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Heat Recovery Ventilation in School Classrooms Within Mediterranean Europe: A Climate-Sensitive Analysis of the Energy Impact Based on the Italian Building Stock

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Abstract

In most European school classrooms, ventilation rates fall far short of standard requirements due to an inefficient use of manual airing, creating an unhealthy environment and increasing the risk of airborne viral transmission among occupants. To promote proper Indoor Air Quality (IAQ) levels, the required ventilation could be achieved by considering NV-oriented measures or Mechanical Ventilation systems with Heat Recovery (MVHR) implementation. This study defines a method to evaluate the potential primary energy implications of implementing MVHR in classrooms in the Mediterranean climate in comparison with NV control, selecting the Italian public-school building stock as a case study. Dynamic energy simulations were conducted across reference building construction types, considering locations representative of the national climate variability. Results show that MVHR can reduce primary energy up to 42.31 kWh/m^2. At the national level, it can achieve an attainable annual primary energy saving of 227 GWh, approximately 30% of current classroom consumption, with more than 70% of this potential located in northern provinces. A regression model was also used to relate energy impact to the Heating Degree Days, offering a scalable and transferable tool to support retrofit policies within similar southern European contexts.

Keywords: heat recovery ventilation; school building stock; Mediterranean climate; indoor air quality; building energy simulation; energy policies; GIS mapping

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1. Introduction

Although building ventilation is acknowledged as a key mechanism for diluting and removing indoor air contaminants [1], numerous investigations in the literature still show that insufficient air exchange remains widespread in school classrooms [2–4], leading to negative consequences for both children's wellbeing [5,6] and learning performances [7,8]. According to the most extensive European survey to date, the SINPHONIE project [9], the great majority of classrooms still rely on Natural Ventilation (NV); notably, 86% of the measured airflow rates fell short of the health-based minimum rate of 4 L/s per person set by EN 16798-1 [10].

The SARS-CoV-2 pandemic has renewed concern for Indoor Air Quality (IAQ) in classrooms, as ventilation was identified as the principal strategy for limiting viral transmission [11,12]. To achieve the proper IAQ in classrooms based on the standard requirements, the ventilation rate should be controlled through NV-oriented measures or equipping classrooms with Mechanical Ventilation systems with Heat Recovery (MVHR). Accordingly, several Italian studies have examined NV-oriented measures such as CO_2-based alerting systems [13], automated window controls [14,15], and detailed airing protocols [12,13,16]. Researchers emphasise, however, that these approaches are suitable only when outdoor and indoor temperatures are comparable, generally in spring or during brief summer periods, while they can cause thermal discomfort during the heating season [17,18].

Moreover, NV cannot filter incoming air or recover heat from exhaust air, resulting in increased exposure to outdoor pollutants and higher thermal energy consumption. MVHR, by contrast, can filter pollutants, regulate the airflow rate, enhance thermal comfort and curtail heating loads in winter [19–23]. One of the main practical limitations of MVHR implementation in existing school buildings is related to the architectural constraints and maintenance requirements. However, the growing availability of decentralised MVHR units, installed at the classroom level, overcomes these barriers as ductworks and air shafts are avoided, reducing the invasiveness of the installation and limiting the maintenance operations. Therefore, installation is generally feasible in all existing school buildings, as demonstrated in [24].

Moreover, standard IAQ levels in classrooms would also imply economic savings for national healthcare systems, reducing both short-term medical interventions (such as paediatric visits, medications, and potential hospital admissions for asthmatic complications) and long-term costs associated with chronic pathologies [3]. As highlighted by [25], considering the health impact on the cost-effectiveness analysis of building retrofit interventions could lead to more profitable investments. Indeed, recent estimates suggest that indoor allergens may cost between EUR 0.01 and EUR 22 billion to public health in Europe, depending on the allergen and the exposed population [26]. A significant study has estimated that achieving the recommended ventilation rate in California elementary school classrooms would increase annual state funding to school districts by USD 33 million, while reducing the costs associated with caregiver time by USD 80 million [27]. For this reason, policies should be defined to equip school classrooms with MVHR, considering the health benefits and the related economic savings for the healthcare system, as suggested by the authors of [28,29]. An illustrative example is provided by the Italian region of Marche, where 9 million euros have been allocated to provinces and municipalities to install about 2250 MVHR units in classrooms [24]. These financial incentives were instrumental in overcoming budgetary constraints faced by provincial and municipal authorities; in the absence of direct subsidies and preferential financing terms, many school districts would have been unable to procure and install MVHR technology at the necessary scale.

Nevertheless, recent European policy developments on building energy efficiency primarily focus on the decarbonization of the building stock, trying to reduce emissions from heating and cooling services [26], leading to incentives for interventions aimed at achieving related targets [30,31]. In this sense, the integration of MVHR in buildings is not always attractive enough to encourage local and national authorities to provide financial incentives [28]. Indeed, the implementation of MVHR implies additional electricity consumption [32], which could result in a significant impact on the building's energy balance [33]. Past studies on this topic have indicated that MVHR is energetically advantageous in northern European climates, while in the southern regions, energy savings vary significantly depending on the local climate [34] and building types [35]. However, recent studies conducted in school classrooms located within the Mediterranean climate reveal annual energy savings between 32% [23,36] and 40% [37], comparing MVHR with NV at equal ventilation rates. For this reason, more insight is required to increase awareness of the potential energy savings related to the implementation of MVHR in classrooms located in southern Europe, encouraging the definition of national and local policies.

The novelty of this work lies in providing a method to assess the energy impact related to MVHR implementation in the classrooms of a considered school building stock. The method has been developed with reference to the Italian schools, selected as a case study within Mediterranean Europe, deepening previous research carried out by the authors [38]. Data from the National School Building Database (NSBD) [39], established under Law 23/1996 [40], were processed to determine the distribution of school classrooms across various climate zones and representative construction typologies. Building energy simulations, with and without MVHR, were then performed to quantify and map the primary energy impact at a national scale. The results were used to define a regression model correlating the energy impacts with the Heating Degree Days (HDDs), offering a valuable basis to support MVHR implementation policies within similar contexts.

