QUALITATIVE AND QUANTITATIVE GUIDELINES FOR CARBON-NEUTRAL KINDERGARTEN DESIGN IN ITALY

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ABSTRACT

In Italy, when building a new school, there are no regulatory or cultural references that consider recent regulations on energy savings and emissions reduction, key environmental considerations that have received increasing notice in society and new teaching methods needs to address these environmental concerns, especially as related to the built environment. The main goal of this paper is to outline qualitative and quantitative guidelines for building low-carbon kindergartens in Italy. These guidelines will define a new building type for schools while also evaluating energy and environmental performance to create a structured and interdisciplinary support tool that can be used by designers during the preliminary phase of the design process. The method starts from the detailed analysis of representative sustainable buildings to define new typological models, then several energy and environmental analyses follow to evaluate the new building type performance, and finally the guidelines are detailed following the environmental and technological system.

KEYWORDS

low-carbon, schools, sustainability, environmental impact, energy efficiency

1. INTRODUCTION

School buildings are now considered specialist buildings, even if they have limited architectural complexity. Currently, there is no dedicated standards that both consider the new teaching methods employed in modern schools (Montessori 2004; Burke 2005; Smidt 2013; Hall 2014; Baglione 2006) that comply with current international and national legislation in terms of energy and emissions requirements (Commissione Europea 2018; Parlamento Europeo 2018; Governo Italiano 2015). Regarding new teaching methods, Maria Montessori enhanced the centrality of the child, underlined that the school environment must be welcoming and customized to make children feel not only free to move, but also at ease, and invites to educate children through a contact with nature. In line with her philosophy, Francis O'Neill set his primary school according to learning by doing and by contact with the external environment.

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Moreover, Loris Malaguzzi said that the school environment is the third educator for children. It is important to stress that last sizing schools' standard dates to 1975 and since this legislation, the sizing and the internal functional distribution were based on principles included in design manuals of 1954 by Centro Studi for school buildings. As far as energy and environmental performance concerns, the aim of the Paris Agreement is to achieve a carbon-free economy by 2050. Furthermore, the energy and emissions requirements by the European Union expect to reduce greenhouse gas emissions by 40% by 2030 and to meet at least 32% of final energy demand using renewables. Buildings, including schools, are responsible for 36% of global energy consumption and 39% of CO_2 emissions. In Italy most schools (63%) were built before 1973 and have poor energy and environmental performance with many critical issues, mainly linked to poor indoor air quality and thermal-hygrometric comfort, as well as inappropriate technological solutions for the external envelope and improper heating and cooling systems.

This paper aims to define qualitative and quantitative guidelines for the construction of zero-carbon kindergartens in Italy that simultaneously meet the demands arising from both the changes in teaching and pedagogical methods and sustainable construction by assuming the systems and technologies necessary for building construction with low environmental impact. These guidelines, that can be used as a tool by designers, aim to guide the preliminary phase of the design process toward interdisciplinary design choices that consider both the typological aspects that characterize the building type and the most appropriate environmental and energy strategies. Moreover, they can serve as a reference for the necessary evaluations that administrations must carry out for public contracts. Given the changes in the school system, it is essential to configure current building types to support the preliminary design of new buildings. Therefore, new building type for kindergarten is required by outlining the environmental and technological systems and comparing them to energy and environmental quantifications to obtain design indications that are not exclusively qualitative. The purpose of the quantitative evaluations is to propose strategies and solutions that can be used in the design to improve the energy and environmental performance of buildings, concerning the typological factors characterizing the building type (mainly functional/formal and technological/technical characteristics). Therefore, these proposals consider the factors that significantly affect the energy balance and the environmental impact of school building type. For this reason some recommendations in the guidelines can be considered qualitative (for instance, the general characteristics or the external layout arrangement) because they are merely suggestions for the designer for obtaining a good design of a school; otherwise, some indications are quantitative because the choice of different strategies and solutions is asseverated by energy and environmental simulations that quantify both the primary energy demand and the CO_2 emissions for the analyzed building type. However, it is important to stress that there are many other factors that influence decision-making during the preliminary phase of the design process that must be considered, such as the initial investment cost, the time needed to complete the work, the availability of materials and the traditions of the region and the construction site.

