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The construction of a forecast Meteorological Year for the city of Milan: impact on building design and energy performance

Filippo Busato[1,4*], *Marco* Cigolotti[2], *Ilaria* Giuliani[3], and *Fabio* Minchio[3,4]

[1]Department of Engineering & Science, Universitas Mercatorum, 00186 Roma (IT)
[2]Studio Cigolotti, 28100 Novara (IT)
[3]Municipality of Milan, 20121 Milano (IT)
[4]Studio 3F-engineering, 37036 San Martino Buon Albergo (IT)

Abstract. The construction of a typical climate year based on CMIP6 data represents an innovative approach to assess the effects of climate change on the energy performance of buildings. The method integrates global climate models with downscaling and bias-correction techniques, allowing the generation of hourly series consistent with future projections and more representative of expected operating conditions than traditional TMYs. The procedure involves selecting CMIP6 models related to the SSP 3-7.0 scenario for the area of interest, reconstructing the main meteorological parameters, and assembling a climate file useful for dynamic simulations and comfort analyses. The article presents a case study dedicated to the climate of Milan, a city particularly sensitive to urban heat islands and summer heat waves, with the aim of assessing the expected variation in thermal loads, consumption, and comfort indicators. The results show how a typical year based on future climate conditions can support adaptation strategies, more resilient design choices, and urban energy planning consistent with decarbonization objectives.

1 INTRODUCTION

Climate is the average state of atmospheric weather at several levels: local, regional, continental, hemispheric or global, monitored over at least 20-30 years. The word climate comes from the ancient greek *klima*, that means "sloped": indeed climate is mainly a function of solar beams' slope over the surface of the earth, according to latitude [1].
The main aspects of climate towards "weather", moreover than the observation timespan, is that of having an almost constant trend over the years, though having variations from year to year on mid-term period.
Several attempts were made through the years (since 70's) in order to develop the so called "Typical Metheorological Year" (TMY), that have been generated for locations all over the world, often on an experimental basis. The first set of Test Reference Year for the European Community was finally released in [2].

* Corresponding author: filippo.busato@unimercatorum.it

In particular, the World Meteorological Organization (WMO) has established that the minimum duration of continuous historical-temporal series of data to be able to identify the climatic characteristics of a given location is at least 30 years; furthermore, there is a specific standard that allows the typical year characteristic of a given location in a certain period to be precisely defined starting from the historical series, this is the [3] UNI EN ISO 15927-4:2005 "*Hygrothermal performance of buildings - Calculation and presentation of climatic data - Part 4: Hourly data for assessing the annual energy use for heating and cooling*". This standard was implemented in order to generate the Italian Test Reference Year [4].
Scientific interest has been captured over the last decades on the thorough investigation on the mechanisms ruling the earth climate, with special regard to the climate change that has been observed recently [5, 6].
Generating future/projected Test Reference Year(s) can be an interesting challenge: the result of the work can generate useful information concerning environmental and social issues, future building codes, energy planning, HVAC systems design.