2. Materials and Methods

2.1. Mediterranean Climate

The European continent, due to its wide extension in latitude, can be divided into the following 8 climates, as reported in Figure 1: Arctic, Boreal, Atlantic, Alpine, Mediterranean, Continental, Anatolian, and Steppic. The Mediterranean climate characterises the Southern part of Europe, which houses countries from Portugal to Turkey, from west to east, respectively. It is a type of temperate climate characterised by warm-to-hot dry summers and mild wet winters due to the presence of the Mediterranean Sea, a semi-enclosed sea between Southern Europe and North Africa.

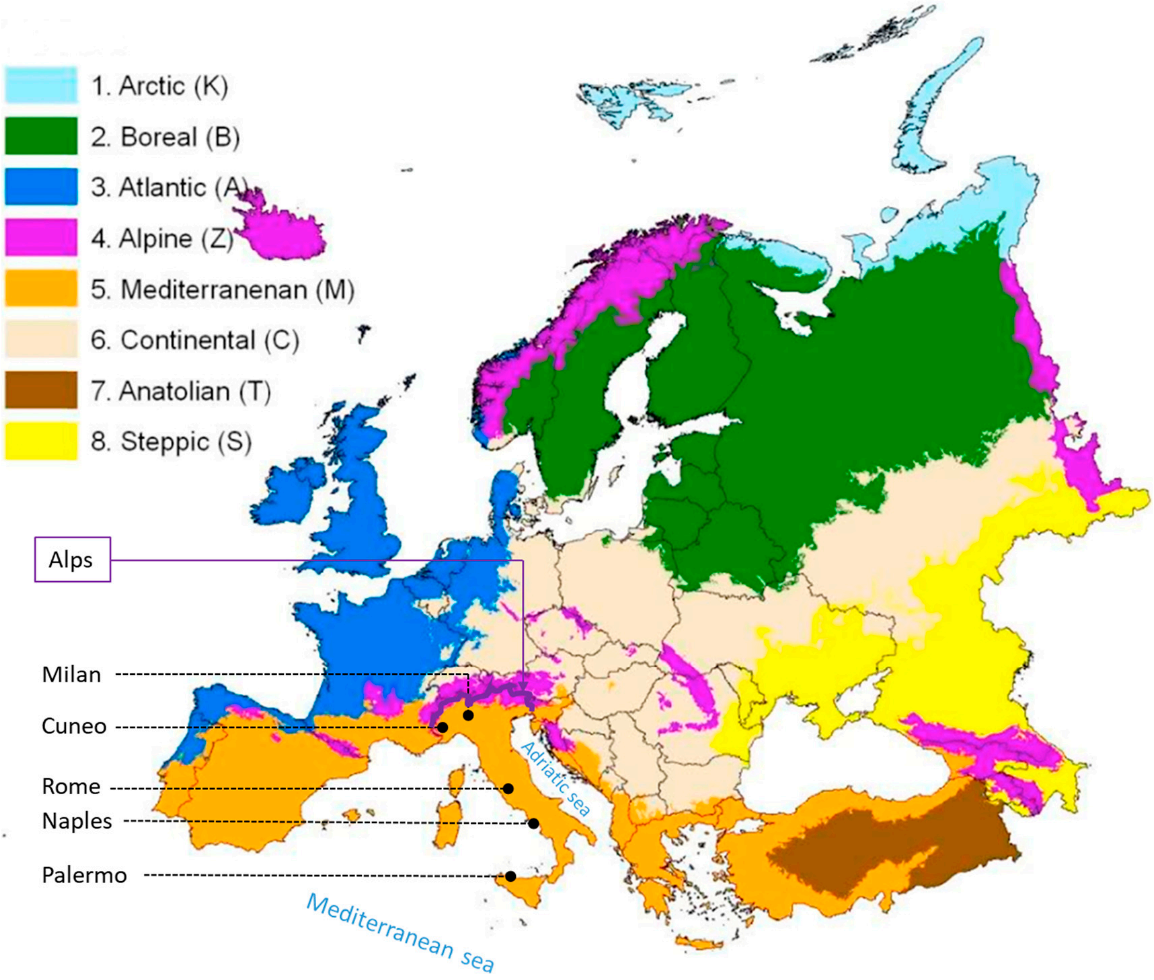


Figure 1. Classification of European climate, from Ref. [41], with further information added by the authors.

Italy, a peninsula projecting into the Mediterranean Sea, is bordered to the north by the Alps, which impose an Alpine climate only on its northernmost areas, while the remainder of the country lies predominantly within the Mediterranean climate. At the national level, Italy is partitioned into six climate zones (A–F) defined by Heating-Degree-Day (HDD) bands that regulate both the heating-season calendar and the building envelope performance requirements of recent constructions [42]. In Table 1, the HDD bands of the Italian climate zone are reported.

Table 1. HDDs of the Italian climate zones.

Climate Zone	HDDs	
	Min	Max
Zone A	$\leq$600	
Zone B	601	900
Zone C	901	1400
Zone D	1401	2100
Zone E	2101	3000
Zone F	$\geq$3001	

2.2. National School Building Stock Background

According to the most recent national survey [43], the country has 40,321 active public school buildings, which contain 339,544 classes and approximately 6.87 million students, with an average of 20 pupils per class.

