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Greening Umbria's Future: Investigation of the Retrofit Measures' Potential to Achieve Energy Goals by 2030 in the Umbria Region

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Abstract: The new European targets of achieving net zero emissions by 2050 have spurred Italy to aim for a 30% reduction in emissions by 2030, compared with 2005 levels. This goal will be achieved through the promotion of renewable energy sources and energy savings in the residential sector, which remains one of the main sectors accountable for total energy consumption, mainly for heating. This study aims at investigating the potential of some retrofit measures implemented in the Umbria Region, chosen as a case study, to reach the goal by 2030. Using parametric energy simulations with the standard calculation method and artificial neural networks (ANN), the energy consumption of Umbria's building stock and potential CO_2 reductions were assessed. Results showed that with current energy policies, a reduction of 28% could be achieved, which is below the goal by 2030, while ANN integration within energy strategies could allow reaching it as early as 2025 or 2029, depending on the restriction set to the ANN and the extent of current energy policies. This study confirmed the potential benefits of using advanced technology in achieving national environmental goals, highlighting that they could be essential tools to be integrated into energy policies to accelerate progress towards ambitious climate goals.

Keywords: green transition; building retrofit measures; energy policy; parametric energy simulations; artificial neural networks (ANN); energy efficiency; CO_2 emissions achievement

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1. Introduction

The need to address climate and environmental challenges has never been more pressing. The building sector is one of the major energy consumers in Europe covering a key role in energy efficiency measures to implement for making significant strides towards reducing energy consumption and improving energy efficiency in the residential sector. The European Union's goals are very ambitious since they expect a greenhouse gas emission reduction of 55% at least by 2030 and to achieve climate neutrality by 2050 [1].

However, while some countries have made progress in reducing emissions, others have continued to increase their consumption due to industrial and economic development [2]. To reach the net zero emission target by 2050, carbon emissions must be halved by 2030 through a variety of energy measures, including the widespread adoption of clean technologies, such as high-insulated building envelopes, heat pumps, and district energy. However, it is worth noting that despite the transition to renewable energy sources, fossil fuels still account for 35% of the total building need in 2021 [3].

European countries are aiming for an important reduction in the residential sector by 2030 to achieve the goal of decarbonizing the whole building stock by 2050, for which the renovation wave for Europe [4] has been launched within the European Green Deal [5], which aims to double annual energy renovation rates in the next 10 years. This means reducing consumption and emissions, improving the quality of life for residents, and generating new employment opportunities. Through national long-term strategies, Italy would like to achieve sustainable development goals and transform the economy over the next three decades by renovating the building sector and becoming a greener, more sustainable country [6].

In this framework, the government's national energy and climate plan aims to reduce greenhouse gas emissions of buildings by 33% compared with 2005 levels and to increase the share of renewable energy sources in the final consumption of energy to 30% [7]. To achieve these goals, Italy relies on energy incentives, just introduced in 2014 and annually updated, i.e., a range of energy policies to encourage the renovation of existing buildings. The efficiency of the adopted energy measures is checked by using a standard calculation method, i.e., the one implemented in energy performance certificates (EPCs), which is the most useful tool to evaluate and collect energy information on national building stocks [8,9], resulting in a useful and common application for mapping building energy performance. EPC has been recently used at the national level to apply the latest incentivizing system, namely, Superbonus 110, to check the improvement of at least two energy classes in the energy retrofitting of buildings. Regardless, all the fiscal deductions for energy efficiency and the use of renewable energy sources used the standard calculation to assess the resulting energy savings. Therefore, the energy policies implemented at the national level are evaluated by using this easier calculation method as well as the energy savings and targets to be reached by 2030 and 2050.

Each European member state has included different energy services in EPC calculation, but the main objective remains to be energy efficiency awareness and the promotion of energy improvements in buildings to reduce carbon emissions. EPC is considered an important driver for building renovation [10,11], although other methods for the building energy performance assessment could be used. On the one hand, the asset rating is based on the real characteristics of the building envelope and its energy services, but conventional climate and operational conditions are adopted; for that reason, it can return unreliable energy consumption. On the other hand, other methods, such as dynamic or hourly calculation according to UNI 52016 [12], could be able to give back more reliable outcomes at the expense of greater complexity for their use.

Although the reliability of the calculation method could be lower than other available energy calculation methods, EPC remains a very simple and easy-to-use tool for understanding the energy performance of buildings [13–15]. Many studies have found that the gap between the standard calculation method and the actual one (i.e., the real energy consumption of buildings) could reach up to 30%, mainly due to the standard assumptions in EPC [16–21], but they also underlined the importance of EPC as a tool for energy performance assessment of the building stock, being the easier available method for an energy assessment. Semple and Jenkins highlighted that buildings are generally associated with 40% of total energy consumption, but the method used to identify this result is based on, albeit limited, different energy services considered in the EPC calculation method [16], pointing out the necessity to adopt a uniform method at the European level. Hu et al. proposed a practical and complex approach based on a fuzzy analytic network to reduce this energy gap, obtaining a not-easy tool to be used or to extend to different contexts [17]; on the other hand, Ferrari et al. proposed an easier approach based on multiple indicators, but it can be extended to another country, but it can be considered reliable only if energy consumption data are available [19]. As underlined in [20,21], the correction of EPC outcomes is a relevant issue to be investigated to check the meeting of the national energy efficiency and carbon targets and to understand if correcting factors have to be used for more realistic energy consumption.

Furthermore, although more reliable energy consumption can be obtained with other calculation methods, a recent study highlighted that EPC can return comparable energy outcomes, especially in the case of highly efficient buildings (i.e., the ones with low energy needs) and when comparing analysis was performed, confirming its use for this kind of application [22].

Other interesting applications of standard calculation can be found in the literature, such as developing national strategies [10], or leveraging their data for the implementation of artificial intelligence to optimize the effects of national energy policies [23], or checking the quality of data reported in EPC [24], confirming the great ease of application of this kind of method.

According to these works, EPC is considered the easier and more useful tool to be used for checking the improvements of energy renovation actions and the achievement of national targets launched within the European Green Deal. Furthermore, EPC should ensure the application of a uniform method at the European level as the same goal has been set, although currently, EPC has differences in the calculation method, as shown in [16,25].

Although many studies have highlighted the potential of using EPC, only a few studies have been carried out on the effect it could have on energy forecasting analysis and on national targets' achievements introduced by the European Green Deal, having recently been issued. For instance, Johansson et al. [26] used EPC to analyze the energy targets' achievement introduced by the government in the town of Kiruna, highlighting the importance of implementing the energy measures reported in EPC and the need for high energy measures' impact to achieve the ambitious targets. Guo et al. [27] investigated the effects of the photovoltaic industry on CO_2 emissions by 2060 in China to meet the neutrality target. Results have shown that the CO_2 emission could be reduced by around 88% by 2060, while the photovoltaic industry could reach neutrality between 2014 and 2015, allowing the reduction of 33 gigatons CO_2-eq by 2060. Energy security and carbon neutralization were analyzed by Wang et al. [28] since they are the main targets for China, highlighting that energy security can negatively affect CO_2 emissions in the long-term impacts. Furthermore, Jiang et al. [29] investigated the potential of CO_2 reduction in Shenzhen, pointing out that the reduction for the building sector could reach 60% by 2030 and that it could be significantly increased by accelerating the energy efficiency of existing buildings. Based on the European directives on the energy performance of buildings, Castellano et al. [30] proposed and developed a straightforward procedure to obtain the environmental impact of building. This method proposed a new formula for CO_2 emissions, resulting in a useful support tool to address climate change mitigation. Conversely, Shi et al. [31] carried out the impact of low-carbon transition in China by adopting a Bayesian network, pointing out that the transformation of energy subsystems plays a key role in the low-carbon strategy.

According to this brief literature description, the use of EPC is widely spread as a tool for energy performance assessment and its application in forecasting analysis. However, as the new targets provided by the European Green Deal were recently introduced, the effect of the European policy on the possibility or not of reaching the new targets has not yet been carried out, although some works found in the literature already addressed the relevance on CO_2 reductions to mitigate climate change. For a more comprehensive literature review, the grouping of the analyzed works by addressed topic is shown in Table 1.

Table 1. Literature review: grouping of some works found in the literature for the main issues addressed in this paper.

Topic	Literature Review
Energy performance certification: issue and peculiarities	[8–15,22,25,26]
Energy performance gap: difference between standard calculation and actual energy consumption	[16–21]
CO_2 emissions assessment: target achievement and reduction	[26–31]

In this framework arises the present work aimed at evaluating the effects of the current energy policies on the residential building sector to highlight issues and potentialities of these strategies and to check the feasibility of achieving the ambitious targets by 2030. Considering the main findings of previous works [8–24], the study was performed by assessing the energy consumption with the standard calculation method of the Umbrian residential building stock, chosen as a case study. Energy consumption was assessed starting from the characterization of the Umbrian heritage based on the most recent data provided by the National Institute of Statistics, and the current energy consumption and the CO_2 target to be reached by 2030 were estimated on the basis of national reports and data. Theoretical energy savings achieved by 2030 were thus assessed by applying a forecasting analysis, assuming a number of interventions consistent with the one observed in recent years. As highlighted by the literature review, this represents the first analysis of the possibility of achieving CO_2 targets by 2030 in the Italian context.

In addition to previous works, the EPC analysis was integrated with the artificial neural network (ANN) implemented in a previous work [23] capable of optimizing the energy strategies in the Umbrian context to improve the energy savings of each energy measure. In this case, a new application of the ANN was proposed, i.e., to improve the energy actions to reach the regional targets by 2030. Therefore, this paper aims to investigate if the current national energy strategies can allow for achieving the ambitious targets set for 2030 and to evaluate if the use of the ANN can help to reach them in less time. The analysis aimed at checking the achievement of the targets set for 2030 and the use of the ANN for purposes related but different from those for which it was implemented is the main new novelties of the present work.

The study aims to understand the real potential of energy strategies by 2030 and to understand if the emission target of the residential sector can be reached. In addition, the integration with the ANN would like to show its effectiveness, allowing the improvement of each energy strategy. Therefore, the present work would answer the following key questions:

(1) Is it possible to achieve the CO_2 emission target fixed for the residential sector by 2030 with the current energy policy?
(2) Can they be achieved by extending the current energy policy until 2025?
(3) Could the CO_2 emission target set for the residential sector for 2030 be achieved by using the outcomes of the ANN?

The proposed study could have important feedback; for instance, it could allow for checking the effectiveness of current energy policies and evaluating whether corrective measures needed to be proposed to make the 2030 goals achievable. In addition, it could also highlight whether theoretically achievable CO_2 reduction could be improved with small corrections of the energy actions or by integrating them with other tools, such as the ANN. The paper is structured as follows: the research procedure is detailed in Section 2, underlying the characteristics of the building stock of the Umbria Region (Section 2.1), and the assumptions and the calculation method adopted in this work (Section 2.2). Section 2.1 is focused on the building stock's geometrical and thermal properties (Section 2.1.1), the state of the art of energy strategies adopted for the building renovation (Section 2.1.2), and the theoretical targets to be reached by 2030 (Sections 2.1.2 and 2.1.3). Section 2.2 is focused on the main characteristics of the calculation method (Section 2.2.1) and the peculiarities of the trained ANN (Section 2.2.2), as well as the energy consumption assessed with the standard calculation (Section 2.2.3) and the investigated energy scenarios (Section 2.2.4). Finally, the energy and emission outcomes were discussed with both ANN integrations in Section 3, while the main findings are remarked on in the conclusion.

2. Materials and Methods

A detailed research procedure was planned (Figure 1) to check the achievement of the Umbrian target by 2030. The present work consisted of two distinct parts: the first one aimed at identifying the state of the art of the Umbria Region (described in Section 2.1), in terms of building stock, energy consumption, and savings, and the second part aimed at defining the assumptions required for the development of the work (Section 2.2).

The Umbrian building stock was first analyzed by defining the main features and thermal properties of residential buildings (Section 2.1.1); this kind of analysis was based on data provided by the National Institute of Statistics [32] and on a recent study carried out by ENEA [33]. It is worth noting that the data from the National Institute of Statistics were updated in 2010–2011; hence, they can be a good representation of the existing building stock since (i) new constructions are less than existing ones, (ii) the energy need of the new constructions is lower, and (iii) the new constructions are not subject to the efficiency measures. However, for that reason, the energy history of the Umbrian building stock has also been studied.

Additionally, national reports on fiscal deductions for the energy efficiency and use of renewable energy sources in the existing buildings [34–39] were examined to identify the most significant and widespread energy strategies in this area. The most widespread solutions capable of significantly increasing the energy efficiency of existing buildings were chosen and subsequently investigated (Section 2.1.2).

Besides, baseline values were also defined for the Umbrian building stock (Section 2.1.3), enabling the estimation of the current CO_2 emissions and the theoretical one related to the heating of the residential sector to be achieved by 2030 in accordance with the new national programs. For the latter analysis, data available online from the Italian Institute for Environmental Protection and Research were also used [40,41].

