since the total floor area is small compared to residential buildings. Therefore, the impact on the overall cooling energy demand remains limited even if the high uptake scenario is followed. The service sector has a considerable impact since the uptake

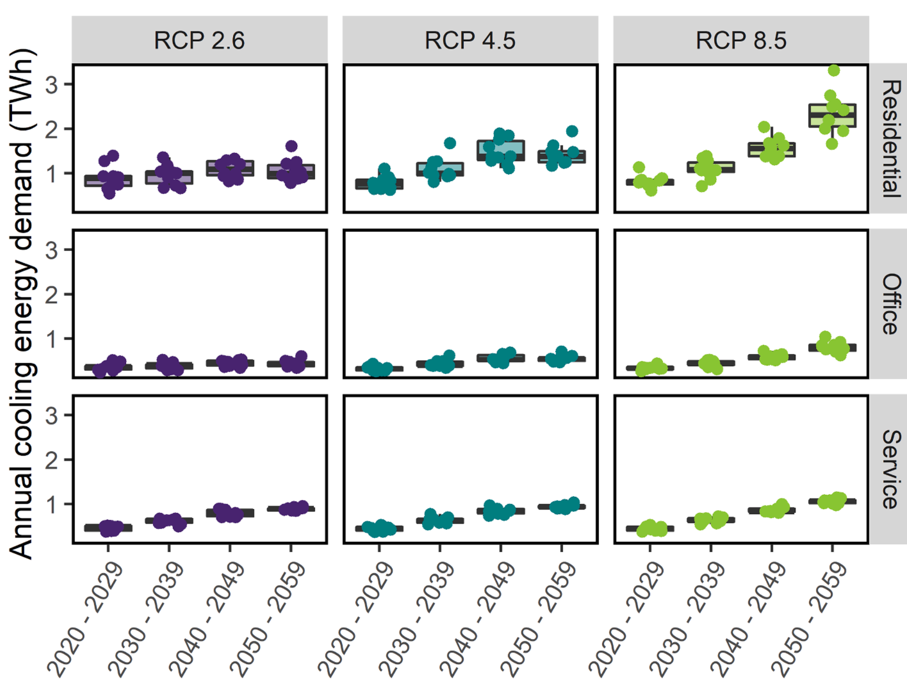

Fig. 7. Future calculated annual cooling energy demand for Switzerland based on climate scenarios, uptake scenarios, building floor areas and the total Swiss population growth (moderate scenario) assuming a best-case energy strategy with highly efficient buildings such as the NEST. The cooled floor area per capita was assumed to be constant over time with 46 m^2 for residential, 7 m^2 for office and 4.5 m^2 for service buildings.

starts already at 50% and likely increases to 90% by 2050 as discussed in Section 3.6. Therefore, following the RCP 4.5 scenario and a moderate population growth, the total demand by 2050 to 2059 would be around 4 TWh for a middle cooling device uptake scenario. This stands in stark contrast to a full uptake scenario in which the cooling demand would be more than three times higher with the other parameters fixed.

3.7. Benchmarking of future national space heating and cooling energy demands

To estimate possible future Swiss demands for heating and cooling, we explore the scenario space with three climate scenarios (RCP 2.6, RCP 4.5, RCP 8.5), four uptake scenarios of cooling devices for residential buildings (Full, High, Middle, Low) and four population projections (Populous, Moderate, Conservative and Constant). Fig. 8 shows the total Swiss energy demands for heating and cooling considering different climate and uptake scenarios under the assumption of a moderate population growth. The influence of population growth on the total energy demand is represented in Fig. 8 by a lighter blue colouring for cooling and a lighter red colour for heating. Additionally, the full parameter space to quantify the influence of climate change, cooling device uptake and population alternations on heating and cooling energy demands is provided in **SI Note 4**.