The NSBD now covers 99% of the stock (except for the autonomous provinces of Trento and Bozen, which compose the Trentino-Alto Adige region), and provides specific information on each school building, such as its location, year of construction, and built volume. However, the registry does not include information regarding the building's thermal characteristics. Therefore, to characterise the widespread school buildings in Italy, the building thermal envelope performances have been assigned based on the location and year of construction of the buildings according to 4 construction types reported in a previous study concerning the characterisation of the Italian building stock [44,45]:

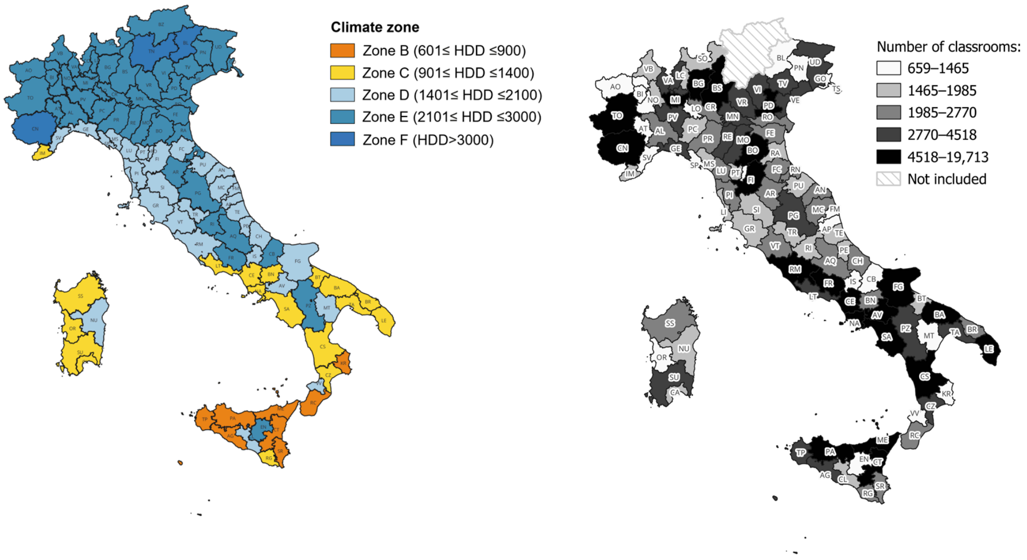
- Traditional building: old buildings, built until the post-war construction boom, made of full bricks or tuff, depending on the construction tradition of the considered region.
- 1960s–1980s Conventional building: refers to buildings built during the period of the most extensive urbanisation in Italy, characterised by walls made of two layers of hollow bricks with an air gap in between.
- 1960s–1980s Largely Glazed building: the largest urbanisation period was also characterised by prefabrication techniques [46], with exterior walls made of insulated sandwich panels and large windows occupying the entire space between the pillars.
- Recent building: refers to buildings built from 1990, after the introduction of the first national regulation on the energy performance of buildings [47], having walls made of two layers of high-density hollow bricks with different thicknesses of insulating layer in-between, depending on the climate zone.

A three-stage procedure was then developed to quantify the energy impact of installing MVHR in classrooms nationwide. First, the NSBD was processed to determine the number of classrooms per province, climate zone, and construction type. Second, dynamic simulations of representative classroom models were conducted to evaluate the effects of MVHR across the range of climates and building envelopes. Third, the simulated savings were extrapolated to national and provincial scales to estimate the annual primary energy implications of prospective MVHR policies.

2.3. Elaborations from the National School Building Database

Public-school building records were downloaded from [39] and reprocessed to form a bespoke database that links each facility (unique ID) to its municipality, province, construction year, and gross volume. This dataset underpins the estimation of classroom numbers and their spatial distribution by climate zone and construction typology, adopting the categories defined in [44].

Each province was assigned the climate zone most frequently observed among its municipalities by elaborating data from [42]; Zone A was excluded as only two of Italy's 7901 municipalities fall within it, a granularity incompatible with the present large-scale analysis. The resulting provincial climate map was produced with QGIS (Figure 2a) [48].



(**a**) (**b**)

Figure 2. QGIS elaboration [48]: (**a**) classification of Italian provinces based on climate zone, (**b**) classroom distribution at province scale.

As a second phase, the number and volume of school buildings for each province have been assessed based on the construction types reported in [44]. In detail, as shown in Table 2, school buildings of the bespoke database built until 1959, from 1960 to 1989, and after 1989 have been associated with Traditional type, 1960s–1980s type, and Recent type, respectively.

Table 2. Construction type and related age of construction.

Construction Type	Age of Construction
Traditional buildings	Until 1959
1960s–1980s Conventional buildings	Between 1960 and 1989
1960s–1980s Largely Glazed buildings *	Between 1960 and 1989
Recent buildings	From 1990

* assuming 6% of school buildings of the 1960s–1980s period [49].

Finally, the number of classrooms by construction type in each province has been evaluated through the proportion reported in Equation (1) and reported in Figure 2b:

$$No.\ classrooms^{ct\ y}_{province\ x} = \frac{\left(No.Classrooms_{region\ z}\right)\cdot\left(Buildings\ Volume^{ct\ y}_{province\ x}\right)}{\left(Buildings\ Volume_{region\ z}\right)} \quad (1)$$

where $No.classroom^{ct\ y}_{Province\ x}$ is the number of classrooms in province x belonging to construction type y; $\left(No.Classrooms_{Region\ z}\right)$ is the total number of classrooms of region z, adding to the list taken from [43] the missed data of Valle d'Aosta region obtained through direct request (Trentino-Alto Adige remains the only one national region excluded from the present analysis), to which province x belongs; $\left(Buildings\ Volume^{ct\ y}_{Province\ x}\right)$ is the total school buildings volume in province x belonging to construction type y; $\left(Buildings\ Volume_{Region\ z}\right)$ is the total school building volume of region z to which province x belongs. The data obtained from Equation (1) are reported in Figure 3, aggregated at a national level by climate zone and building type, having been assigned to the 6% of schools built between 1960 and 1990 the Largely Glazed construction type [49].