Once defined, the Umbrian building characterization, the baseline values of energy consumption and CO_2 emissions, the working assumptions, and the calculation approach adopted in this work were detailed (Section 2.2). Particularly, energy analysis in agreement with standard calculation (Section 2.2.1) was carried out starting from the Umbrian building stock characterization to define (i) the state of the art of the building stock of the Umbria Region, (ii) the energy consumption of the Umbrian building stock and the CO_2 emissions considering the real energy mix of the region, and (iii) the energy savings resulting from each energy strategy. Furthermore, the artificial neural network implemented in a previous work (of which the main peculiarities are reported in Section 2.2.2) was applied to improve the same energy strategies and to assess the theoretical CO_2 emissions of the Umbrian building stock. Finally, the achievement of CO_2 targets considering different energy policies and strategies (with and without improvement with the ANN) was checked and discussed.

According to this premise, the work consisted of the following steps:

1. Definition and thermal characterization of the Umbrian building stock (Section 2.1.1) based on data provided by the National Institute of Statistics [25] and national report [33];
2. Evaluation of the energy measures in place across the Umbria Region (Section 2.1.2) based on national reports on fiscal deductions for energy renovation of existing buildings [34–39]. This step was focused on estimating the number of interventions implemented and energy savings reached every year in Umbria (from 2014 to 2021);
3. CO_2 reference value assessment (Section 2.1.3) on the basis of data from the Italian Institute for Environmental Protection and Research [40,41];
4. Definition of the main assumptions made for the standard calculation (Section 2.2.1) and artificial neural network application (Section 2.2.2);
5. Assessment of the reference values for energy consumption for the Umbrian building stock (Section 2.2.3) adopting the standard calculation provided by UNI TS 11300 [42–46] and considering the energy savings achieved every year according to step 2. The outcomes were checked considering the ones obtained in step 3;
6. Number of interventions and energy savings definition (Section 2.2.3) for each energy strategy to be implemented from 2022 to 2030 considering the main finding of step 2;
7. Assessment of the theoretical energy and CO_2 reduction by 2030 due to the application of different energy efficiency actions (Section 3.1);
8. Improvement of the main energy actions with the ANN and theoretical energy and CO_2 reduction assessment as a result of the network (Section 3.2).

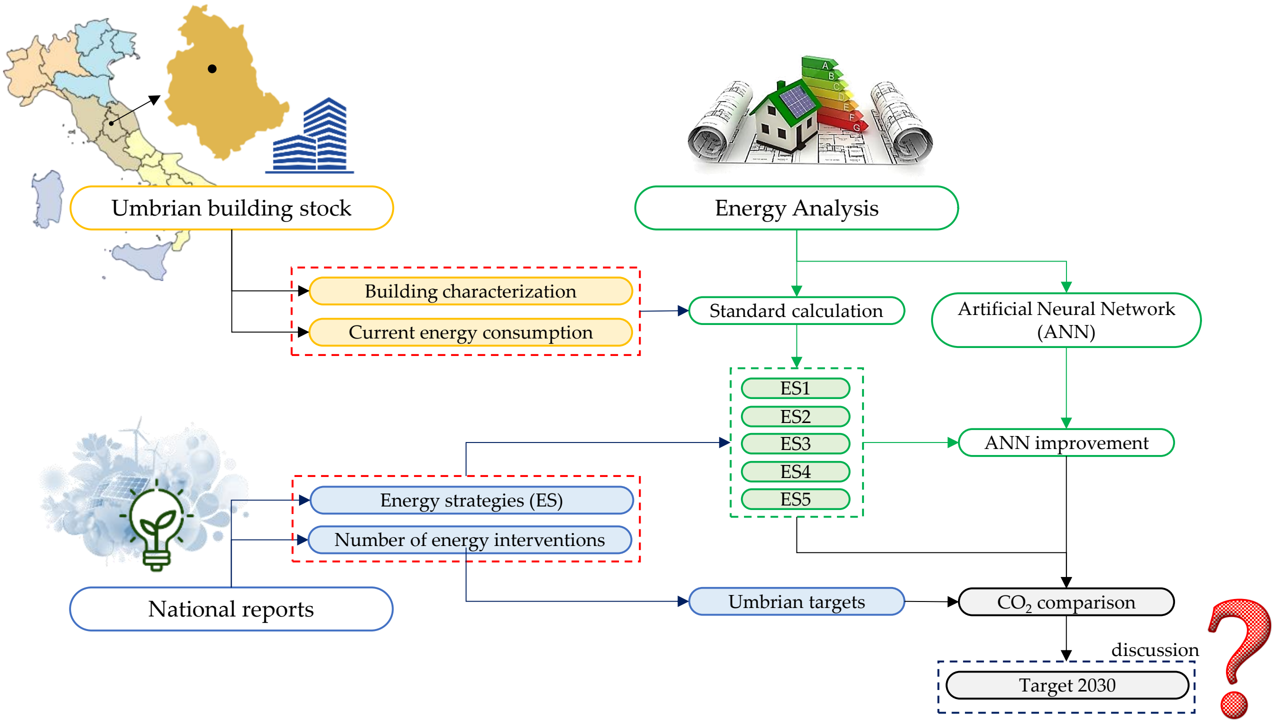


Figure 1. Research procedure adopted for the energy performance assessment of Umbrian building stock and analysis of CO_2 target achievement by 2030.

2.1. Umbria Region State of the Art: Buildings, Energy Consumption, and Energy Savings

2.1.1. Umbrian Building Stock

A key point of the Umbrian energy assessment lies in the characterization of the Umbrian building stock; particularly, the type and geometrical dimensions of existing buildings were assessed from data provided by the National Institute of Statistics [25] available online, while thermal properties were defined based on a previous work carried out by ENEA [33], as already conducted in a previous study [23] for the artificial neural network implementation. However, limited information and correlations are available from [25] (such as the number of residential buildings per number of floors, the number of buildings per number of building units, and the number of building units per net surface range reported in Appendix A); for that reason, the following steps were followed for the Umbrian building characterization for each municipality:

- Step 1: a correlation between the number of buildings per number of floors (Table A1) and the number of buildings per building unit (Tables A2 and A3) was established by using an iterate approach and double-checking on both the number of buildings and the number of building units. In this way, the number of building units (as grouped by the National Institute of Statistics into "one unit", "two units", "three or four units", "five to eight units", "nine to fifteen units", and "more than sixteen units) for the number of building floors (as grouped by the National Institute of Statistics into "one floor", "two floors", "three floors", and "four and more floors") was defined;
- Step 2: once the number of building units for the number of floors was correlated, the net surface distribution of the building units was investigated. The analysis allows for defining the most widespread net surfaces, considering the range provided by [25] (National Institute of Statistics groups data into "$\leq$29 m^2", "30–39 m^2", "40–49 m^2", "50–59 m^2", "60–79 m^2", "80–99 m^2", "100–119 m^2", "120–149 m^2", and "$\geq$150 m^2").

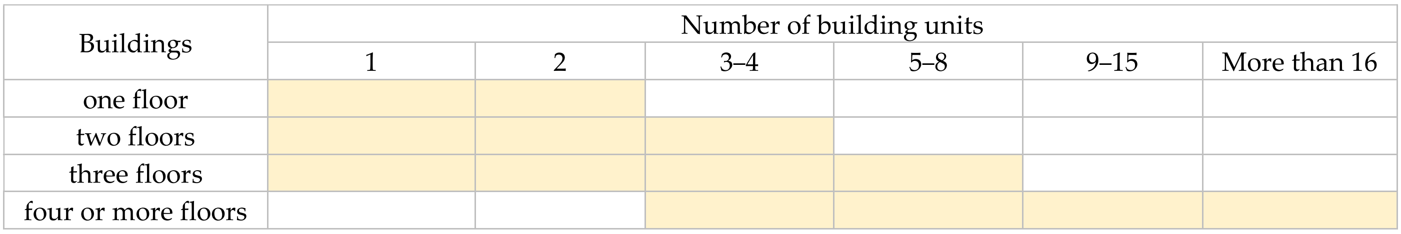
To perform step 1, the assumptions shown in Figure 2 were made; results related to the most representative cities (the ones that have a number of buildings greater than 2% of the total of Umbria) are reported in Table 2. It is worth noting that this percentage distribution was assessed considering the whole Umbrian building units' sample provided by [32]. As shown, Umbria is predominantly characterized by buildings on one or two floors (around 30.6% of the sample shown in Table 2 and about 48.7% overall), of which more than 22% (40% of the whole sample) are on two floors with only one building unit (i.e., single-family houses (SFH)). Among the multifamily houses (MFH), i.e., the ones with two or more building units, a greater number of buildings with three floors can be highlighted (around 28% of the sample shown in Table 2 and about 31% overall), with a significant prevalence of buildings with two building units. Only in the biggest cities (such as Perugia and Terni) a greater number of buildings with four or more floors were found.

On the basis of step 1, the distribution of the net surfaces was thus evaluated to check the most widespread solutions; the ones found in the most representative Umbrian cities are shown in Figure 3, highlighting that the building units are greater than 60 m^2.

The thermal properties of the building envelope and the heating characterization of the building stock were based on a previous work carried out by ENEA [33]. Particularly, this study carried out a thorough analysis of the thermal properties of building components based on the year of construction of buildings, thermal insulation, and materials. For instance, buildings built before 1991, i.e., before the issue of the second and most important Italian energy regulation, were generally built without or with a small thickness (up to 2 cm) of thermal insulation materials, corresponding to greater thermal transmittance values (falling into 0.75 and 3.5 W/m^{2}K range); on the other hand, the new construction can have a lower variability of the thermal transmittance, which can fall within the 0.2–0.3 W/m^{2}K range.

The same considerations were made for transparent surfaces; however, their thermal transmittance is less variable, mainly between 1.3 and 3.0 W/m^{2}K.

Besides, the same study provided information on heating systems, thanks to the integration of the database of the National Institute of Statistics with data from Informative System on Energy Performance Certificates (SIAPE in Italian). In Umbria, the widespread heating system (Figure A1) used in existing buildings consists of standard boilers (around 72%), followed by condensing boilers (around 15%); other heating systems, such as heat pumps (less than 6%), are common only in new construction. This last one can be used also as an integration heating system or for cooling. Moreover, natural gas is the main energy carrier used for heating in Umbria (more than 56% of the sample), followed by biomass (32% of the sample) and g.p.l. (6.9% of the sample).



Buildings	Number of building units					
	1	2	3–4	5–8	9–15	More than 16
one floor	▨	▨				
two floors	▨	▨	▨			
three floors	▨	▨	▨	▨		
four or more floors			▨	▨	▨	▨

Figure 2. Assumptions to perform step 1: number of building units considered for buildings on "one floor", "two floors", "three floors", and "four or more floors".

Based on the state of the art of the Umbrian building stock, the sample was grouped into four different periods of construction (before 1976, between 1977 and 1991, between 1992 and 2005, and after 2005) to take into account the different thermal properties according to the national regulation evolution and to correlate the properties of the building components with the year of construction of the building stock. Particularly, data from ISTAT highlighted that in all the Umbrian municipalities, the majority of the buildings are built before 1976 (values around 50–70%), followed by buildings built between 1991 and 2005 (between 30% and 10% on average). This analysis pointed out that the whole residential building stock has poor thermal properties since it was built before the second and most important national energy regulation. The found trend for the most representative cities of the Umbria Region is shown in Figure 4.

Table 2. Percentage distribution of buildings (grouped per building floor (BF) and into "n. 1", "n. 2", "n. 3–4", "n. 5–8", "n. 9–15", and "n. ≥16" building units) in the most representative Umbrian cities (the ones with more than 2% of the sample).