2 CONSTRUCTION OF THE ENSEBLE OF THE CLIMATIC PROJECTIONS

For the construction of the climate reference year (TRY), the basic data were extracted from the dataset, developed by the CMCC Foundation (Euro-Mediterranean Center on Climate Change) and freely accessible through the CMCC Data Delivery System (DDS) [7, 8]. This is the most up-to-date and spatially detailed statistically downscaled dataset of CMIP6 projections available for Italy, with a spatial resolution of approximately 5.5 km (~0.05°) and temporal coverage from 1985 to 2100. Downscaling was performed using the Empirical Quantile Mapping (EQM) method, applied to nine CMIP6 global climate models under two emission scenarios (SSP1-2.6 and SSP3-7.0). Of the two available scenarios, the SSP3-7.0 scenario was selected as it is more consistent with current global emission trajectories in the absence of a significant reversal of climate policies, and was therefore adopted for precautionary purposes in resilience planning and assessment.
The original dataset includes nine GCMs for the daily variables mean temperature (*tas*), minimum temperature (*tasmin*), maximum temperature (*tasmax*), relative humidity (*hurs*), surface wind speed (*sfcWind*), and cumulative precipitation (*pr*). However, the variables *tasmin-adjust*, *tasmax-adjust*, and *hurs-adjust* are not available for the CESM2 and CMCC-CM2-SR5 models. Since daily minimum and maximum temperature and relative humidity are fundamental variables for calculating TRY—as they directly determine the thermal and hygrometric loads of buildings and are the basis for selecting typical months—the main ensemble was constructed on the seven models for which these variables were simultaneously available.
For the variable *sfcWind*, whose contribution to the definition of TRY is secondary to the thermal and hygrometric variables—since wind speed affects energy loads mainly through infiltration losses and external surface convection, effects that have a lesser impact on the selection of representative months than temperature and humidity — the variable is not available for the CNRM-ESM2-1 and EC-Earth3-Veg models. The wind ensemble was therefore calculated on the 5 models for which the data was available, maintaining the ensemble at 7 models for all other variables.
The multi-model ensemble was constructed using the standard method of arithmetic mean of the realizations of the individual models, an approach well established in the scientific literature that reduces the uncertainty associated with the internal variability of individual GCMs and provides a robust estimate of the expected climate signal.
Some plots about the firs results, for the city of Milan and years 2070 to 2100 can be appreciated in the following Fig 1, while the completeness of the model is shown in Fig 2.

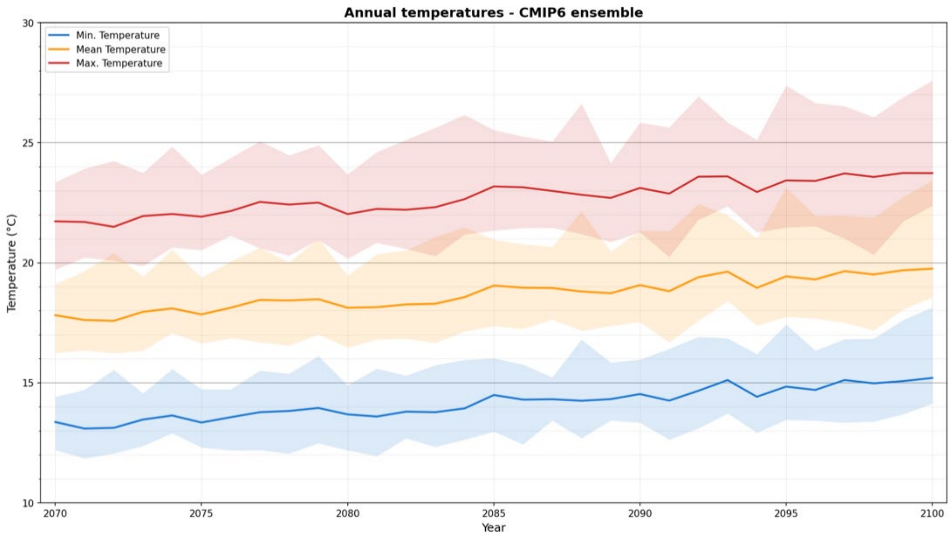

Fig 1. Yearly minimum (blue), average (yellow), and maximum (red) temperatures for 2070–2100. Shaded areas represent the inter-model variability.