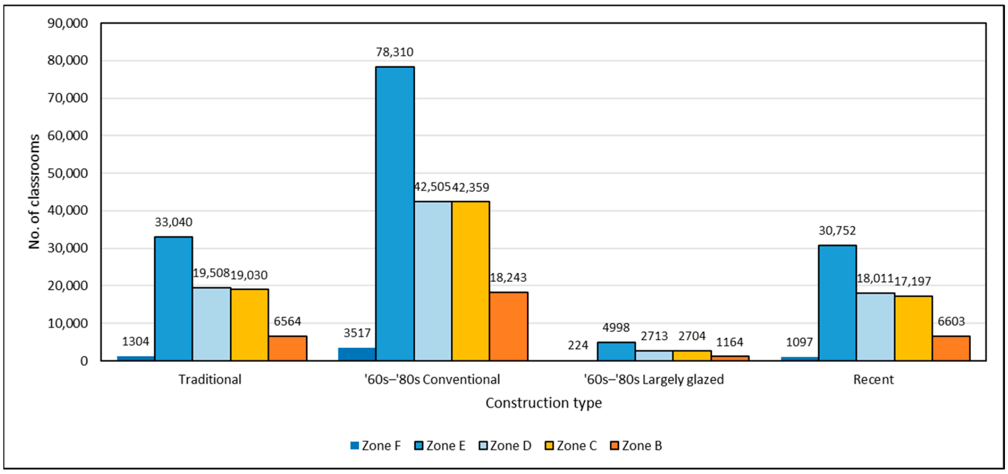


Figure 3. No. of classrooms by construction type and climate zone.

2.4. Energy Simulations

This section details the procedure used to quantify the energy implications of installing MVHR in classrooms across varying construction typologies and climatic contexts. Building energy models, differing in envelope thermal performance and location, were simulated with IES VE [50], comparing the primary energy consumption with NV and MVHR. Five weather files, each linked to a reference city for climate zones B to F, were selected to capture the national climatic variability. The location of the reference cities is reported in Figure 1. The simulation period was set according to a typical annual school calendar. Heating-season boundaries were defined based on the climate zone, as per Italian regulations [42]. Table 3 lists the reference locations and corresponding season lengths.

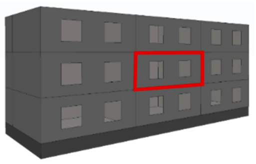
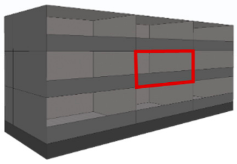
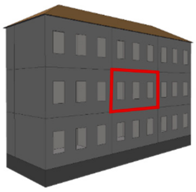
Table 3. Reference cities and related details of the heating season.

Climate Zone	Reference City	HDD	Heating Season
Zone B	Palermo	751	1 December–31 March
Zone C	Naples	1034	15 November–31 March
Zone D	Rome	1415	1 November–15 April
Zone E	Milan	2404	15 October–15 April
Zone F	Cuneo	3012	No Limitations

2.4.1. School Building Construction Models

School building energy models have been defined according to the four construction types described in Section 2.1, assigning the thermal properties of the construction elements as outlined in [44]. As the energy simulations aim to evaluate the energy impact at the classroom scale, simplified models have been defined. Three-dimensional representations of the models, together with the characteristics of the façades, are displayed in Table 4.

Table 4. Three-dimensional representation and facades' characteristics of the representative school building construction models.

Three-Dimensional Representation	Construction Type	Wall Thickness	U-Value (Wall)	Wall Heat Capacity	Window-to-Wall Ratio	U-Value (Windows)	SHGC
		[cm]	[W/(m^{2}K)]	[kJ/(m^{2}K)]	[%]	[W/(m^{2}K)]	[-]
	Recent conventional building	34.0	0.36	260	23	2.14	0.63
	1960s/1980s Conventional building	35.0	0.98	264	23	2.91	0.76
	1960s/1980s Largely Glazed building	14.0	0.36	53	63	2.91	0.76
	Traditional building	54.0	0.98	587	23	2.91	0.76

In these models, only results related to the middle classroom surrounded by other classrooms connected to a distribution space have been considered. This classroom position has been selected as representative of the most significant number of cases, and it provides conservative results, as it is characterised by the lowest heat loss during the heating season.

The classroom geometry has been designed to represent the most common classroom pattern in the Italian public school building stock, as outlined in the technical literature concerning educational buildings [49,51,52]. For Traditional building models, a rectangular classroom with a floor area of 56 m^2, coupled with a classroom height of 4.5 m, has been considered. For all the other building models, a floor area of 48 m^2 coupled with a floor-to-ceiling height of 3 m has been assumed.

Overall, nine energy models have been defined based on the construction period and location, as reported in Table 5. To extend the outcomes on a large scale, results related to a random orientation have been considered. To this end, each school building model has been simulated in each location, considering the different main orientations (north, south, west, and east), to account for the average results ultimately. Therefore, a total of 36 simulations have been performed.

Table 5. Defined construction models and related locations.

Reference Models	Locations
2 Traditional buildings	Milan, Cuneo Rome, Naples, Palermo
1 1960s–1980s Conventional building	All
1 1960s–1980s Largely Glazed building	All
5 Recent buildings	Cuneo Milan, Rome Naples Palermo

2.4.2. Usage Profiles, Internal Gains, and Building Service Systems Modelling

As the simulations focus on classroom energy use, a representative weekly occupancy profile was established. A conservative schedule assumes that classrooms are occupied from 08:00 to 13:00, Monday through Friday, with no occupancy on weekends. Internal heat-gain schedules for lighting, equipment, and occupants follow UNI EN 16798 [10]. Based on the national average class size [43], occupancy was set at 21 individuals—20 students plus one teacher.

The heating system was modelled as a gas-based boiler serving radiators, the configuration most commonly found in Italian schools. The default ApacheHVAC components in IES VE [50] were selected and auto-sized for each construction type and location. System availability aligns with the heating-season dates listed in Table 3, and the operative set-point temperature was fixed at 21 °C, as prescribed in [42]. To achieve this set point at the start of occupied periods, the system was programmed for preheating before occupancy begins.

Natural and Mechanical Ventilation System Configuration

The ventilation rate design was set according to the Italian Regulation (D.M. 09/2022 [53]) to ensure proper IAQ. The Regulation prescribes the indoor environmental category II and low-pollution building of the European Standard UNI EN 16798 [10], which applies to both NV and MVHR systems. Thus, based on the considered category, 7 L/(s pp) and 0.7 L/(s m^2) for school classrooms were applied through the equation provided by method 1 of the Standard.