BF	**1**		**2**				**3**					**≥4**			
BU	**1**	**2**	**1**	**2**	**3–4**	**5–8**	**1**	**2**	**3–4**	**5–8**	**9–15**	**3–4**	**5–8**	**9–15**	**≥16**
Assisi	0.25	0.00	1.88	0.24	0.11	0.04	0.00	0.81	0.29	0.10	0.03	0.08	0.03	0.02	0.02
Castiglione del Lago	0.20	0.00	0.79	0.34	0.15	0.05	0.00	0.32	0.11	0.04	0.01	0.03	0.01	0.02	0.00
Città di Castello	0.14	0.00	1.75	0.06	0.03	0.02	0.00	1.08	0.44	0.20	0.06	0.20	0.09	0.03	0.04
Foligno	0.29	0.00	2.70	0.48	0.21	0.09	0.00	1.20	0.31	0.14	0.06	0.22	0.10	0.08	0.06
Gualdo Tadino	0.09	0.00	1.19	0.06	0.02	0.01	0.00	0.60	0.10	0.03	0.01	0.08	0.03	0.01	0.01
Gubbio	0.49	0.00	1.69	0.23	0.15	0.06	0.00	0.88	0.41	0.18	0.05	0.16	0.07	0.04	0.03
Perugia	0.42	0.00	4.92	0.00	0.00	0.00	0.56	2.49	0.67	0.50	0.24	0.91	0.68	0.33	0.39
Spoleto	0.30	0.00	1.96	0.59	0.27	0.13	0.00	0.70	0.18	0.09	0.03	0.15	0.07	0.07	0.04
Todi	0.16	0.00	1.07	0.05	0.02	0.01	0.00	0.57	0.19	0.07	0.03	0.09	0.03	0.02	0.02
Narni	0.16	0.00	0.79	0.32	0.18	0.05	0.00	0.44	0.17	0.05	0.02	0.08	0.03	0.03	0.02
Orvieto	0.27	0.00	0.83	0.12	0.09	0.06	0.00	0.36	0.20	0.13	0.03	0.08	0.05	0.02	0.02
Terni	0.44	0.00	2.68	0.49	0.29	0.16	0.00	1.44	0.47	0.26	0.14	0.39	0.22	0.20	0.32

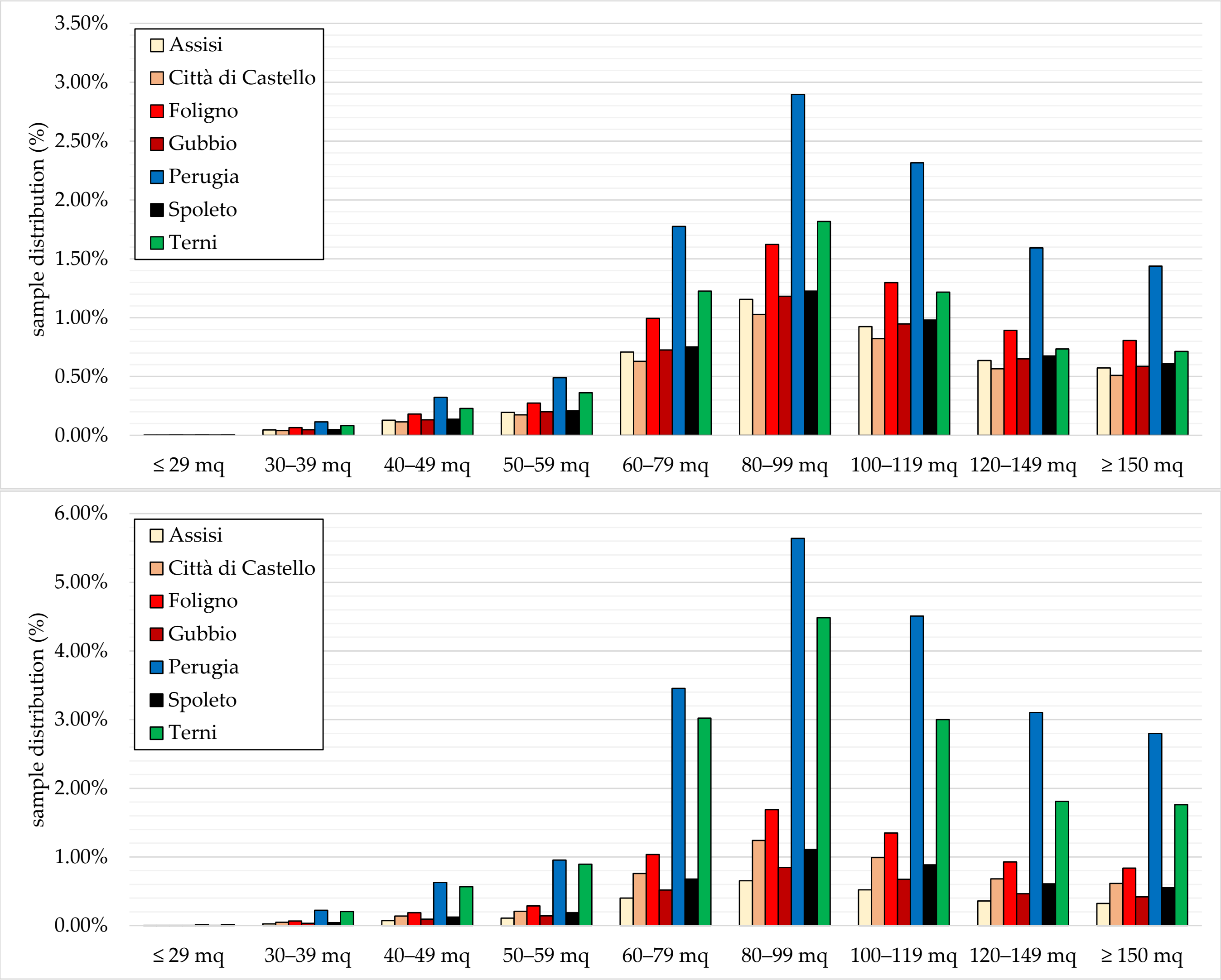


Figure 3. Net surface distribution for single-family houses (above) and multifamily houses (below) in the most representative Umbrian cities.

Based on these premises, archetypes with the geometrical characterization described above were defined and used for the parametric energy simulations; the thermal properties of the building opaque components applied in this analysis are shown in Table 3, while the heating systems for heating and the energy mix previously described were considered.

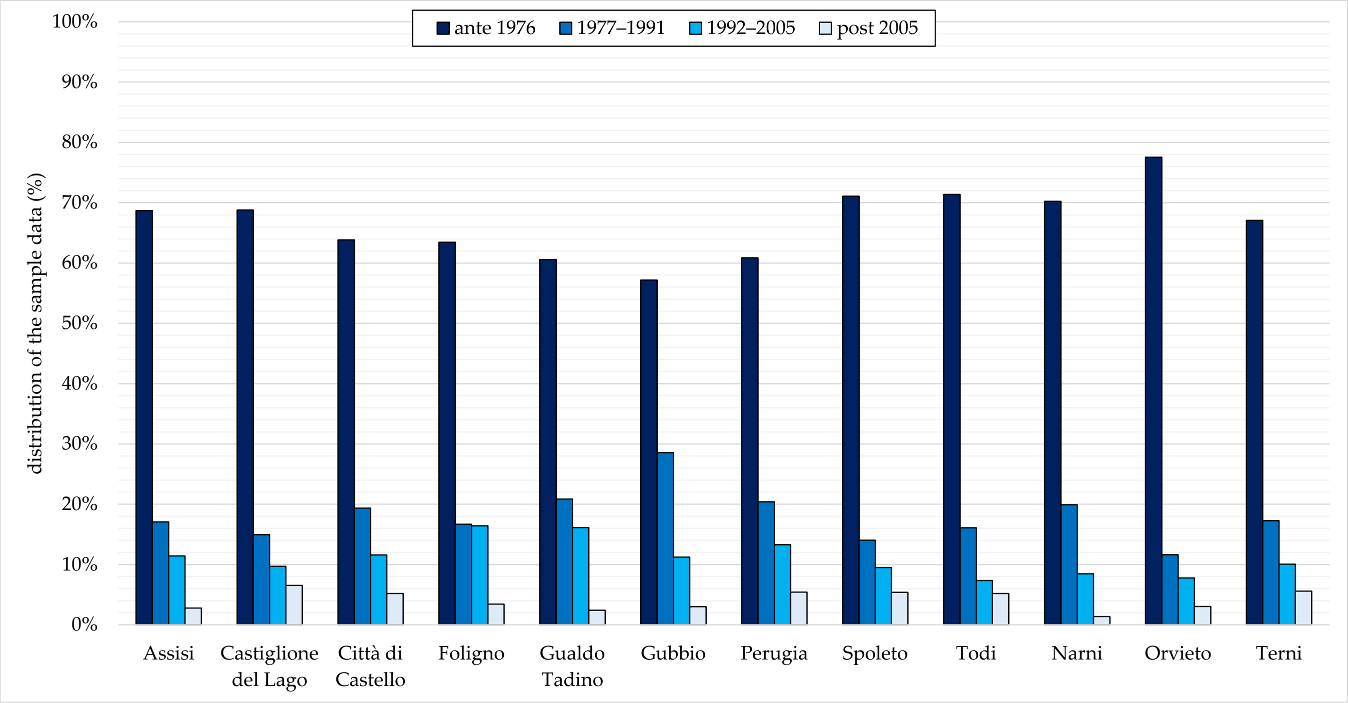


Figure 4. Year of construction of the building stock for the most representative cities of Umbria.

Table 3. Thermal properties of the building envelope adopted for the parametric energy analysis.

Components	Period of Construction	Thermal Transmittance (W/m^2K)
Walls	before 1976	3.22–0.75
	1977–1991	1.56–0.60
	1992–2005	0.53–0.33
	after 2005	0.33–0.13
Pavements	before 1976	1.68–1.15
	1977–1991	0.67–0.55
	1992–2005	0.38–0.34
	after 2005	0.27–0.20
Ceiling	before 1976	1.68–1.15
	1977–1991	0.67–0.55
	1992–2005	0.38–0.34
	post 2005	0.27–0.20

2.1.2. Energy Measures in Place

Another important point for the present analysis consists in the definition of the number of new interventions that could be implemented by 2030. This analysis was performed considering national reports [34–39] by analyzing the number of interventions performed from 2014 and the energy savings obtained for each intervention. Analysis revealed that thermal coating, standard boiler replacement with a condensing one, window replacement, and heat pump installations were the energy measures most implemented in the Umbria Region in the last decade, although the heat pumps are mainly used as an integration of existing heating systems or for cooling (Table 4).

Table 4. Number of interventions implemented from 2014 in Umbria for the energy efficiency of the residential sector [34–39].

Energy Strategies	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Thermal coating	376	371	342	331	489	409	295	327
Windows	1848	1677	1701	2075	2556	2865	2450	4392
Solar collector	355	204	158	150	129	132	95	318
Solar shading	0	579	775	967	827	786	1149	374
Condensing boiler	527	458	629	724	2444	3008	4303	10,811
Heat pump	165	258	239	208	1283	1866	2855	6939
Building automation	0	0	7	22	133	83	61	72

The trend in the last decade distinguishing the interventions due solely to the last implemented energy policy (i.e., Superbonus) and the other ones was thus studied (Figure 5), highlighting an increasing trend in the number of interventions, although this was not matched by an increase in the energy savings per intervention (Figure 6). The found trend pointed out that, more recently (from 2018), energy efficiency actions were also implemented in more performing buildings that would not need energy efficiency measures.

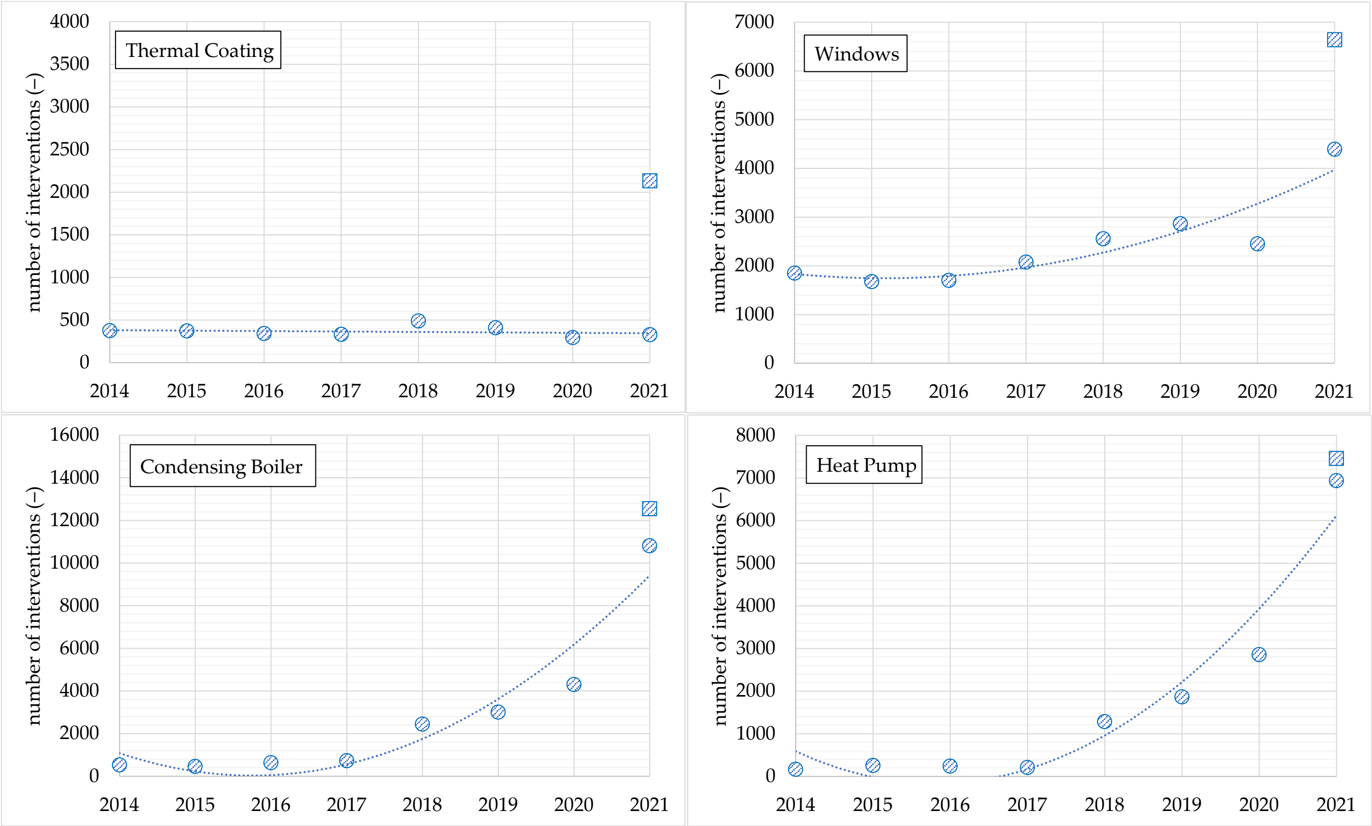


Figure 5. Number of interventions for the main energy strategies implemented in the residential sector in Umbria [34–39].