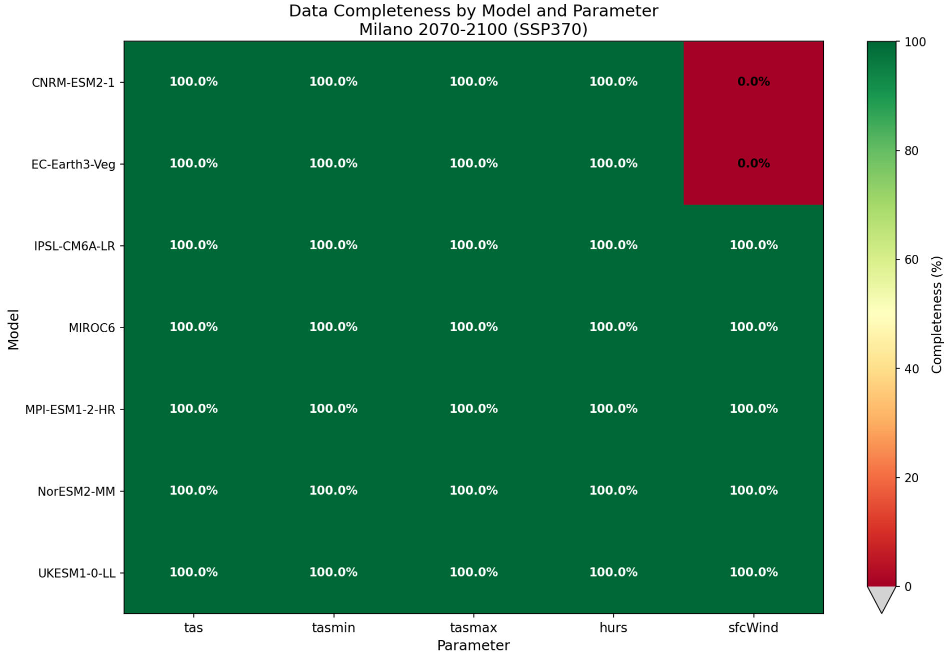

Fig 2. Yearly Completeness of the model.

2.1 From a 30 years projection to a single year

In order to form a single year the procedure of [3] was adopted. The pivot variable is the air temperature. Each month of the final TRY is a complete month selected from the 31 same months of different years; the criteria is the average air temperature. The selected month is that one with the average temperature that is closest to the average monthly temperature of

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the same month across the 31 years (2070-2100). The following Fig 3 illustrates the procedure. Months are numbered from 1 (Jan) to 12 (Dec) in column headers, while years are on row headers. The pivot table is populated with monthly average temperatures, last column is the yearly average temperature, while the column footer is the average temperature of each month over the 31 years.