In the case of MVHR, a single unit was assumed in each classroom as a widely adopted solution for classroom retrofit due to its low invasiveness. An internal specific fan power (SFP$_{\text{int}}$) of 690 [Ws/m^3] was assumed, in line with the average value estimated from recent typical commercial dual flow heat recovery units [54–56]. A function profile was set to define the supply air temperature based on the hourly outdoor temperature, considering a heat recovery efficiency of 73% (the minimum seasonal efficiency required for a heat recovery unit, as per UE n. 1253/2014 [57]). Equation (2) reports the function profile used:

$$t_s = 0.73{\cdot}t_a + 0.27{\cdot}t_o \tag{2}$$

where t_s is the air temperature entering the classroom [°C]; t_a is the exhaust air temperature [°C] (equal to the indoor air temperature); and t_o is the hourly outdoor temperature [°C].

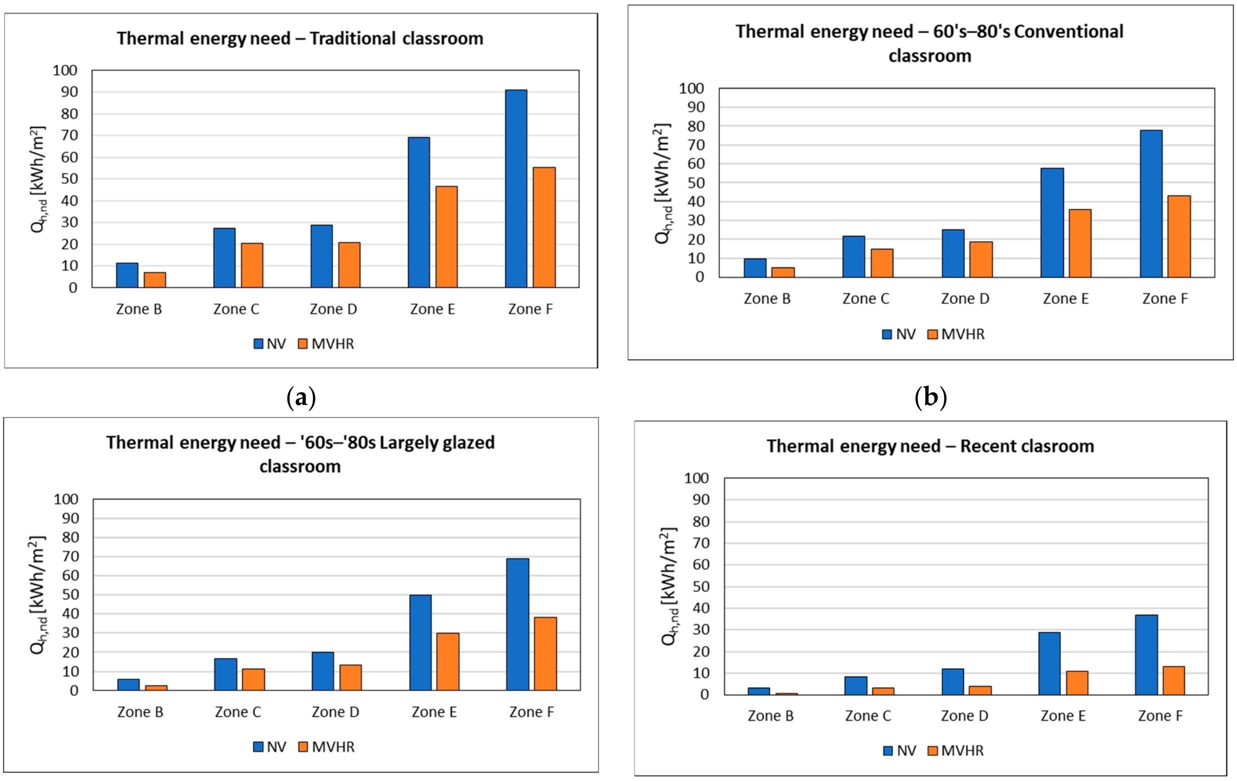
3. Results and Discussion

In this section, the potential energy impact associated with the adoption of MVHR in Italian public school classrooms is reported and discussed. Firstly, the results of the energy simulations are presented, highlighting the different energy impacts based on construction type and climate zone. Then, the extension of the results to the national and provincial scales are provided to cover possible retrofit policies.

3.1. Thermal Energy Needs Savings

In Figure 4, the thermal energy needs $Q_{h,nd}$ of the reference classrooms were reported, comparing the NV and MVHR configurations. The energy savings provided by the MVHR system, thanks to heat recovery, are primarily influenced by the HDDs, resulting in greater thermal energy reductions in colder climates than in warmer ones.

On the other hand, considering the same climate zone, the amount of recovered energy decreases as the thermal envelope performance increases, i.e., moving from Traditional to 1960s–1980s Conventional, to 1960s–1980s Largely Glazed, and finally to Recent buildings. However, the thermal envelope performance is a smaller influencing factor than climate.



(**a**) (**b**)

(**c**) (**d**)

Figure 4. Thermal energy needs in classrooms with NV and MVHR systems: Traditional building (**a**), 1960s–1980s Conventional building (**b**), 1960s–1980s Largely Glazed building (**c**), Recent building (**d**).

For example, considering the Traditional building construction type, the thermal energy needs reduction goes from 4.3 kWh/m^2 to 36.0 kWh/m^2 moving from zone B to zone F, while for the same climate zone, e.g., zone F, there is a reduction of 24 kWh/m^2 to 36.0 kWh/m^2 moving from Recent buildings to Traditional building.