2.1.3. CO_2 Emissions Baseline

Another key point of the work consists of the baseline evaluation of energy consumption and CO_2 emissions related to the heating of the building sector. However, national reports and data from the Italian Institute for Environmental Protection and Research [40,41] provided only aggregated values, indicating the range of percentages due to the heating service; particularly, around 6.9 million of CO_2 emissions in 2019, 9.3 million in 2010, and

12.1 million in 2005 were recorded in Umbria. Around 20% is attributed solely to the heating of residential buildings (i.e., more than 2.4 million in 2005). According to these reports, the baselines related to 2005, 2010, and 2021 were thus estimated and adopted as reference values:

- 2005: it is the baseline value to take into account to assess the CO_2 target to be achieved by 2030 (estimated at about 1.62 million of CO_2 emissions);
- 2010: it is the baseline value (about 1.87 million of CO_2 emissions) used to check the reliability of the energy analysis as the reference buildings were based on data from the National Institute of Statistics updated in 2010–2011;
- 2021: it consists of the baseline starting value of the forecasting analysis. This last value was assessed, considering the recorded CO_2 emissions and correcting it for the energy savings achieved through energy policies each year, provided by national reports and reported in Table 5.

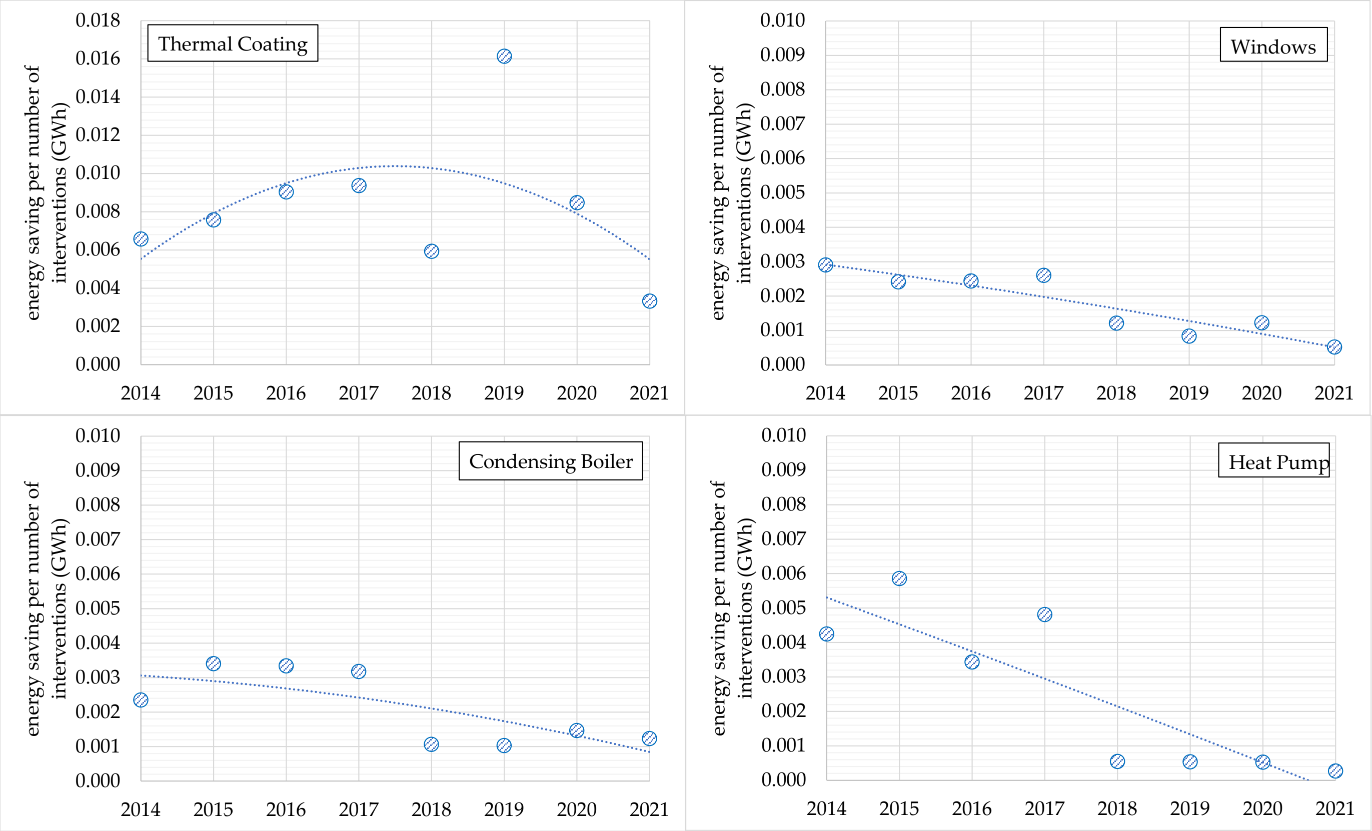


Figure 6. Energy savings per number of interventions of the main energy strategies implemented in the residential sector in Umbria [34–39].

According to this approach, considering data provided by national reports on energy savings and CO_2 emission reduction achieved by applying the different energy strategies [34–41], the residential building stock of Umbria could have consumed around 7800 GWh in 2021, corresponding to about 1.82 million of CO_2 emissions.

This means that the CO_2 emissions of the Umbrian building stock should be reduced by 0.20 million to reach the target of 1.62 million by 2030 (assessed by reducing by 33% the value of 2005).

Table 5. Energy savings (GWh) achieved for the main energy strategies implemented in the Umbrian residential building sector [34–39].

Energy Strategies	2014	2015	2016	2017	2018	2019	2020	2021
Thermal coating	2.47	2.81	3.09	3.1	2.9	6.6	2.5	8.17
Windows	5.37	4.05	4.15	5.4	3.1	2.4	3	5.73
Solar collector	1.38	0.86	0.75	0.7	0.4	0.4	0.4	1.61
Solar shading	0	0.17	0.22	0.3	0.1	0.2	0.3	0.24
Condensing boiler	1.24	1.56	2.1	2.3	2.6	3.1	6.3	28.81
Heat pump	0.7	1.51	0.82	1	0.7	1	1.5	3.86
Building automation	0	0	0.11	0.1	0.2	0	0	0.04
Total	11.32	11.04	11.48	13.6	10.6	14.2	14.2	49.52

2.2. Calculation Method and Working Assumptions

2.2.1. Standard Calculation

The standard calculation method is detailed in the package of standards UNI 11300 [42–46] and consists of monthly average energy balance considering monthly mean values both for outdoor conditions (such as air temperatures and solar radiation) and indoor ones. This method allows for assessing the primary energy need for heating (but also for the other energy services) on the basis of the thermal properties of the building envelope and energy efficiency of technical building systems.

Currently, this method is adopted to draw up energy performance certifications (EPCs) by using standard input data (such as by setting 20 °C within the residential environments), outdoor conditions (by setting conventional outdoor conditions provided by national regulations), and operating schedules of buildings (such as the heating period).

The energy need for heating is assessed through a monthly balance between the heat losses through the building envelope and the total heat gains (including solar and internal heat gains), corrected by a utilization factor. Although the lower accuracy in estimating actual energy consumption, previous works have highlighted the good reliability of the outcomes compared with other calculation methods, such as with the hourly scale [12], or when a comparative analysis is performed [22].

According to this premise, in the present work, the standard calculation method is adopted by using conventional parameters:

- Outdoor conditions: conventional data of monthly air temperatures, solar irradiation on vertical surfaces with different orientation and horizontal surface (both the directive and diffuse components), and vapor pressures provided by national regulation [47] were set;
- Indoor air temperature: standard set-point value equal to 20 °C was set;
- Heating period: conventional period was considered for the two climatic zones found in Umbria: from 1 November to 15 April (D zone) and from 15 October to 15 April (E zone).

2.2.2. Artificial Neural Network

The neural network used in the present work was trained in [23] by exploiting parameters and results used for the energy parametric analysis. Specifically, based on a national report [33], several building archetypes were defined that well represent the existing Italian building stock. These archetypes were used to carry out a parametric energy analysis in which many different parameters were varied, including:

- Type and building geometry: both single-family and multifamily buildings were considered by varying their useful floor area between 40 and 160 sq m;
- Thermal properties of building envelope components: more than 150 types of vertical opaque walls and more than 40 of horizontal ones (both lower and upper floors) and some types of glazed components were defined according to the findings of the nationwide study [33]. The corresponding transmittance value was thus calculated for each component, obtaining values falling within the range of 0.13–3.50 W/m^{2}K for opaque components and between 1.3 and 3.0 W/m^{2}K for transparent components;

- Technical building system: thanks to the integration of different databases and national reports, in [33], the types and characteristics of the most common technical building systems were defined, associating with useful floor area, climatic zone, building insulation level of buildings, and energy services;
- Climatic conditions: in order to carry out a representative energy analysis across the country, the most representative cities were selected as a function of the number of built buildings, population, and climatic conditions. Twenty-five locations ranging from 568 to 4264 heating degree days were chosen overall.

Based on this characterization, more than 10 million energy simulations were performed in [33] by adopting the standard calculation method, i.e., EPC, and some input parameters and outcomes were used for training a multilayer perceptron neural network with the back error propagation algorithm. In particular, the ANN, able to calculate the primary energy need of buildings (target), was trained with the following input parameters: global solar radiation, heating degree days, net surface, net volume, building envelope surfaces, thermal transmittance of building components (both opaque components and transparent surfaces), technical building system type, power, nominal efficiency, and energy carrier. A schematization of the methodological approach adopted for the ANN application and the input parameters to be supplied are reported in Figure 7.

It is worth noting that ANN outcomes (i.e., energy needs for heating) were converted in CO_2 emissions, considering the conversion factors provided by the official gazette or Umbria Region [48], depending on the energy carriers (Table 6).

It is worth noting that the implemented ANN did not take into account some factors that affect urban development policymaking, such as technological development, economic level, and human cost. Since the investigated period analyzed in this work is quite narrow (2022–2030), the ANN can be considered a useful support tool to be used to improve energy efficiency strategies. Nevertheless, it is recommended to check its outcomes every year to make corrections ongoing.

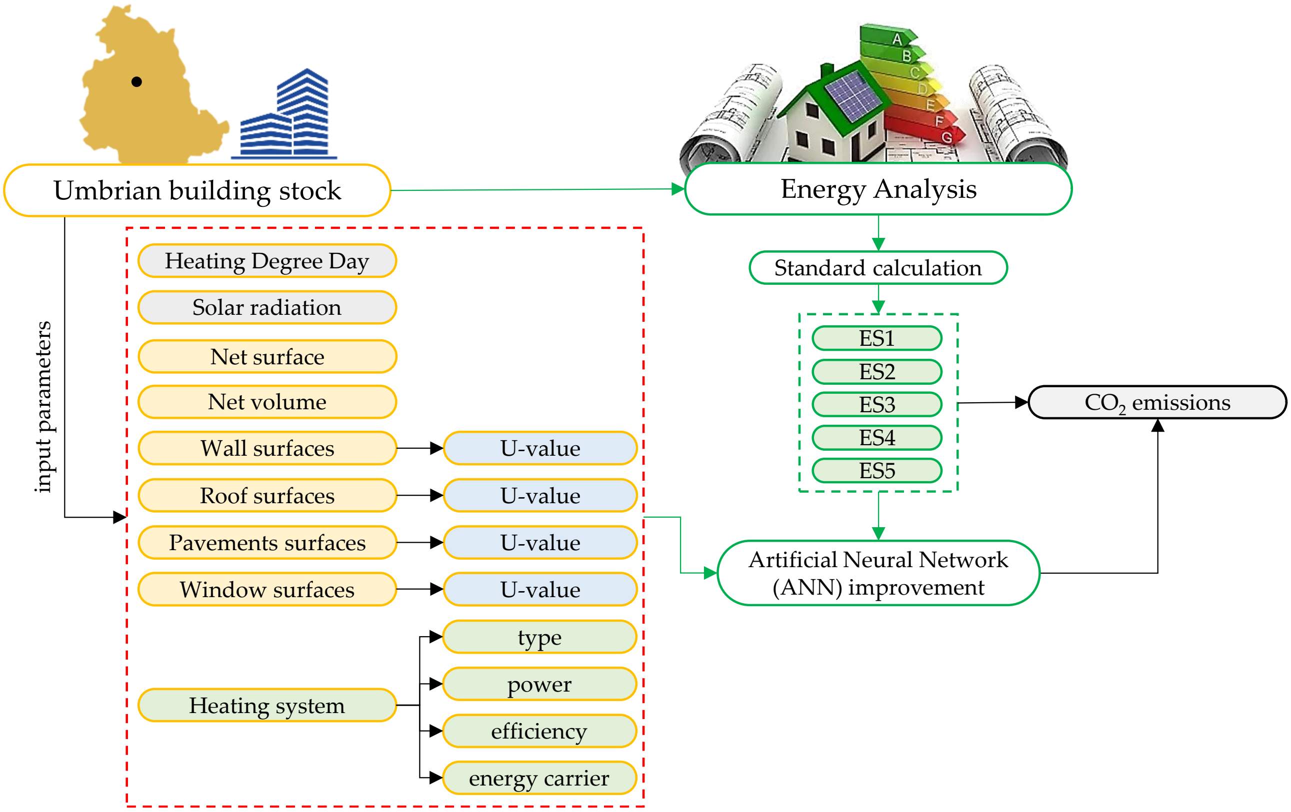


Figure 7. Methodological approach for the artificial neural network application.