Average of tas	Column Labels												
Row Labels	January	February	March	April	May	June	July	August	September	October	November	December	Grand Total
2070	6,414	8,633	11,965	16,487	21,881	28,510	30,036	29,344	23,342	17,854	11,512	7,156	17,812
2071	5,418	8,872	13,421	16,877	23,151	27,831	29,533	29,386	23,772	17,392	10,047	5,095	17,615
2072	4,911	8,409	13,132	17,404	21,835	27,286	29,534	28,948	23,815	17,710	11,141	6,534	17,579
2073	6,294	7,981	12,806	17,489	23,105	27,457	29,520	30,114	23,611	18,426	11,204	6,728	17,953
2074	7,370	10,080	14,600	16,729	22,647	26,769	28,772	29,503	23,833	18,586	11,456	6,251	18,097
2075	5,004	7,438	13,846	17,564	21,782	26,952	29,686	30,775	23,935	17,698	11,488	7,267	17,847
2076	7,757	10,070	12,862	17,329	23,507	27,358	28,709	30,078	23,958	18,111	11,011	6,473	18,126
2077	6,807	9,706	12,442	18,151	23,241	27,821	30,302	31,522	24,166	18,164	11,068	7,385	18,449
2078	8,157	10,296	14,925	16,984	23,374	27,170	30,318	30,813	23,056	17,878	10,924	6,581	18,427
2079	6,705	9,668	13,319	17,524	23,320	28,868	29,815	30,398	24,789	18,365	11,723	6,682	18,478
2080	7,645	9,574	12,773	17,518	22,436	27,053	29,850	30,221	23,921	18,961	11,188	6,028	18,124
2081	5,251	8,996	14,113	16,620	22,076	27,743	30,343	30,775	23,937	18,388	12,000	6,897	18,148
2082	4,826	8,749	14,896	17,404	21,880	28,598	30,597	30,716	25,131	17,452	11,717	6,562	18,261
2083	5,905	8,124	13,870	16,165	22,603	27,188	29,497	31,169	25,427	20,081	12,226	6,504	18,291
2084	8,258	9,740	15,135	16,982	22,734	27,164	30,138	30,429	24,615	18,300	11,972	6,952	18,565
2085	7,598	9,988	14,950	16,661	24,266	29,488	30,299	32,029	24,439	18,373	12,073	7,731	19,047
2086	7,377	10,087	13,712	17,426	23,609	27,942	30,978	32,069	24,755	19,738	11,870	7,287	18,959
2087	7,859	8,214	13,231	17,775	23,546	28,557	30,585	31,504	25,078	18,807	13,224	8,226	18,947
2088	7,156	9,270	13,422	17,907	23,558	27,832	29,809	31,260	25,156	18,812	12,085	8,980	18,801
2089	7,158	9,245	13,580	17,304	23,398	27,969	30,179	31,321	24,617	19,195	12,820	7,303	18,730
2090	8,043	9,832	14,052	16,743	23,444	27,934	30,782	32,111	25,630	19,708	12,659	7,181	19,066
2091	7,915	10,234	14,302	17,597	23,036	27,216	30,456	31,129	24,517	19,538	12,550	6,675	18,815
2092	7,834	10,864	14,741	18,963	23,065	28,171	30,845	32,298	25,887	20,074	12,413	7,303	19,396
2093	7,779	10,747	15,446	18,531	24,722	28,574	32,091	31,897	24,755	20,100	12,555	7,654	19,627
2094	7,665	9,926	13,627	17,442	22,823	27,577	31,677	31,838	24,861	18,484	12,679	8,178	18,953
2095	9,274	9,518	13,836	16,616	23,931	30,756	32,006	32,123	25,028	18,890	13,021	7,465	19,431
2096	7,762	10,197	14,855	18,086	24,141	28,454	31,280	32,450	25,627	18,835	12,330	7,266	19,303
2097	7,667	10,975	14,774	18,573	23,168	29,800	31,397	32,763	25,624	19,907	12,446	8,090	19,648
2098	8,808	9,410	14,337	19,213	23,984	28,482	30,412	31,933	25,727	19,419	12,545	9,128	19,510
2099	8,807	10,110	14,423	17,293	23,933	28,938	31,376	33,260	25,900	20,458	13,675	7,354	19,685
2100	7,317	10,442	15,244	19,878	24,830	29,212	30,772	31,929	25,145	19,985	13,378	8,252	19,751
Grand Total	**7,185**	**9,530**	**13,956**	**17,524**	**23,194**	**28,086**	**30,374**	**31,165**	**24,647**	**18,829**	**12,032**	**7,199**	**18,692**

Fig 3. Pivot table of average monthly temperature in years 2070-2100.

So the TRY will have the following selected sample months, according to the highlighted values in Fig 3:

- Jan 2089
- Feb 2095
- Mar 2083
- Apr 2079
- May 2097
- Jun 2092
- Jul 2081
- Aug 2083
- Sep 2089
- Oct 2096
- Nov 2081
- Dec 2090

The month selection is based on *tas*, but carries all of the other variables of the selected month, then also for:

- *tasmin*;
- *tasmax*;
- *hurs*;
- *sfcwind*.

2.2 From daily average to hourly temperatures

In order to form a single year the procedure was that of "shaping" the hourly distribution from the daily average *tas*, by re-creating the same "daily shape" of the existing TRY [4]. So from the hourly data of Milan, for each day an average *tas*, *tasmin*, *tasmax* were calculated from the hourly time series. Then for each hour temperature value, t a shaping coefficient sc_t was calculated as follows:

$sc_t = (t - tasmin) / (tasmax - tasmin)$ [actual TRY] (1)

Then hourly values of *t* for the future/projected TRY were calculated as follows:

$t = tasmin + sc_t \times (tasmax - tasmin)$ [future/projected TRY] (2)

From hourly values of relative humidity *hurs,* of the existing TRY, vapor pressure p_v values were calculated by means of the following equation:

p_{sat} [Pa] $= exp(23{,}5771 - 4042{,}9 / (T_{sat}$ [K] $- 37{,}58))$ (3)

A shaping coefficient was then calculated from hourly values towards the daily average value, and applied to calculate hourly *hurs* values (form hourly values) of the future/projected TRY. Similarly was the path to generate hourly values for *sfcWind*.
Values of global radiation on horizontal, direct and diffuse radiation, were considered the same as in existing TRY. The assumption is correct with reference to global radiation on horizontal (since it does not depend on climate but is only due to astronomical algorithms), while the distribution between direct and diffuse radiation strongly depends on the sky model assumed; this falls out of target of the present work.

3 RESULTS

The following Fig 4 presents a pivot table run on the existing TRY [4], with hourly average values of the typical day of each month. Fig 5 presents the same pivot table run on the future/projected TRY (2070-2100).

Average of TEMP	Column Labels																							
Row Labels	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Grand Total
January	3,3	3,0	2,8	2,7	2,5	2,3	2,1	2,1	2,0	2,1	3,0	4,1	5,5	6,3	6,7	7,0	6,8	6,1	5,3	4,8	4,3	3,9	3,7	3,4	4,0
February	6,6	6,4	6,2	5,8	5,5	5,2	5,0	4,8	4,8	5,2	5,9	6,8	7,7	8,7	9,3	9,7	9,9	9,8	9,1	8,5	8,1	7,7	7,3	6,9	7,1
March	9,6	9,0	8,6	8,3	8,0	7,8	7,4	7,3	7,6	8,3	9,4	10,4	11,4	12,6	13,5	14,2	14,4	14,4	13,8	12,9	12,2	11,5	10,9	10,1	10,6
April	12,2	11,9	11,6	11,2	10,8	10,5	10,3	10,5	11,3	12,2	13,2	14,1	15,0	15,9	16,4	16,6	16,5	16,4	16,0	15,1	14,4	13,8	13,3	12,7	13,4
May	17,8	17,3	16,9	16,7	16,4	16,0	15,9	16,3	17,3	18,2	19,2	20,3	21,3	22,1	22,6	23,1	23,0	22,6	22,2	21,7	20,7	19,7	19,2	18,6	19,4
June	21,3	20,8	20,2	19,7	19,2	19,0	19,0	19,7	20,5	21,7	22,7	23,7	24,5	25,2	26,1	26,5	26,6	26,4	26,0	25,5	24,7	23,7	22,8	22,1	22,8
July	23,2	22,6	22,0	21,5	21,1	20,8	20,8	21,4	22,2	23,4	24,3	25,4	26,3	26,9	27,7	28,1	27,9	27,9	27,6	27,0	25,9	25,1	24,5	24,0	24,5
August	23,2	22,6	22,1	21,7	21,2	20,9	20,7	20,9	21,9	23,1	24,1	25,1	26,1	26,7	27,5	27,8	27,6	27,5	27,1	26,3	25,5	24,9	24,3	23,7	24,3
September	18,4	17,9	17,5	17,2	17,0	16,8	16,5	16,4	17,1	18,1	19,2	20,2	21,4	22,4	23,2	23,8	23,8	23,5	22,8	22,0	21,2	20,5	19,7	19,0	19,8
October	13,3	13,0	12,8	12,5	12,4	12,2	12,1	12,0	12,3	13,0	13,7	14,6	15,3	16,0	16,4	16,7	16,7	16,3	15,8	15,2	14,7	14,3	13,9	13,5	14,1
November	7,3	7,1	6,9	6,7	6,5	6,5	6,5	6,4	6,3	6,5	7,1	7,7	8,1	8,5	9,0	9,0	9,1	8,7	8,3	8,1	7,9	7,7	7,5	7,3	7,5
December	3,1	2,9	2,7	2,5	2,2	2,0	1,9	1,8	1,9	2,1	3,0	3,7	4,5	4,9	5,3	5,5	5,4	4,9	4,5	4,4	4,3	4,0	3,7	3,3	3,5
Grand Total	**13,3**	**13**	**13**	**12**	**12**	**12**	**12**	**12**	**12**	**13**	**14**	**15**	**16**	**16**	**17**	**17**	**17**	**17**	**17**	**16**	**15**	**15**	**14**	**14**	**14,3**