3.2. Primary Energy Density Impact

The transition from NV to MVHR has an energy impact that is influenced by three factors: (i) the variation of the thermal energy input on the heat generator $\Delta q_{H,\,g,in}$; (ii) the variation of electrical energy absorbed by the water loop pump of the heating system $\Delta e_{el,\,d,\,in}$; and (iii) the increase in electricity consumption relating to fans $e_{el,\,f,\,in}$. These factors have been evaluated for each construction type in each reference location, in terms of annual primary energy per square meter of classroom floor [kWh/m^2], to define the primary energy density impact Δe_p of MVHR adoption, as given by Equation (3):

$$\Delta e_p = \Delta q_{H,\,g,in} \cdot f_{p,\,tot,\,ng} + \left(\Delta e_{el,\,d,\,in} - e_{el,\,f,\,in}\right) \cdot\, f_{p,\,tot,\,el} \tag{3}$$

where $f_{p,\,tot,\,ng}$ and $f_{p,\,tot,\,el}$ are the primary energy conversion factor for natural gas and electricity, respectively [58].

The primary energy density impact Δe_p related to each reference location is plotted in Figure 5, considering the mean value among the considered construction types. The vertical whiskers delimit the minimum and maximum Δe_p observed among the construction types, thereby conveying the intra-sample spread within the same location.

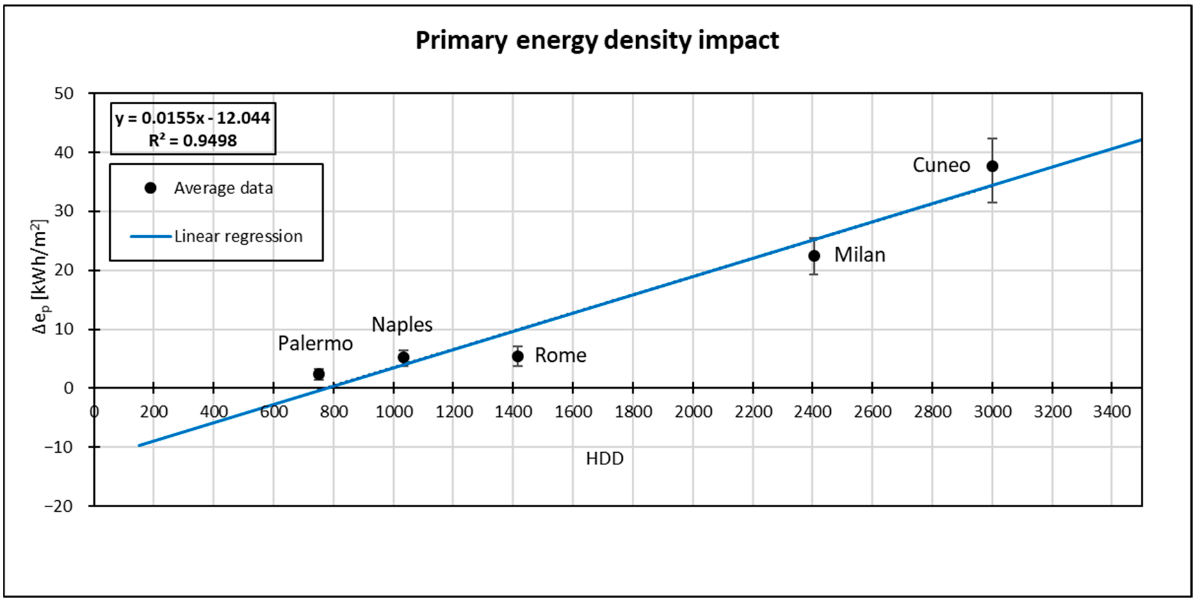


Figure 5. Average classroom primary energy density impact as a function of HDDs.

As shown in the chart, the considered locations exhibit only positive values, indicating that the use of MVHR results in a reduction in annual primary energy consumption. Naturally, the factor that most influences the potential energy saving is the climate zone, which provides an increase as the HDDs increase. As highlighted for $Q_{h,nd}$ (Section 3.1), considering the same climate zone, the primary energy savings decrease as the thermal envelope performance increases. The influence of the construction types on the Δe_p grows with HDDs; in the warmer zones (Palermo, Naples, and Rome) the intra-sample spread reaches a maximum of 3.3 kWh/m^2, while it reaches 10.8 kWh/m^2 in Cuneo, showing that the thermal envelope performance is a smaller influencing factor than climate.

In addition, the sample data were used to build a simple least-squares fit equation (blue line):

$$\Delta e_p = 0.0155\, HDD - 12.004 \quad (4)$$

The coefficient of determination ($R^2 \approx 0.95$) denotes an excellent goodness-of-fit, confirming that HDDs explain ≈ 95% of the variance in primary energy impact within the examined range. The slope (0.0155 kWh/m^2 per HDD) quantifies the incremental energy savings as climate becomes harsher, while the negative intercept implies a threshold at ~780 HDD; below this value, the fitted line predicts a non-positive Δe_p; i.e., MVHR is expected to increase the annual primary energy consumption. The narrow confidence band of the fit up to ≈2400 HDDs and the limited scatter of the empirical points underline the robustness of this relationship expressed by Equation (4); however, the widening error bars at higher HDDs reveal that construction-specific attributes, e.g., building envelope thermal characteristics, become increasingly influential in colder climates. This divergence suggests that, while HDDs account for most of the variance, the thermal performance of the building envelope must also be considered to assess the energy impact of MVHR in classrooms at sites with over 2500 HDDs, where the variation can be as high as ±20%.

3.3. National Primary Energy Impact

The results related to the primary energy density impact discussed in the previous section, coupled with the data elaborated in Section 2.3, have been used to evaluate the potential implications of implementing MVHR across the entire national classroom stock. In this regard, the transition from NV to MVHR reveals a potential to reduce the primary energy consumption related to the national stock by 0.23 TWh.

According to the last available survey on school buildings' energy consumption [59], the national stock has an annual primary energy consumption of 7.3 TWh. Therefore, estimating that approximately 10% of school building volume is associated with classroom space (about 46 Mm^3), a primary energy consumption of 0.73 TWh can be attributed to it, which could therefore be reduced by 30% through the transition from NV to MVHR.