Table 6. Conversion factors in CO_2 emissions (kg/kWh) for the main energy carriers used in the Umbria Region [48].

Energy Carriers	Conversion Factor
diesel	0.28
g.p.l.	0.24
electricity	0.46
natural gas	0.21
biomass	0.05

2.2.3. Energy Consumption of Umbrian Building Stock

Since official data are missing, in accordance with a previous study [22] where the reliability and accuracy of the standard calculation were highlighted when the comparative analysis was performed, energy simulations using the standard calculation method (EPC) of the archetypes of the Umbrian building stock were carried out, allowing the energy consumption estimation due to solely heating.

Based on the Umbrian building stock characterization, in terms of the number of building units and buildings, thermal properties of the building components, year of construction, and heating systems, the theoretical energy consumption for heating was assessed by means of the standard calculation method, i.e., adopting monthly energy balance, as described in the national regulations [42–46], and by using standard climate and operational conditions. Energy consumption outcomes were reported in Figure 8 for a fixed range of heating degree days (ordinate axis on the left), distinguishing the building type (SFH, MFH) and highlighting the number of building units for each range (ordinate axis on the right). This analysis pointed out that the theoretical energy consumption of the residential building stock (associated with 2010–2011 since data from ISTAT are related to this period) could have been around 8000 GWh, corresponding to around 1.87 million of CO_2 emissions (value assessed considering the energy carrier mix found in Umbria in 2010, described in previous Section 2.1, and by taking into account the conversion factors provided by the official gazette of the Umbria Region reported in Table 6).

Although slightly different from the value recorded in 2010 (about 0.21% in relative terms; see Section 2.1.3), this value and the energy simulations were considered reliable and usable for the present comparative analysis.

Moreover, according to Figure 8, the following assumption was also made: all the scenarios may have to take into account the redevelopment of 40% of SFH and 60% of MFH since SFH consumes around 35–40% of total energy consumption for heating.

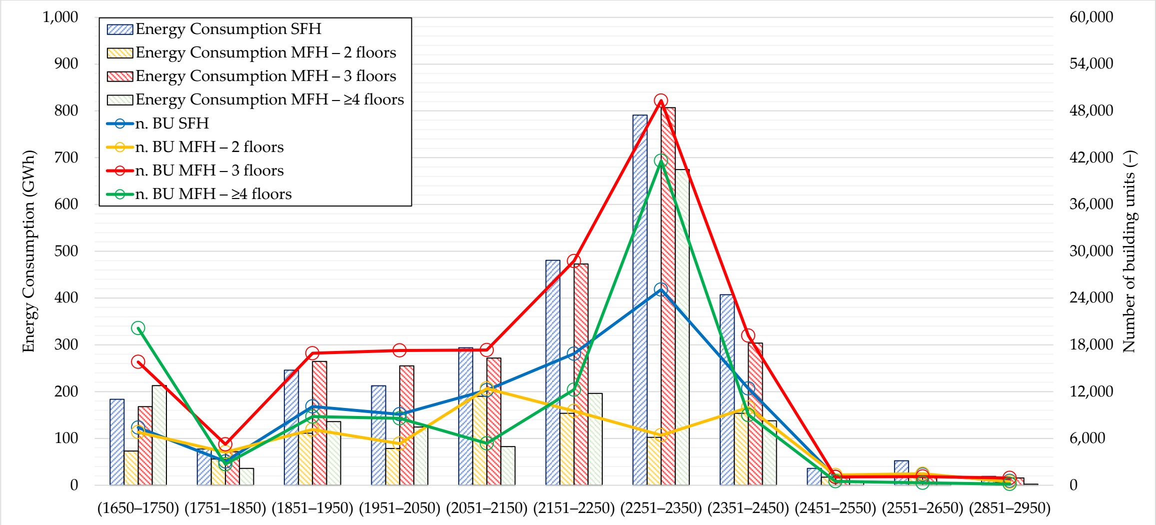


Figure 8. Energy consumption of the Umbrian residential building units (BU) calculated with the standard method (EPC).

2.2.4. Scenario Definition

Several scenarios were thus defined based on the findings of previous analyses (see Section 2.1.2); specifically, the number of interventions for each energy strategy was thus estimated with an increasing or decreasing trend, as shown in Figure 5 for the most widespread energy measures, and a mean energy saving for each energy strategy was calculated. The assessed number of interventions to be implemented in the next years and the mean energy savings for each one, reported in Table 7, were considered for the forecasting analysis.

Finally, the widespread energy strategies that could bring more energy efficiency for the building sector were improved using the artificial neural network. Specifically, the most popular measures—such as the thermal coating on external walls, replacement of existing heating systems with condensing ones, and window replacement—were selected and improved as they provide significant energy savings.

Several possible scenarios were thus defined which differ in limits set for the application of the ANN:

- Scenario 1: it consists of the baseline scenario without improving the energy strategies with the ANN. It was performed by renovating 40% of SFH and 60% of MFH on the basis of the estimated energy consumption of existing buildings (see Section 2.1.3);
- Scenario 2: all the energy measures were implemented as in scenario 1, but the thermal coating action was improved with the ANN; i.e., it was implemented on the buildings chosen by the ANN based on their energy consumption;
- Scenario 3: all the energy measures were implemented as in scenario 1, but both the thermal coating and window actions were improved with the ANN (not necessarily implemented in the same buildings);
- Scenario 4: all the energy measures (thermal coating, windows, and condensing boiler replacement) were improved with the ANN but not necessarily implemented in the same buildings;
- Scenario 5: all the energy measures were improved with the ANN and implemented in the same buildings (as long as possible); i.e., one existing building is renovated with all of them (thermal coating, windows, and condensing boiler replacement);
- Scenario 6: all the buildings to be renovated were chosen by the ANN without limits.

Furthermore, all the defined scenarios were investigated in three different national energy policies hypothesized in this work:

- Policy 1: it was assumed that the Superbonus incentive may conclude at the end of 2023;
- Policy 2: it was assumed that the Superbonus incentive may conclude at the end of 2024;
- Policy 3: it was assumed that the Superbonus incentive may conclude at the end of 2025.

Table 7. Number of interventions and the energy savings (kWh/intervention) adopted for the forecasting analysis.

Energy Strategies	**Number of Interventions (-)**								**Mean Energy Savings (kWh/Intervention)**
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	
Thermal coating	357	346	335	325	316	306	297	288	8646.0
Windows	2755	3103	3495	3936	4433	4994	5625	6335	1279.4
Solar collector	172	153	136	121	108	96	86	76	3223.0
Solar shading	874	1120	1435	1840	2357	3021	3871	4961	224.0
Condensing boiler	3034	3215	3407	3611	3826	4055	4297	4554	1593.7
Heat pump	1820	1918	2021	2130	2244	2365	2493	2627	1336.5
Building automation	54	62	72	82	94	108	124	143	1320.9

3. Results and Discussion

3.1. CO_2 Reduction as a Result of Energy Measures

As stated, the forecasting analysis started in 2022 since official data are provided until 2021. Due to the unavailability of the number of interventions implemented in 2022, the same one found in 2021 was assumed.

The energy consumption of the whole residential Umbrian building stock was thus assessed as well as the energy savings due to the implementation of the energy efficiency actions, and the CO_2 reduction concerning the 2005 value was assessed. The first comparison, reported in Figure 9, is concerned with only energy strategies in the three adopted energy policies without considering ANN improvement. It is worth noting that these outcomes could represent the more probable trends for the Umbrian building stock.

A first relevant finding can be pointed out: an important CO_2 reduction compared with the 2005 value seems to be achieved in Umbria. The estimated reduction in 2021 could be around −25% compared with −23% recorded in 2010. The current energy policy of Superbonus 110 implemented to further reduce the CO_2 emissions of the building stock could allow getting close to the 2030 target (reduction of 27.4 ÷ 28.3%) but not achieving it. Furthermore, it is worth noting that the extension of the current energy policy (Superbonus) could allow significantly increasing CO_2 reductions, although the goal (reduction of 33% for the residential sector) could not be reached by intervening only in the heating of buildings even by extending this fiscal deduction until 2030. In fact, it was found that each year of the incentive extension results in an average annual reduction of 0.6%.

The found trend makes it possible to underline that the application of specific energy incentives without setting any kind of limit (for instance, on the energy consumption or the year of construction of the existing buildings) may not allow achieving the ambitious target fixed for the residential sector by 2030 by intervening only in the heating service. Other energy efficiency solutions could be implemented in addition to the ones adopted in this work, such as the replacement of the existing boiler with a heat pump or the installation of photovoltaic panels, but they could not be always feasible, as shown in a recent work [49]. In addition, it is worth noting that this type of intervention is poorly suited to the Umbrian building stock needs, limiting its effectiveness. Nevertheless, the found trends confirmed the need for other energy incentive systems or optimization of the existing ones by introducing focused limits.

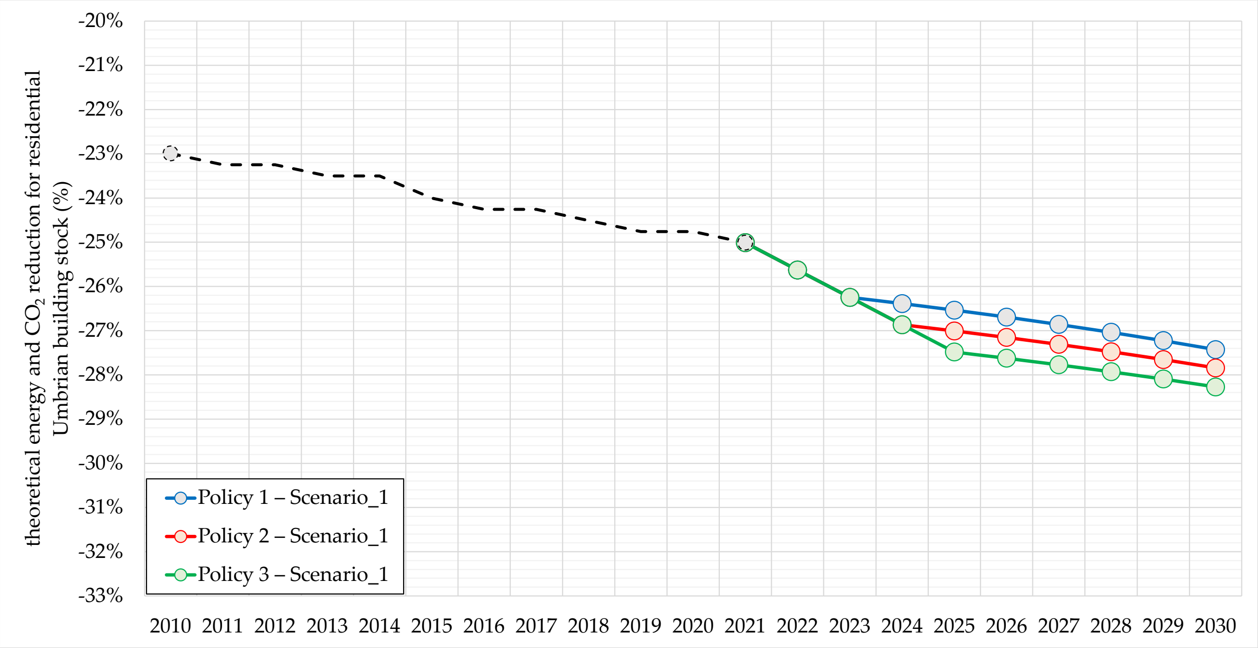


Figure 9. Energy and CO_2 emission reductions in the three considered energy policies.