To discuss the influence of climate change and cooling device uptake on the benchmarked future heating and cooling energy demands, the horizontal (climate change) and vertical (cooling device uptake) variation is discussed. For the horizontal comparison (RCP scenarios), the "High" cooling device uptake scenario and the decade 2050–2059 is selected. In this case, the lowest expected cooling energy demand would be 5.5 TWh (following the RCP 2.6 scenario) and the highest would be 8.6 TWh (following the RCP 8.5 scenario) with a difference of 3.5 TWh or approximatively 50%. For the vertical comparison, the climate scenario is fixed at RCP 4.5 and the same decade (2050–2059) is analysed for all cooling device uptake scenarios. In the "Low" uptake scenario, the cooling demand would be 3.5 TWh. In case all Swiss households would be equipped with cooling devices ("Full" uptake), the cooling energy demand would be as high as 13.5 TWh, which is 10 TWh higher compared to a "Low scenario". The highest benchmarked demand is therefore almost four times larger compared to the lowest cooling demand (RCP 4.5, 2050–2059, "Low" uptake). This shows that the cooling device uptake is critical since it could be the major driver toward higher cooling energy demands.

The total Swiss cooling energy demand is likely to increase significantly while heating remains the prevailing form of energy demand in all RCP and cooling device uptake scenarios until at least the middle of the 21st century[1]. The total heating energy demand would decrease due to climate change at a constant population size. But as visible in Fig. 8, these savings are largely compensated by the expected population growth. Based on the heating demand per area discussed in Section 3.5, the total heating energy demand would be approximatively 60% higher if no building renovations are carried out to improve the area-specific heat demand of the Swiss building stock.

[1] We point out that the primary energy demand to supply the heating and cooling energy demands depends on the specific efficiencies of heating and cooling devices which convert primary energy to heating and cooling energy. For example: The primary energy demand of a heat pump depends not only on the efficiency of the device, but also on how the electricity was generated. Therefore, to allow a comprehensive comparison between heating and cooling energy demands, the conversion efficiencies of specific technologies are not considered and the primary energy demand has to be calculated in a follow-up step based on current and future conversion technologies.

3.8. Impact of the increased cooling energy demand on the energy system

The following illustrative example is thought to showcase possible impacts of the increasing number of cooling devices on future energy systems. If we assume that the future annual cooling demand of 5 TWh occurs during 8 h of the day for 8 weeks of the year, this would approximately result in an average cooling power of 10 GW during this period by using a Coefficient of Performance (COP) of four for cooling devices (cooling energy output over electricity input). This would result in an average electricity demand of 2.5 GW during cooling hours and very likely even higher peak electricity demand [28]. This demand would need to be covered by the equivalent of e.g. several large Swiss hydropower plants (1 GW output per power plant). Alternatively, the electricity required for cooling could be supplied by photovoltaic (PV) cells with an area of 12 to 25 km^2 at an average power output of 100–200 W/m^2 during the hours of cooling demand. This area would correspond to less than 1% of the populated Swiss area [47]. The timely overlap of cooling demand and the supply of PV electricity is however favourable since cooling peak demands typically occur some hours after peak PV production and it is estimated that over 50% of the growing cooling energy demand could be supplied using PV [48]. **See SI Note 3** for correlations between cooling energy demands and ambient air temperature. The readers are encouraged to work on an in-depth analysis of the impact of cooling devices in future energy systems based on the results presented in this work.

4. Conclusion and outlook

We show that future building space cooling energy demands in Switzerland could significantly increase due to climate change, the uptake of cooling devices and population growth. We provide benchmark space heating and cooling energy demands based on population-weighted climate scenarios and real-world building energy demands.

We find that particularly the uptake of cooling devices (climate change-driven or driven by other factors) has a dominant influence on the total future cooling energy demand, outweighing the influence of population growth and variations in all scenarios considered. The scenario-based total cooling demand expectations calculated in this study range from 3 TWh (RCP 2.6 climate scenario, low population growth, low uptake) to over 17.5 TWh (RCP 8.5 climate scenario, high population growth, full cooling device uptake). A "moderate" scenario would result in a cooling demand of around 5 TWh (RCP 4.5, moderate population growth, high device uptake), which is still expected to have considerable impacts on the future energy system. Despite a significant decrease due to a warming climate and building renovations, heating energy demands are expected to remain the dominant building energy demands over cooling in every scenario until the middle of the 21st century.

The significant increase in cooling demand, over the next century, necessitates actions to implement strategies to minimizing the additional load on the energy system. Such strategies could involve passive cooling [25] or district cooling [49] which have already been implemented, planned or are under evaluation in other cities [50]. Addressing cooling will also require climate-adapted architecture of new buildings and climate sensitive city planning [51].