In the subsequent sections, analyses were conducted to disaggregate the national primary energy impact by climate zone, construction type, and provincial territory, thereby supporting the definition of local and national policies.

3.3.1. Climate Zone and Construction Type

The chart in Figure 6 visually represents the annual primary energy that could be saved for each construction type (divided per climate zone) if all the classrooms of the Italian public school building stock were equipped with MVHR.

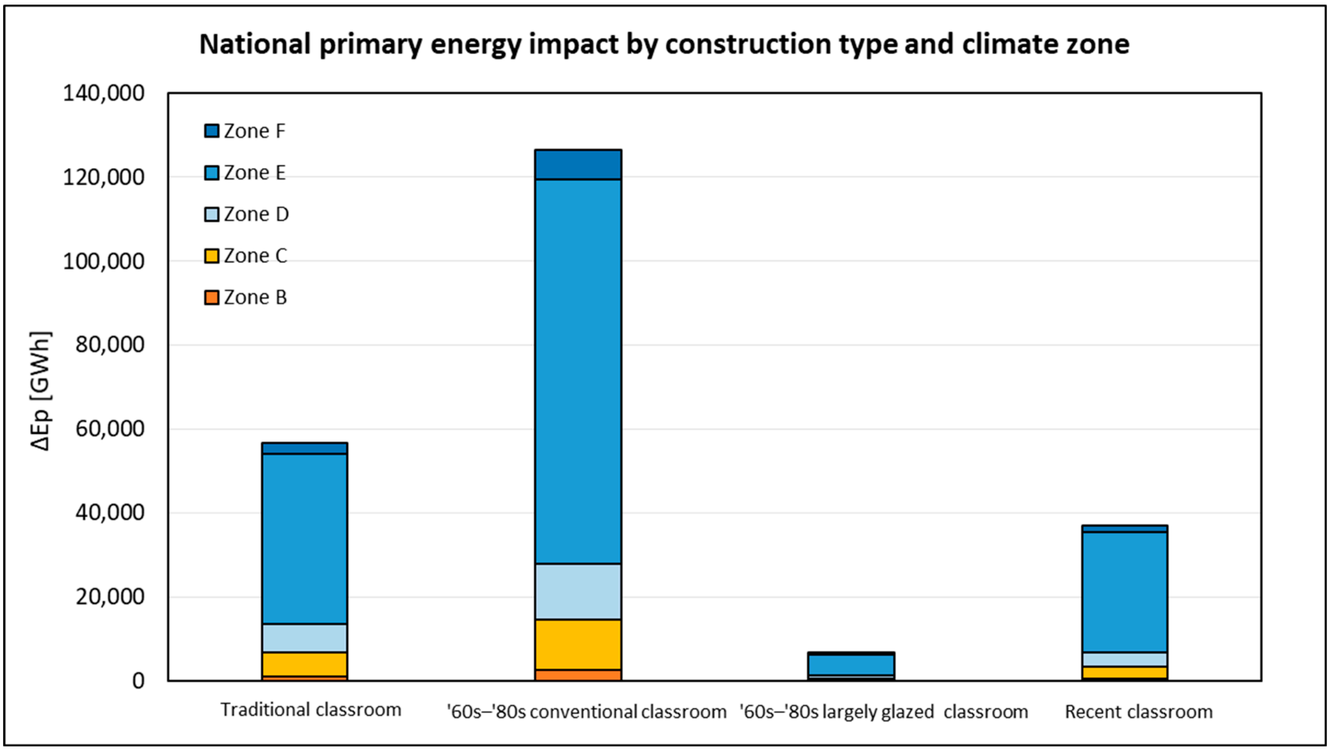


Figure 6. National primary energy impact based on construction type and climate zone.

Within the spectrum of construction typologies, 1960s–1980s Conventional buildings exhibit the most significant scope for lowering national primary energy consumption, offering a projected reduction of 126.46 GWh, which corresponds to 56% of the total theoretical saving. This dominance stems from the fact that classrooms of this category account for approximately 53% of all Italian classrooms. Although the Traditional type yields the highest primary energy density savings per classroom, its aggregate national contribution is minor, estimated at 56.80 GWh, because only 23% of the overall classroom stock falls into this category. Classrooms in Recent buildings, representing 21% of the total, are associated with a projected primary energy reduction of 37.03 GWh. By contrast, the 1960s–1980s Largely Glazed category delivers the least benefit, at 6.77 GWh, reflecting its modest share of the stock (about 3% of national classrooms).

On the other hand, considering the climate zones, Zone E stands out as the most promising zone for energy savings, contributing 165.95 GWh, which is 73% of the total energy saved. The other climate zones present relatively low contributions; zones C and D show similar values, as do the associated numbers of classrooms (23% and 24% of the total), and the related primary energy density savings are also close. Although zone F represents the area with the most severe climate, its associated energy impact is only 5% of the total, as it hosts only 2% of the classrooms. Finally, Zone B shows the lowest contribution, at 2%, due to the lowest primary energy density savings and the smallest number of classrooms (9% of the total).

According to the outcomes reported in this section, national policy planning should be designed to prioritise the integration of MVHR systems in traditional and 1960s–1980s construction types, primarily focusing on school buildings located in climate zone E.

3.3.2. Provincial Scale

To evaluate the spatial distribution of the primary energy impact, ΔE_p, across the Nation, in Figure 7, the energy savings attainable in various provinces of Italy have been reported according to six classes. The map reveals a pronounced north-to-south gradient that closely follows the climate-zone classification based on HDDs (Figure 2a), highlighting three distinct areas.