3.2. CO_2 Reduction as a Result of Energy Measures Improved with the ANN

The energy consumption of the whole residential Umbrian building stock was thus assessed, and the energy savings due to the implementation of the energy efficiency actions improved by using the ANN, and the CO_2 reduction concerning the 2005 value was assessed. Results are shown in Figures 10–12, distinguishing for each considered energy policy and for the adopted energy actions improved with the ANN (from scenario 2 to scenario 5).

Interesting insights can arise from these figures; as already stated in the previous work, the use of the implemented ANN could allow further increasing the energy savings for each selected energy strategy (thermal coating, windows, and replacement of heating system with condensing boiler) of a variable percentage, depending on the type of intervention. From scenario 2 (thermal coating) to scenario 5 (concerning all the energy measures), i.e., the ones where limits on the ANN application have been set, the ANN was capable of increasing energy efficiency by 10%–18%, depending on the energy scenarios. More in detail, the thermal coating on external walls (scenario 2, blue lines in the figures) is the measure on which the ANN can have the greatest impact, allowing for achieving the goal as early as 2029 (policy 1—Figure 10), 2027 (policy 2—Figure 11), or 2025 (policy 3—Figure 12).

In the national energy policy 1, i.e., the one where it was assumed that the Superbonus ends in 2023, the ANN would not allow reaching the CO_2 targets by 2030 in all the other scenarios (from 3 to 5) due to their lower influence on energy savings, although scenario 4 would come remarkably close (−32.8%). On the other hand, in the other two national energy policies, i.e., the ones where it was assumed that the Superbonus ends in 2024 or 2025, the ANN might be capable of achieving the CO_2 target also with the other energy scenarios but only by 2030 (policy 2—Figure 11) or 2028–2029 (policy 3—Figure 12).

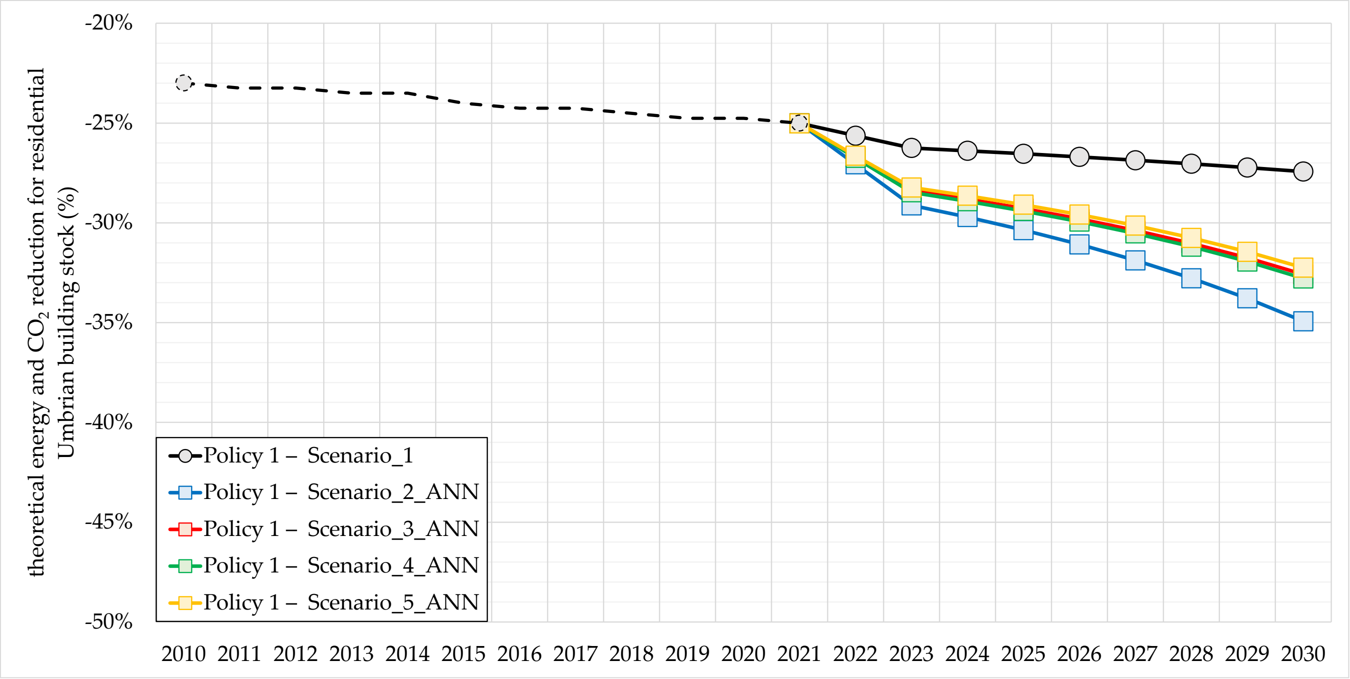


Figure 10. Energy policy 1: comparison of the energy and CO_2 emission reductions in the different scenarios.

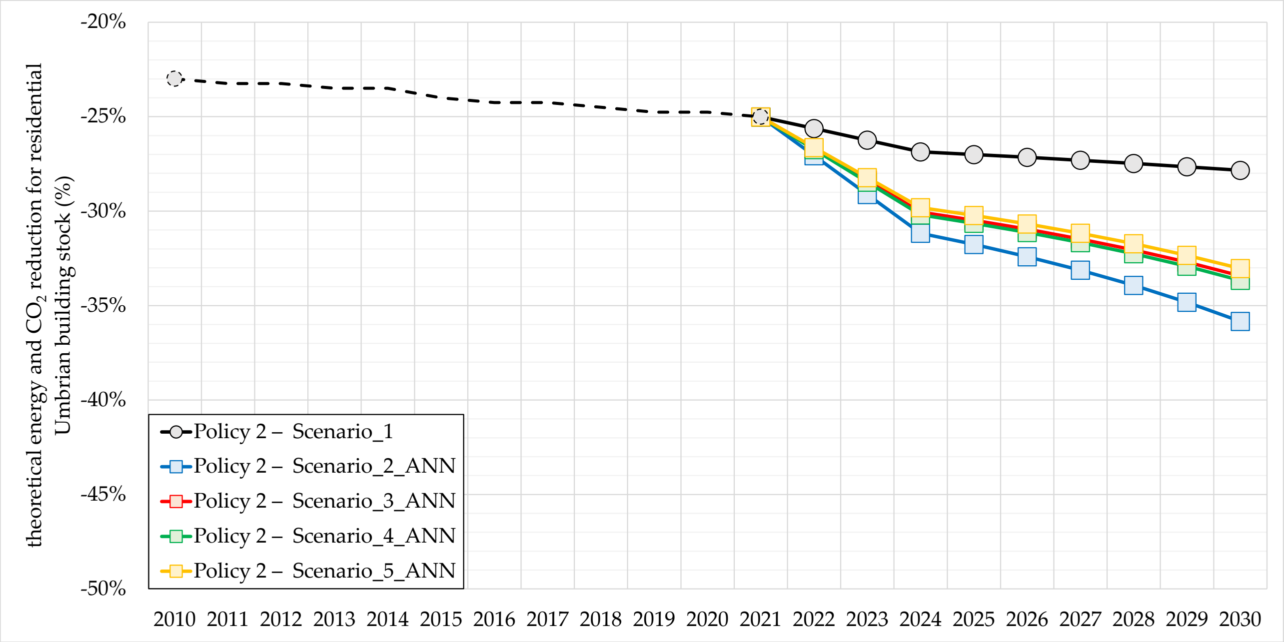


Figure 11. Energy policy 2: comparison of the energy and CO_2 emission reductions in the different scenarios.

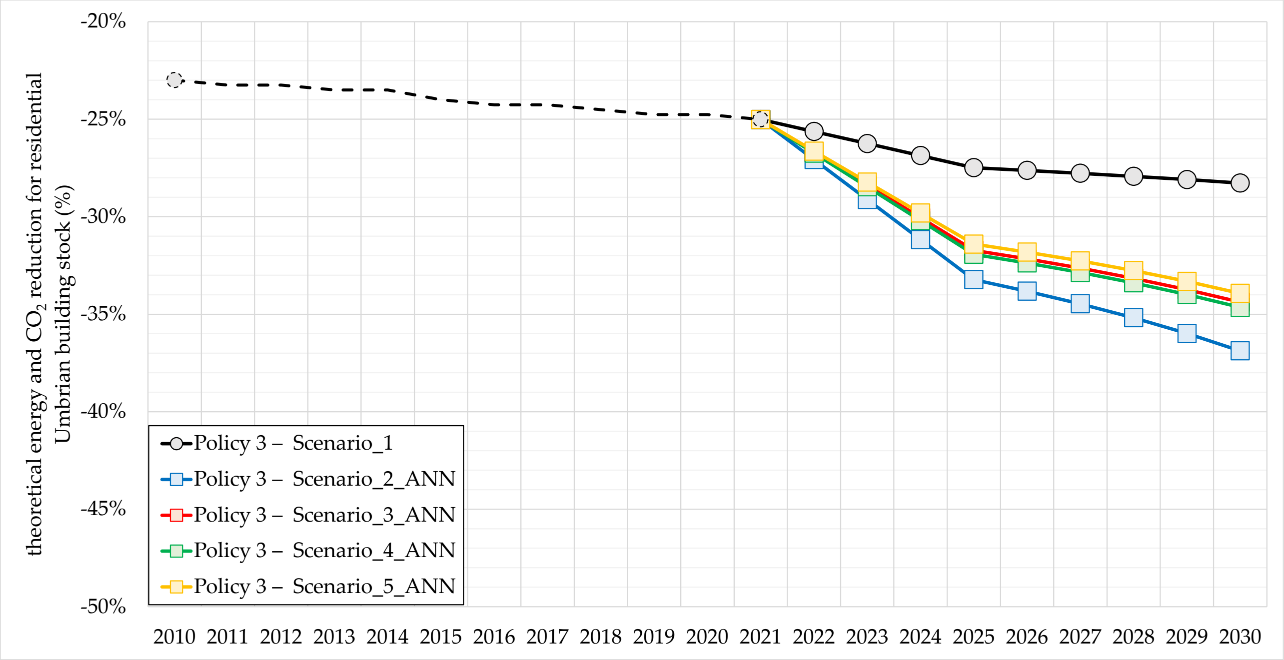


Figure 12. Energy policy 3: comparison of the energy and CO_2 emission reductions in the different scenarios.

In addition, another interesting and well-known outcome can also be remarked: scenario 5, i.e., the one that includes all the energy efficiency actions in the same buildings, involves smaller energy savings. This trend is due to the energy balance of buildings. Energy measures can be divided into two main categories: interfering and noninterfering interventions. In other words, each interfering energy action can affect the energy savings of other energy measures, leading to a reduction of the same. This is what happens in scenario 5, where the implementation of all the energy actions in the same building leads to an energy improvement of the same, but lower energy savings in the Umbrian context.

This trend is remarkable in all the considered national policies, pointing out, probably, from the point of view of a common target, the lower energy convenience in the implementation of different interfering actions in the same buildings. In addition, it is worth noting that the ANN is more able to improve energy savings if the actions are not interfering with each other or if they are implemented in different buildings. This finding could also indicate the need for a further improvement of the ANN to optimize the interfering interventions.

Furthermore, as also highlighted in a previous study, the ANN allows obtaining greater energy savings for the scenario related to the replacement of the existing boiler (around 115–154 GWh in 8 years, depending on the considered energy policy) than the window one (around 110–117 GWh in 8 years, depending on the considered energy policy) due to the worse efficiency of existing heating systems.

Regardless of the energy policy, the use of the ANN could allow reaching the goal of CO_2 emissions before 2030, highlighting a further convenience in the use of the ANN as a support tool for medium-to-long-term forecasting analysis of energy efficiency strategies in the Umbria Region.

Finally, the last energy scenario (scenario 6) was analyzed; in this case, no limits were set to the ANN, allowing for the optimization of choosing buildings; i.e., the buildings to be renovated were indicated by the ANN on the basis of the estimated energy consumption from the ANN itself. The comparison of this last scenario is shown in Figure 13 in all the adopted national policies concerning the outcomes returned by applying the same energy strategies without ANN improvement.