Fig 4. Pivot table for the air temperature of the existing TRY (hour/month).

Row Labels	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Grand Total
January	5,6	5,4	5,2	5,2	4,9	4,6	4,3	4,4	4,3	4,4	5,2	6,4	7,7	8,5	8,9	9,2	8,8	8,2	7,4	6,7	6,4	6,0	5,8	5,4	6,2
February	8,0	7,7	7,4	6,9	6,5	6,0	5,8	5,4	5,3	5,7	6,8	8,0	9,5	11,1	12,0	12,5	12,8	12,6	11,7	10,8	10,3	9,7	9,1	8,5	8,7
March	12,2	11,4	11,0	10,6	10,1	9,9	9,3	9,2	9,6	10,6	12,0	13,1	14,4	15,7	17,0	17,9	18,1	18,0	17,2	16,2	15,3	14,4	13,7	12,6	13,3
April	16,2	15,8	15,3	14,7	14,0	13,4	13,1	13,4	14,3	15,6	16,9	18,1	19,4	20,6	21,0	21,2	21,0	20,8	20,2	18,8	17,8	17,0	16,3	15,7	17,1
May	20,9	20,3	19,8	19,5	19,1	18,7	18,5	19,0	20,2	21,2	22,3	23,5	24,6	25,5	26,1	26,7	26,6	26,1	25,8	25,2	24,0	22,9	22,3	21,6	22,5
June	26,8	26,3	25,6	25,1	24,6	24,3	24,4	25,0	25,7	26,9	27,9	29,0	29,8	30,5	31,5	31,9	32,0	31,7	31,2	30,6	29,8	28,7	27,8	27,1	28,1
July	28,5	27,8	27,1	26,4	26,0	25,7	25,6	26,3	27,2	28,6	29,7	30,9	32,0	32,7	33,5	34,0	33,8	33,8	33,5	32,8	31,5	30,6	29,9	29,3	29,9
August	29,7	29,0	28,4	27,9	27,4	27,1	26,8	27,0	28,2	29,6	30,8	32,0	33,1	33,7	34,6	34,8	34,4	34,2	33,6	32,7	31,8	31,1	30,5	29,8	30,8
September	23,3	22,7	22,1	21,7	21,4	21,2	20,8	20,7	21,4	22,5	23,6	24,7	26,0	27,2	28,0	28,7	28,8	28,3	27,5	26,6	25,7	25,0	24,1	23,3	24,4
October	17,3	16,8	16,3	16,0	15,8	15,5	15,5	15,3	15,8	16,6	17,8	18,9	20,1	21,1	21,7	22,1	21,9	21,3	20,5	19,7	19,0	18,5	17,9	17,4	18,3
November	11,2	10,9	10,5	10,2	9,9	9,8	9,7	9,6	9,4	9,7	10,8	11,6	12,1	12,8	13,7	13,9	13,9	13,4	12,8	12,5	12,3	12,0	11,6	11,3	11,5
December	6,4	6,0	5,8	5,4	5,0	4,7	4,6	4,5	4,7	4,6	5,9	7,0	7,9	8,4	9,0	9,2	9,1	8,4	8,0	7,9	7,7	7,3	6,8	6,3	6,7
Grand Total	**17,2**	**16,7**	**16,3**	**15,8**	**15,4**	**15,1**	**14,9**	**15,0**	**15,6**	**16,4**	**17,5**	**18,7**	**19,8**	**20,7**	**21,5**	**21,9**	**21,8**	**21,4**	**20,8**	**20,1**	**19,3**	**18,6**	**18,0**	**17,4**	**18,2**

Fig 5. Pivot table for the air temperature of the future/projected TRY (hour/month).