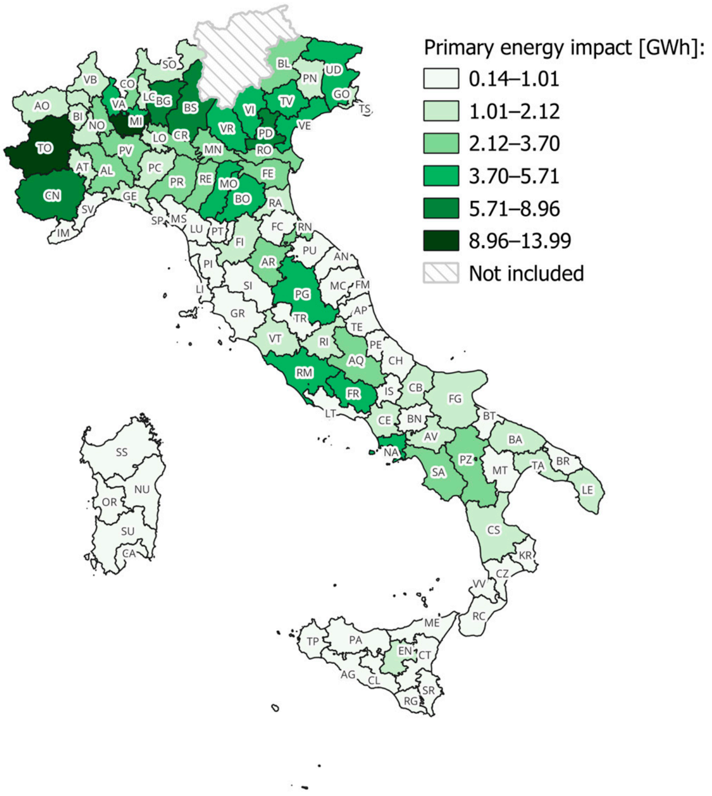


Figure 7. Primary energy impact at a provincial scale, QGIS elaboration [48].

First, a broad northern belt extending from the western Alps to the north-eastern Adriatic, where both the high climatic severity and the dense classroom stock (Figure 2b) produce the highest energy savings, providing more than 70% of the national ΔE_p. Second, a central band with intermediate energy savings on the central strip (due to the climate severity) and low energy savings on the lateral strips due to provinces mainly falling in climate zone D (except for the province of Rome, which has a higher number of classrooms than the average). Third, a southern band (including the islands), which mainly shows energy savings within the two low classes (0.14–1.01 GWh and 1.01–2.12 GWh), despite hosting a number of classrooms comparable with the ones in Northern Italy (Figure 2b).

These spatial disparities highlight the need for a tiered policy framework that allocates resources based on the marginal benefits of deploying MVHR systems. In particular, local policies should prioritise the planning and installation of MVHR systems in provinces along the northern belt, where over half of the national energy savings are concentrated.

4. Conclusions

As manual airing is inadequate to achieve proper IAQ levels in European school classrooms during the heating season, NV-oriented measures or MVHR should be implemented. This work assesses the potential energy impact of adopting MVHR to ensure the European Standard ventilation rate in classrooms located within Mediterranean climates. Italian public school building stock was selected as a case study for this aim. The National School Building Database was used to evaluate the distribution of classrooms across the country according to four representative construction types and five climate zones. Subsequently, dynamic building energy simulations were conducted to assess the primary energy impact of adopting MVHR, highlighting the influence of different building envelope thermal performances and climate zones. Furthermore, analyses were performed at both national and provincial scales to map the potential effects of implementing MVHR in the classroom stock.

Based on the simulation results, a reduction in primary energy density was found for all the representative construction types within the national climate. The HDDs primarily influence the amount of energy saved, while the building envelope's thermal performance has a secondary role. For example, in the case of the Traditional building type, the primary energy density saving ranges from 3.20 kWh/m^2 for zone B to 42.31 kWh/m^2 for zone F, while, within the same climatic zone, e.g., zone B, the saving ranges from 1.47 kWh/m^2 to 3.20 kWh/m^2 moving from Recent to Traditional buildings. Furthermore, a regression equation was defined as a first-order tool to estimate the primary energy impact of MVHR in school classrooms based on specific local HDDs, revealing a limit of approximately 780 HDDs to achieve potential energy savings.

Additional analyses were conducted, extending the primary energy density results to the national classroom stock. As a result, approximately 30% of the primary energy consumption in the classrooms was estimated to be saved by implementing MVHR across the entire stock. Further investigations suggest prioritising MVHR planning policies in provinces within northern Italy, which account for more than 70% of the national savings. Conversely, the potential national savings decrease when moving to the south, in line with the mitigation of climate change.

In conclusion, this research proposes a transferable method for assessing the energy impact of the MVHR implementation in school classroom stock, supporting the definition of national and local policies. Additionally, the outcomes provided by the regression equation could be utilised to preliminarily forecast the energy impact of MVHR in school buildings located in similar contexts.

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Nomenclature

Symbols	Definition
SFP	Specific Fan Power—(Ws/m^3)
t	Temperature—(°C)
$\Delta q_{H,\,g,in}$	Annual variation of the thermal energy input on the heat generator—(kWh/m^2)
$\Delta e_{el,\,d,\,in}$	Annual variation of electrical energy absorbed by the water loop pump—(kWh/m^2)
$e_{el,\,f,\,in}$	Annual fan electricity consumption—(kWh/m^2)
Δe_p	Annual primary energy density variation—(kWh/m^2)
$f_{p,\,tot,\,ng}$	Total primary energy conversion factor for natural gas—(kWh/kWh)
$f_{p,\,tot,\,el}$	Total primary energy conversion factor for electricity—(kWh/kWh)
ΔE_p	Annual primary energy variation—(GWh)
Subscripts/superscripts	
ct	Construction Type
y	Considered construction type
x	Considered Province
z	Considered Region
s	Supply
a	Indoor
o	Outdoor
int	Internal
Acronyms/abbreviation	
IAQ	Indoor Air Quality
MVHR	Mechanical Ventilation system with Heat Recovery
NV	Natural Ventilation
MV	Mechanical Ventilation
NSBD	National School Building Database
HDD	Heating Degree Day
MIUR	Ministero dell'Istruzione, dell'Università e della Ricerca
GSE	Gestore dei Servizi Energetici

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