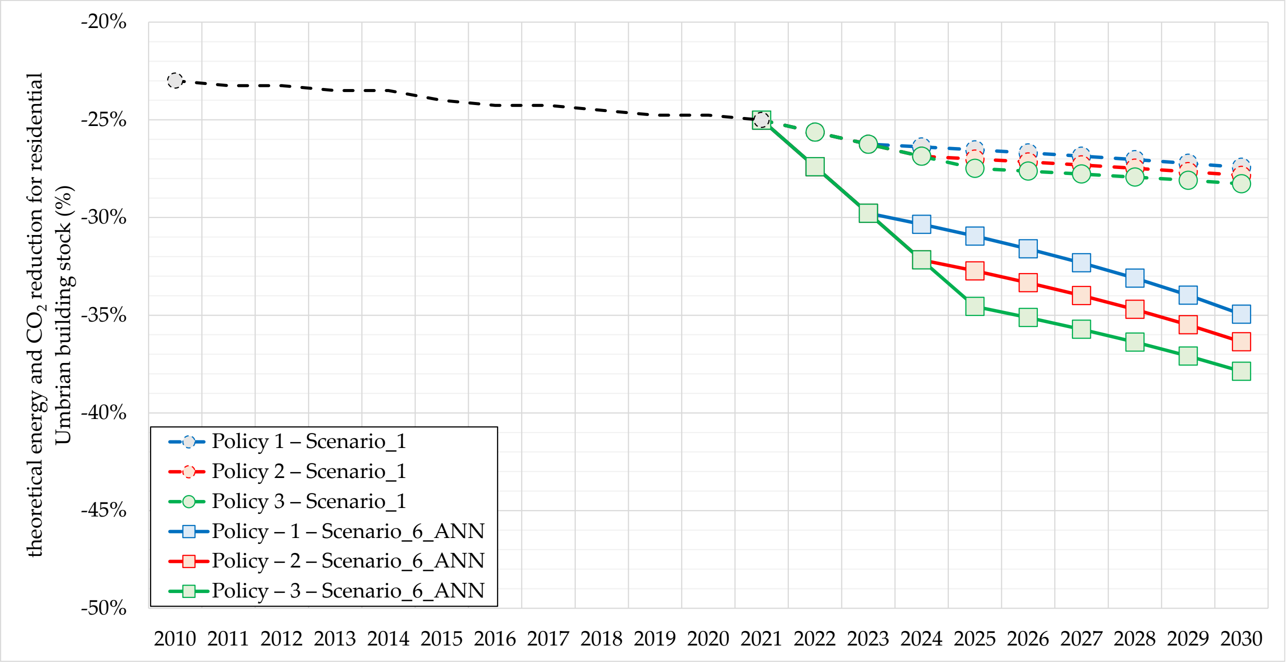


Figure 13. Energy policy comparison: energy and CO_2 emission reductions in scenario 6.

As already stated, scenario 1 would not be able to achieve the regional target; on the other hand, the ANN could allow already reaching it by 2025 if the current energy incentive ended in 2024.

Compared with the previous scenarios (from 2 to 5), scenario 6 would allow for further reducing the emissions of the building stock of around 0.7% on average (corresponding to more than 200,000 t_{CO2}), resulting in the best energy scenario to be implemented. However, the accuracy and the convenience of this last scenario is significantly affected by the energy policy; particularly, in the case of energy policy 1, little difference can be found between scenarios 1 and 6 (Table 8), indicating that the trained network is not able to optimize the energy measures in such a short time. Conversely, if the fiscal deduction is maintained for a long time (such as in energy policy 3), the ANN could be able to decrease the CO_2 emissions by about 1.5% point more.

According to these results, the achievement of the regional target in CO_2 reduction by 2030 in the residential sector seems that it could not be reached by intervening only in the heating service with the current energy policy. Nevertheless, as it is the most energy-intensive service for the residential sector, it is essential to implement energy measures to reduce the energy needs for heating the building stock. However, without the use of more focused energy strategies, it seems that a further reduction of 5% could be achieved compared with the values recorded in 2010 (recorded in −23%). On the other hand, the integration of the current energy strategies with the trained artificial neural network could allow achieving the ambitious target as early as 2025 (without setting limits to the ANN and if the current energy policies were extended until 2025) or 2029 (setting focused limits to the ANN and if the current energy policies were not extended beyond 2023). Furthermore, the integration of the ANN into the implementation of national or regional energy policies or energy strategies would seem to improve the achievable outcomes.

Anyway, it is worth noting that the present study was performed on standard analysis and taking into account only the heating, being the most energy-intensive service. These assumptions can also represent the limitations of the work, opening up for interesting future developments, such as analysis where all the energy services are taken into account or more accurate calculation methodologies can be used.

Table 8. Energy scenarios with artificial neural network comparison: increase in CO_2 emission reduction (%) compared with scenario 1.

ANN	Policy 1	Policy 2	Policy 3
Scenario 2	10.34	11.58	13.02
Scenario 3	7.10	8.27	9.58
Scenario 4	7.38	8.59	9.95
Scenario 5	6.64	7.73	8.96
Scenario 6	10.37	12.30	14.39

4. Conclusions

The building sector covers a key role in addressing climate and environmental challenges since it is one of the major energy consumers in Europe. To achieve the new ambitious European goal, i.e., a greenhouse gas emission reduction of 55% at least by 2030 and climate neutrality by 2050, it is essential the focused energy measures implementation aimed at reducing the consumption of buildings.

In this framework arises the present work focusing on evaluating the effects of the current energy policies on the residential building sector in the regional context to highlight issues and potentialities and check the feasibility of achieving the ambitious targets fixed by 2030.

The study was performed by characterizing the residential building stock of the Umbria Region, chosen as a case study, and carrying out parametric energy simulations to assess the current energy consumption and CO_2 emissions for heating, as it is the most energy-intensive service, according to the standard calculation method, i.e., the one adopted in energy savings assessment in the national fiscal deduction application.

The results suggested that (i) the current energy strategies, such as Superbonus 110, may not be enough to achieve the 2030 target of reducing CO_2 emissions in the Umbrian residential buildings, allowing for reaching (ii) the maximum of around −28% on the basis of the extension of the current energy strategies.

Furthermore, the implementation of more energy strategies on the same buildings allows for increasing the energy savings of the same (as already known), but it may not be convenient from the point of view of a common target, as interfering actions in the same buildings entail lower energy savings overall.

Nevertheless, the integration of the energy strategies with the artificial neural network (ANN), trained in a previous work for the Umbria Region, could allow for greater energy savings in all the investigated scenarios. In this case, the ambitious target could be achieved in as early as 2025 (without setting limits to the ANN and if the current energy policies were extended until 2025) or 2029 (setting focused limits to the ANN and if the current energy policies were not extended beyond 2023). Hence, the use of the ANN in the national energy strategies' implementation would seem to improve the achievable outcomes, confirming its essential support for the optimization of medium-to-long-term energy efficiency strategies in the Umbria Region. This result could open up a new interesting application for the ANN; in fact, it could be used by policymakers to maximize CO_2 reductions while optimizing economic resources. In addition, the use of the ANN for specific energy strategies, such as the thermal coating of external walls, would allow policymakers to define more accurate restrictions for energy incentive systems.

Furthermore, the present study has also highlighted limitations of ANN application, such as the lack of ability to optimize interfering interventions or maximize energy savings and CO_2 reductions when actions are applied in a too short time. The ANN seems to be more able to improve energy savings if the actions are not interfering with each other and when the fiscal deduction is extended for a long time.

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Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

ANN	artificial neural networks
Bf	building floor
BU	building units
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPC	energy performance certification
ES	energy strategies
ISTAT	National Institute of Statistics
MFH	multifamily house
SIAPE	Informative System on Energy Performance Certificates
SFH	single-family house
U	thermal transmittance

Appendix A

Table A1. Number of buildings per number of floors for each municipality of the Umbria Region [32].

City	HDD	Number of Floors				City	HDD	Number of Floors			
		1	2	3	≥4			1	2	3	≥4
Acquasparta	1947	99	832	424	38	Monte Santa Maria Tiberina	2487	45	259	174	15
Allerona	2173	29	238	227	19	Montecastrilli	2076	153	869	372	37
Alviano	1822	63	419	128	9	Montecchio	2051	197	422	197	47
Amelia	2038	297	1640	1030	154	Montefalco	2269	170	1400	345	30
Arrone	1800	169	436	114	33	Montefranco	2047	70	259	106	26
Assisi	2198	505	4523	2472	298	Montegabbione	2446	35	287	162	18
Attigliano	1872	43	260	194	41	Monteleone di Spoleto	2914	61	354	188	8
Avigliano Umbro	2167	291	599	229	40	Monteleone d'Orvieto	2275	74	316	271	37
Baschi	1665	173	761	376	60	Montone	2279	33	267	134	36
Bastia Umbra	1994	128	2130	1255	343	Narni	1802	317	2675	1353	312
Bettona	2149	158	651	190	28	Nocera Umbra	2318	248	900	400	37
Bevagna	2004	206	958	422	33	Norcia	2608	296	1615	414	53
Calvi dell'Umbria	2095	64	678	182	5	Orvieto	1905	531	2210	1441	335

Table A1. *Cont.*

City	HDD	Number of Floors				City	HDD	Number of Floors			
		1	2	3	≥4			1	2	3	≥4
Campello sul Clitunno	2085	122	686	83	3	Otricoli	1745	163	531	144	22
Cannara	1985	82	703	292	72	Paciano	2187	12	192	162	22
Cascia	2452	305	891	192	35	Panicale	2228	101	876	525	101
Castel Giorgio	2382	63	547	168	7	Parrano	2167	59	177	122	13
Castel Ritaldi	2109	57	566	137	35	Passignano sul Trasimeno	2084	74	680	409	113
Castel Viscardo	2287	33	433	390	41	Penna in Teverina	1914	206	127	23	1
Castiglione del Lago	2099	393	2679	964	127	Perugia	2289	831	9840	8920	4599
Cerreto di Spoleto	2355	55	363	177	9	Piegaro	2152	137	828	349	68
Citerna	2277	22	386	369	51	Pietralunga	2364	53	467	344	29
Città della Pieve	2306	196	1082	625	94	Poggiodomo	2910	10	120	103	8
Città di Castello	2347	285	3714	3543	706	Polino	2886	9	124	44	10
Collazzone	2266	102	548	204	24	Porano	2173	26	192	145	22
Corciano	2204	212	1210	1084	376	Preci	2394	131	560	244	15
Costacciaro	2403	10	228	422	16	San Gemini	1978	51	332	394	92
Deruta	2013	136	738	809	205	San Giustino	2132	108	982	1174	123
Fabro	2027	62	368	328	54	San Venanzo	2211	102	600	226	24
Ferentillo	1838	55	399	322	44	Sant'Anatolia di Narco	2124	48	120	103	5
Ficulle	2160	51	319	280	68	Scheggia e Pascelupo	2416	38	335	392	64
Foligno	1899	571	6973	3407	894	Scheggino	2076	27	232	65	7
Fossato di Vico	2382	395	331	229	44	Sellano	2312	75	252	260	47
Fratta Todina	1915	34	338	155	22	Sigillo	2287	50	306	438	77
Giano dell'Umbria	2344	104	663	348	48	Spello	2075	246	1504	470	36
Giove	1896	102	305	252	49	Spoleto	2427	590	5923	1996	654
Gualdo Cattaneo	2243	203	1251	536	34	Stroncone	2186	247	1040	445	63
Gualdo Tadino	2334	187	2551	1484	239	Terni	1650	872	7224	4633	2249
Guardea	2069	107	446	155	17	Todi	2193	313	2292	1693	318
Gubbio	2357	979	4267	3020	604	Torgiano	2014	100	623	505	68
Lisciano Niccone	2109	84	200	31	9	Trevi	2208	178	1375	487	90
Lugnano in Teverina	2127	59	384	178	10	Tuoro sul Trasimeno	2104	93	715	333	63
Magione	2094	387	1971	1015	200	Umbertide	2192	140	1346	1201	459
Marsciano	1978	266	1926	1197	332	Valfabbrica	2084	116	531	329	51
Massa Martana	2262	337	748	309	71	Vallo di Nera	2128	5	97	82	19
Monte Castello di Vibio	2215	58	375	208	16	Valtopina	2162	37	236	131	12

Table A2. Number of buildings per number of building units for each municipality of the Umbria Region [32]: part 1.