A limitation of this study is caused by the lack of cooling demand data in Switzerland. While the data from the NEST building enables a comprehensive analysis of cooling and heating demands for residential and office building units, it is most likely not representative for all buildings across Switzerland. Therefore, we encourage the publishing and releasing of cooling energy demand data for different building types to enable an estimation of current and future demands based on broader data basis. Furthermore, this study benchmarks the cooling and heating energy demands without considering the efficiencies of the conversion technologies used to meet them. A next step would be the determination of the influence of specific heating and cooling technologies on the

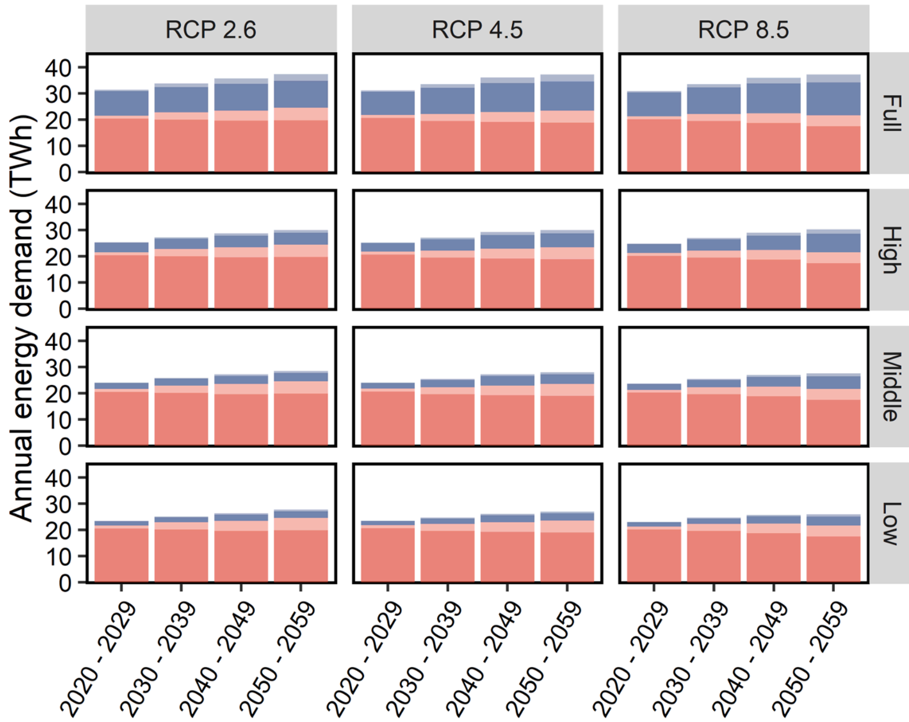

Fig. 8. Annual heating and cooling energy demands for Switzerland considering different climate and uptake scenarios assuming a best-case energy strategy with highly efficient buildings such as the NEST. Heating energy demands are plotted in red, cooling demands in blue. The lighter red and blue areas are due to population growth (Moderate scenario). Whereas the "Full" cooling device uptake scenario assumes that every building is equipped with cooling devices, the "High", "Middle" and "Low" scenarios expect an uptake of cooling devices according to the CDD development and socio-economic factors.

primary energy demands and the spatio-temporal impacts on the energy system infrastructure.

5. Data availability

- Climate model data were obtained form MeteoSwiss. The climate models are part of the CH2018 dataset [35].
- Past weather records were downloaded from the station portal of MeteoSwiss: https://gate.meteoswiss.ch/idaweb
- Population distribution data was obtained from the Swiss Federal Office of Statistics: https://www.housing-stat.ch/de/start.html
- The NEST building data is available on request. More information is available online: https://info.nestcollaboration.ch

CRediT authorship contribution statement

Robin Mutschler: Conceptualization, Data curation, Formal analysis, Writing - original draft. **Martin Rüdisüli:** Conceptualization, Writing - original draft. **Philipp Heer:** Resources, Writing - review & editing. **Sven Eggimann:** Conceptualization, Data curation, Formal analysis, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.116636.

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