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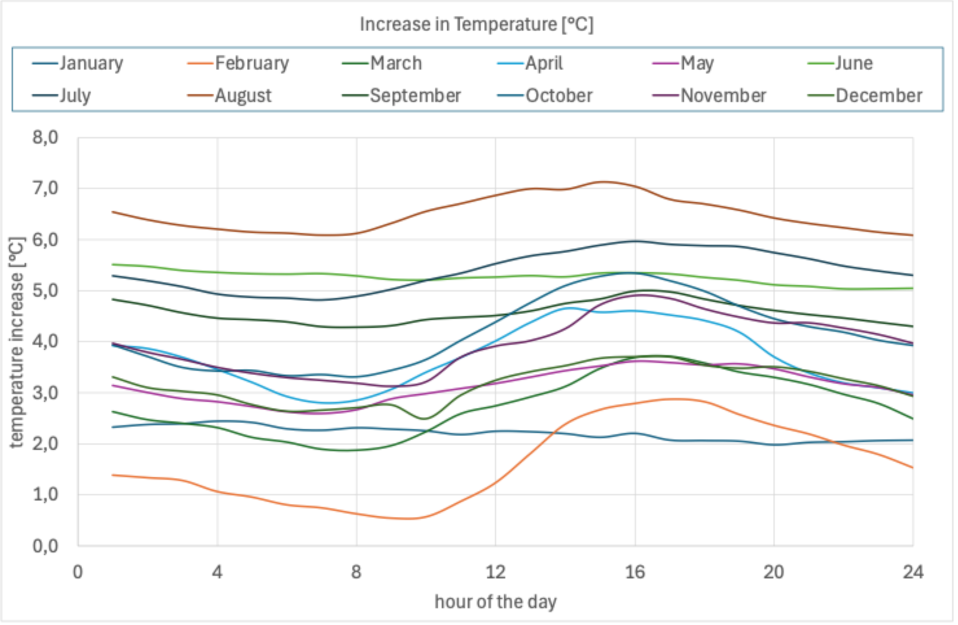

Fig 6. Projected hourly temperature increase on the average day.

Fig 6 shows the increase in hourly average value of the typical day of each month, from existing TRY to future/projected TRY. As it can be seen, the yearly average temperature increases by 3,9 °C. Considering a base room temperature for heating at 21 °C and for cooling at 20 °C, the Heating/Cooling degree-days were calculated from the existing TRY and the future/projected one. The results can be appreciated in Table 1, that also presents the extreme temperature values throughout the year.

Table 1. Heating degree-days, cooling degree-days, highest and lowest t variation.

	HDD	**CDD**	**Highest *t* (°C)**	**Lowest *t* (°C)**
Actual TRY	2278	479	33,7	-1,8
Future/Projected TRY	1565	1156	37,6	-0,8
% var	-31,3%	+141%		

3.1 Consequences on buildings' energy performance

A simple building model was adopted in a TRNSYS simulation in order to determine heating net demand *Hnd* and cooling net demand *Cnd*, and compare the results for the same building in the actual Milan climate [4] and the future/projected one.
The building model is that used for previous evaluation in the field of integrated energy and structural refurbishment, [9] and [10] and its façades are shown in the following Fig 7. It is a building created on the basis of an average north Italian, non refurbished apartment building from the 60's-70's. Each floor contains a 150 m^2 apartment, equipped with high efficiency boiler (non-condensing) and radiators' heating system. The cooling needs during summer are

provided by direct-expansion split system. Since it is invariant towards the climate, domestic hot water production was neglected.

Fig 7. Prospects of the building used for simulation (Basili et al., 2024).

Results in terms of monthly energy demand are shown in Fig 8.