City	HDD	Building Units					
		1	2	3–4	5–8	9–15	More Than 16
Acquasparta	1947	785	369	164	65	8	2
Allerona	2173	212	195	83	22	1	0
Alviano	1822	430	149	35	4	0	1
Amelia	2038	1661	825	423	150	54	8
Arrone	1800	294	178	134	106	32	8
Assisi	2198	4255	2103	976	332	94	38
Attigliano	1872	242	198	58	28	12	0
Avigliano Umbro	2167	718	239	152	43	6	1
Baschi	1665	727	437	171	31	4	0
Bastia Umbra	1994	1818	1166	515	177	99	81
Bettona	2149	595	256	118	30	25	3
Bevagna	2004	1012	410	148	34	14	1
Calvi dell'Umbria	2095	550	265	89	22	2	1
Campello sul Clitunno	2085	461	241	141	43	6	2
Cannara	1985	575	371	159	38	6	0
Cascia	2452	737	339	215	82	37	13
Castel Giorgio	2382	391	246	115	28	4	1
Castel Ritaldi	2109	315	315	126	22	16	1
Castel Viscardo	2287	407	324	119	37	5	5
Castiglione del Lago	2099	1982	1335	589	196	54	7
Cerreto di Spoleto	2355	305	171	103	22	3	0
Citerna	2277	433	249	105	33	8	0
Città della Pieve	2306	1062	509	250	126	46	4
Città di Castello	2347	3784	2269	1346	598	179	72
Collazzone	2266	452	252	126	37	9	2
Corciano	2204	938	922	524	314	90	94
Costacciaro	2403	459	169	43	2	3	0

Table A2. *Cont.*

City	HDD	Building Units					
		1	2	3–4	5–8	9–15	More Than 16
Deruta	2013	891	572	230	111	65	19
Fabro	2027	412	211	118	50	16	5
Ferentillo	1838	415	259	116	25	4	1
Ficulle	2160	337	233	118	24	4	2
Foligno	1899	5979	3373	1461	643	275	114
Fossato di Vico	2382	536	296	122	34	9	2
Fratta Todina	1915	292	179	62	13	3	0
Giano dell'Umbria	2344	643	281	145	73	20	1
Giove	1896	412	193	75	22	6	0
Gualdo Cattaneo	2243	1271	519	175	39	14	6
Gualdo Tadino	2334	2559	1328	404	128	31	11
Guardea	2069	419	185	92	24	5	0
Gubbio	2357	4357	2215	1443	623	174	58
Lisciano Niccone	2109	262	37	16	9	0	0
Lugnano in Teverina	2127	424	128	59	16	3	1
Magione	2094	1724	1052	539	180	67	11
Marsciano	1978	1672	1208	557	184	72	28
Massa Martana	2262	884	332	163	70	16	0
Monte Castello di Vibio	2215	414	172	51	14	6	0

Table A3. Number of buildings per number of building units for each municipality of the Umbria Region [32]: part 2.

City	HDD	Building Units					
		1	2	3–4	5–8	9–15	More Than 16
Monte Santa Maria Tiberina	2487	306	136	42	8	1	0
Montecastrilli	2076	775	398	181	60	16	1
Montecchio	2051	551	165	95	44	7	1
Montefalco	2269	1172	567	167	34	5	0
Montefranco	2047	274	139	30	16	1	1
Montegabbione	2446	287	143	59	11	2	0
Monteleone di Spoleto	2914	408	122	69	10	2	0
Monteleone d'Orvieto	2275	430	201	62	5	0	0
Montone	2279	168	151	115	25	11	0
Narni	1802	1895	1508	856	266	90	42
Nocera Umbra	2318	742	449	289	85	15	5
Norcia	2608	1361	596	312	90	17	2
Orvieto	1905	2195	966	732	489	105	30
Otricoli	1745	433	246	136	37	7	1
Paciano	2187	193	111	62	18	4	0
Panicale	2228	771	516	223	59	25	9
Parrano	2167	153	81	104	28	5	0
Passignano sul Trasimeno	2084	520	375	224	110	34	13
Penna in Teverina	1914	185	84	60	20	7	1
Perugia	2289	11,794	4983	3146	2358	1131	778
Piegaro	2152	929	299	109	39	4	2
Pietralunga	2364	465	272	106	23	27	0
Poggiodomo	2910	40	71	88	38	3	1
Polino	2886	89	55	29	13	1	0
Porano	2173	135	82	100	50	18	0
Preci	2394	611	209	111	17	2	0
San Gemini	1978	248	234	239	113	24	11
San Giustino	2132	887	899	435	119	43	4
San Venanzo	2211	547	217	137	47	4	0
Sant'Anatolia di Narco	2124	160	76	33	5	2	0
Scheggia e Pascelupo	2416	468	242	94	17	6	2

Table A3. *Cont.*

City	HDD	Building Units					
		1	**2**	**3–4**	**5–8**	**9–15**	**More Than 16**
Scheggino	2076	142	103	75	7	4	0
Sellano	2312	92	195	243	89	13	2
Sigillo	2287	464	259	121	23	3	1
Spello	2075	1169	778	247	53	9	0
Spoleto	2427	4517	2582	1200	584	206	74
Stroncone	2186	981	546	206	48	11	3
Terni	1650	6224	3852	2305	1275	688	634
Todi	2193	2452	1227	600	218	87	32
Torgiano	2014	525	458	215	69	25	4
Trevi	2208	1149	656	239	75	11	0
Tuoro sul Trasimeno	2104	553	389	178	63	20	1
Umbertide	2192	1208	934	556	332	89	27
Valfabbrica	2084	583	313	99	24	5	3
Vallo di Nera	2128	111	47	31	10	4	0
Valtopina	2162	200	146	50	18	2	0

Table A4. Building units' distribution per construction period (A = before 1976, B = 1977–1991, C = 1992–2005, and D = after 2005) per municipality of the Umbria Region [32].

City	HDD	Construction Period				City	HDD	Construction Period			
		A	**B**	**C**	**D**			**A**	**B**	**C**	**D**
Acquasparta	1947	76.2	14.5	7.7	1.6	Monte Santa Maria Tiberina	2487	84.9	7.2	6.0	1.8
Allerona	2173	52.9	20.6	19.5	7.1	Montecastrilli	2076	52.3	23.0	19.1	5.7
Alviano	1822	70.4	19.1	9.2	1.3	Montecchio	2051	67.8	21.0	8.0	3.2
Amelia	2038	65.7	16.3	12.8	5.2	Montefalco	2269	50.8	23.1	21.6	4.4
Arrone	1800	87.2	8.1	3.0	1.8	Montefranco	2047	78.9	12.4	8.2	0.4
Assisi	2198	68.7	17.1	11.4	2.8	Montegabbione	2446	79.7	13.0	4.9	2.4
Attigliano	1872	65.0	16.0	11.1	7.9	Monteleone di Spoleto	2914	83.6	13.7	2.6	0.1
Avigliano Umbro	2167	63.0	20.3	12.9	3.8	Monteleone d'Orvieto	2275	76.5	15.1	6.5	2.0
Baschi	1665	76.6	11.5	8.9	3.1	Montone	2279	71.6	19.9	8.4	0.1
Bastia Umbra	1994	52.1	24.8	18.7	4.4	Narni	1802	70.2	19.9	8.5	1.4
Bettona	2149	70.1	11.4	11.3	7.2	Nocera Umbra	2318	43.4	13.2	33.0	10.4
Bevagna	2004	70.8	14.0	11.3	3.9	Norcia	2608	66.4	25.7	6.9	1.0
Calvi dell'Umbria	2095	82.4	9.0	7.2	1.3	Orvieto	1905	77.5	11.6	7.8	3.0
Campello sul Clitunno	2085	57.1	26.0	12.8	4.1	Otricoli	1745	58.1	19.3	21.4	1.1
Cannara	1985	64.1	17.9	10.9	7.1	Paciano	2187	79.5	10.4	7.9	2.2
Cascia	2452	53.8	33.6	11.4	1.2	Panicale	2228	69.0	16.7	8.6	5.6
Castel Giorgio	2382	82.9	11.7	4.0	1.3	Parrano	2167	78.3	10.3	8.0	3.4
Castel Ritaldi	2109	58.6	21.2	13.5	6.6	Passignano sul Trasimeno	2084	59.8	21.8	15.4	3.0
Castel Viscardo	2287	77.9	15.8	5.1	1.2	Penna in Teverina	1914	68.0	16.0	10.8	5.2
Castiglione del Lago	2099	68.8	15.0	9.7	6.5	Perugia	2289	60.9	20.4	13.3	5.4
Cerreto di Spoleto	2355	88.2	9.0	2.4	0.4	Piegaro	2152	73.0	12.9	9.4	4.7
Citerna	2277	81.0	10.3	5.6	3.2	Pietralunga	2364	77.4	14.8	6.4	1.3
Città della Pieve	2306	68.1	17.3	10.1	4.5	Poggiodomo	2910	27.8	47.6	22.9	1.6
Città di Castello	2347	63.8	19.4	11.6	5.2	Polino	2886	78.4	17.5	3.2	0.9
Collazzone	2266	49.4	19.4	20.9	10.3	Porano	2173	52.5	37.3	8.6	1.7
Corciano	2204	48.2	22.0	22.6	7.2	Preci	2394	67.4	25.8	6.4	0.5
Costacciaro	2403	73.9	12.6	9.5	4.0	San Gemini	1978	57.4	26.0	11.8	4.8
Deruta	2013	60.0	16.6	13.0	10.4	San Giustino	2132	67.5	15.5	11.9	5.2
Fabro	2027	71.0	16.0	9.9	3.1	San Venanzo	2211	72.8	15.1	9.2	3.0
Ferentillo	1838	83.4	9.0	4.7	2.9	Sant'Anatolia di Narco	2124	87.5	7.1	4.2	1.1
Ficulle	2160	73.8	14.3	6.0	5.9	Scheggia e Pascelupo	2416	79.4	15.7	3.1	1.8
Foligno	1899	63.4	16.7	16.4	3.4	Scheggino	2076	90.2	8.1	1.5	0.2
Fossato di Vico	2382	64.0	16.6	14.8	4.7	Sellano	2312	80.5	3.2	16.1	0.3
Fratta Todina	1915	67.7	14.1	10.7	7.5	Sigillo	2287	76.1	14.2	7.5	2.2
Giano dell'Umbria	2344	65.1	16.1	10.2	8.5	Spello	2075	48.6	24.6	22.7	4.1
Giove	1896	68.8	18.4	9.5	3.2	Spoleto	2427	71.1	14.0	9.5	5.4
Gualdo Cattaneo	2243	69.7	17.2	9.6	3.5	Stroncone	2186	70.6	14.0	11.4	4.0
Gualdo Tadino	2334	60.6	20.9	16.1	2.4	Terni	1650	67.1	17.3	10.1	5.6
Guardea	2069	72.8	13.8	11.6	1.8	Todi	2193	71.4	16.1	7.3	5.2
Gubbio	2357	57.2	28.6	11.2	3.0	Torgiano	2014	58.2	14.9	17.8	9.1
Lisciano Niccone	2109	65.6	14.5	14.5	5.4	Trevi	2208	66.2	18.5	10.0	5.3
Lugnano in Teverina	2127	78.1	12.8	8.4	0.7	Tuoro sul Trasimeno	2104	69.5	17.1	8.0	5.5
Magione	2094	55.0	20.0	17.2	7.8	Umbertide	2192	58.5	23.4	11.4	6.8
Marsciano	1978	60.3	20.5	11.6	7.6	Valfabbrica	2084	74.2	14.7	7.8	3.4
Massa Martana	2262	68.7	11.4	10.0	9.9	Vallo di Nera	2128	55.3	25.1	19.6	0.0
Monte Castello di Vibio	2215	74.2	12.1	10.3	3.3	Valtopina	2162	10.5	17.3	67.5	4.7

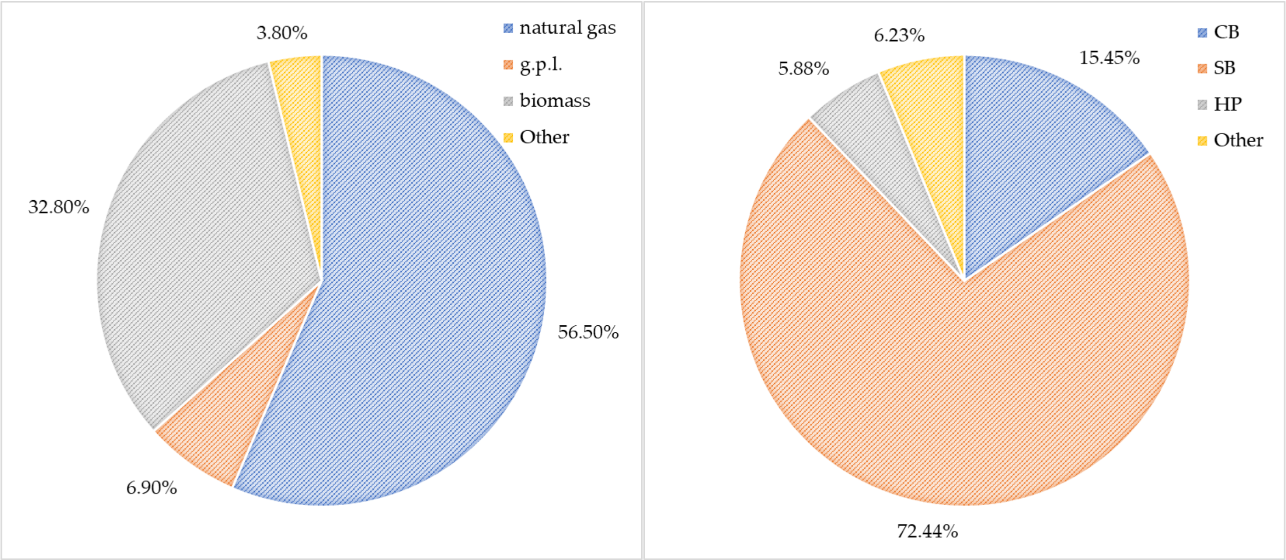

Figure A1. Energy carriers and heating systems (SB = standard boiler, CB = condensing boiler, HP = heat pump) most widespread in the Umbria Region.

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