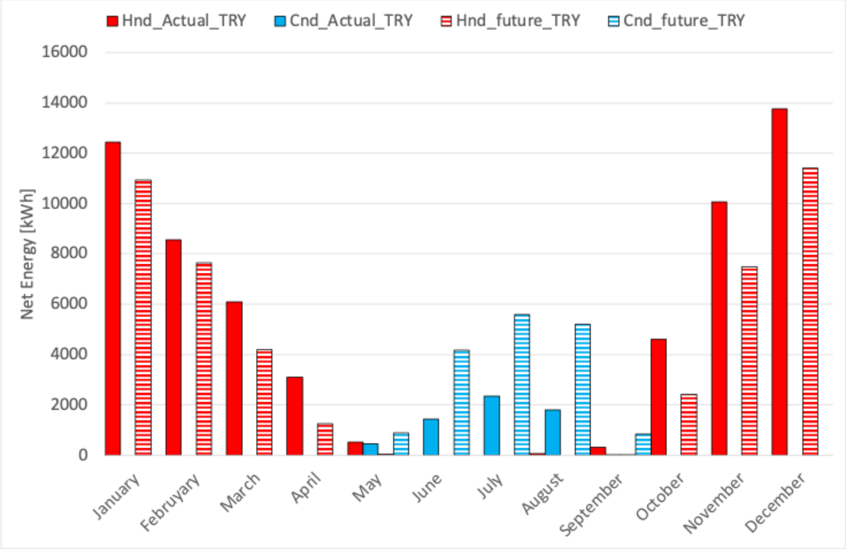

Fig 8. Monthly energy net demand comparison.

Table 2. Variation of specific heating and cooling net demand over the year.

	H_{nd} [kWh/(m^2 y)]	C_{nd} [kWh/(m^2 y)]
Actual TRY	132,22	13,37
future TRY	100,80	37,07
difference	-24%	177%

Table 3. Variation of heating and cooling peak power net demand.

	Heating peak (kW)	Cooling peak (kW)
Actual TRY	39,7	10,4

future TRY	35,9	14,8
difference	-10%	42%

As it can be seen from the figures in Table 2 and Table 3, the specific net energy demand for heating decreases by a fourth (-24%), while that for cooling almost triples (+177%); at the same time there's a moderate decrease of heating peak power (-10%) and a consistent increase in cooling peak power (+42%). A figure of reduction of heating energy demand that is greater than that of reduction in peak load (and conversely for cooling) is mainly due to the fact that extreme conditions do not vary as significantly as the average ones (Table IV). The number of hours with t > 26 °C increases from 789 (existing TRY) to 2290 (future/projected TRY).

A further consideration can be inferred about the primary energy consumption of the building. If an average 92% efficiency is assumed for the heating boiler and a 2,5 SEER for the split system, with a conversion factor of electric to primary energy equal to 2,42, specific primary energy consumption decreases from 156,7 [kWh/(m^2 y)] with actual TRY to 145,5 [kWh/(m^2 y)] with future/projected TRY (-7,2%).

4 CONCLUSIONS

The construction of a future/projected Test Reference Year is a delicate operation that is not defined by standards. However trying to assemble a future Test Reference Year is crucial for the evolution of building codes as well as for urban planning, and quite relevant for HVAC systems design.

The work that has been done for the city of Milan shows quite interesting results: in terms of heating degree-days they could decrease of about 1/3, but moreover cooling degree days could increase of more than 140% by the end of the century.

While a moderate increase in extreme temperatures is expected, a significant decrease in heating net demand will follow, and a dramatic increase in cooling net demand is projected. Therefore accurate measures should be developed in terms of building codes in order to contain peak loads in summer, but a greater attention should be paid to the seasonal efficiency for cooling, especially for office building that will most likely have a cooling/heating energy ratio higher than that of residential buildings.

Hopefully an accurate development of the models and a further refinement of them as per variables other than temperatures is expected to happen in the next years, as well as a progressive verification of the model's performance with respect to climate measurements.

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