2. BACKGROUND

At present, the only legislation for school designing in Italy dates to 1975 (Governo Italiano 1975). This regulation includes design requirements for the distribution and internal organization of the building and the sizing of the functional units according to the grade level of the school and the number of students. The design support manuals (Sole 1995; Arie 2006) are equally inappropriate because they are based on the same regulation (Governo Italiano 1975). In 2013, the Ministry of Education, University and Research (MIUR) developed qualitative guidelines (MIUR 2013) that define the new areas needed for contemporary schools, but these guidelines do not refer specifically to dimensional requirements. Moreover, the cited documents do not deal with the energy performance and environmental impact of buildings intended for such purposes. Consequently, they do not deal with, for instance, the minimum environmental criteria (CAM) to be met and the energy and environmental strategies to be adopted, in the context of creating smart buildings with low environmental impact. Furthermore, they do not define the internal functional distribution with consideration of the energy and environmental performance of the building. The research mainly deals with particular features that do not consider the overall design in an integrated way. Many specific studies address the main causes of discomfort within the classroom functional unit, including poor indoor air quality (IAQ), insufficient air exchange rate (Fisk 2017), inadequate indoor air temperature, unsuitable size in relation to the number of students, and high concentration of pollutants, which inevitably affect children's health (D'Ambrosio Alfano et al. 2013; Wargocki and Wyon 2007; Mendell and Heath 2005; Zeiler 20007; Dijken et al. 2005), their school performance (Sadat, et al. 2016; Bluyssen et al. 2018; Coley et al. 2007) and their concentration during learning hours (Wargocki and Wyon 2006). Regarding the ventilation system, which is inevitably linked to the internal air quality, many studies have been conducted to understand whether there should be natural ventilation or mechanical ventilation within classes (Stabile et al. 2017; Al-Rashidi et al. 2012; Stabile et al. 2015; Li et al. 2020; Simanic et al. 2019) is advisable. For instance, Li et al. (Li et al. 2020) compared 3 different ventilation systems to propose a new system combined with transpired solar air collectors to reduce energy and keep the concentration of pollutants below 1000 ppm. Additionally, Simanic et al. (Simanic et al. 2019) demonstrated that a controlled ventilation system with heat recovery can maintain satisfying indoor comfort in terms of both indoor air temperature and pollutant concentration by monitoring 7 low-energy schools built in Sweden. Other authors have analyzed the window-to-wall ratio (WWR) on the façade. Carols J.S. defines the best WWR for a classroom of an existing school in Portugal, linking this value to the geometry, orientation, natural lighting conditions and annual thermal energy consumption of the room (Carlos 2018). Zomorodian et al. outlined the characteristics that an opening of a university classroom should have in terms of size, glazing and solar shading properties by considering the thermal and visual comfort of the students (Zomorodian and Tahsildoost 2017). Finally, Ashrafian et al. (Ashrafian and Moazzen 2019) optimized the WWR value and the solar shading system for both east- and west-oriented classrooms in terms of energy demand, predicted mean vote (PMV) and average daylight factor. Other researches exploit natural light and efficient artificial lighting equipment within classes to decrease energy demand and to understand both how these factors affect users and how they are influenced by user behavior (Doulos et al. 2019; Lourenço et al. 2019). For instance, Lizana et al. developed a method for evaluating indoor comfort, energy demand, primary energy from nonrenewable sources and CO_2 emissions for existing school buildings using a limited input data set (Lizana et al. 2018), and Barbosa et al. (Barbosa et al. 2020) monitored several parameters (indoor temperature, pollutant concentration, energy consumption) of various classes belonging to schools in Portugal to suggest the best building passive retrofitting technique for improving indoor comfort. Finally, recent research on school buildings aimed to monitor recently constructed nZEB buildings to understand the difference between what has been simulated in terms of energy demand during the design phase and what is actually required by the building during operation (Simanic et al. 2020), to outline a reference model for the construction of energy-efficient schools as the school population grows (Attia et al. 2020) or for understanding how environmental and energy performance can be improved for existing nZEB buildings (Wang et al. 2019).

3. METHODOLOGY

The methodology for determining the qualitative and quantitative guidelines for the construction of zero-emissions kindergartens is divided into 7 phases.

- Study of representative sustainable school buildings. A critical analysis (including site analysis, environmental and technological systems analysis, and the identification of environmental and energy strategies) of several representative sustainable school buildings were identified and evaluated in terms of functional organization, spatial distribution and the application of the principles of sustainability. The buildings were built between 2003 and 2015. The typological factors distinguishing contemporary school buildings, the most common technological solutions, the materials used and the most common environmental and energy strategies were identified.
- Definition of new typological models for the building type used for kindergartens. The critical analysis performed with several representative buildings allows the definition of three recurring building models with respect to geometry, sizes, internal distribution, and techniques. Moreover, for defining the dimensional characteristics of the new typological models (for instance, main dimensions of the buildings, size of the functional bands, surface area for each student etc . . .) an arithmetic mean was performed considering the parameters related to the chosen representative school buildings. Obviously, by checking that they were in line with the current sizing legislation for their intended use. So, three different typological models were defined: one with a compact shape and internal courtyard (model I1) and two with a linear shape, with 3 classrooms (model I2) and 6 classrooms (model I3), respectively. Initially, these models were configured by considering factors related to energy (i.e., thermal transmittance of the external envelope elements, periodic thermal transmittance, surface mass, efficiency of the generation systems) and adopting the characteristics of the reference building outlined by current Italian law (Governo Italiano 2015).
- Definition of load-bearing structure solutions.
- Definition of technologies suitable for the external envelope and identification of the appropriate insulation thickness with reference to 5 different Italian climatic zones. To this end, different technological solutions for the external envelope were analyzed and compared, combined with different solutions for a load-bearing structure (5 different technological solutions for the vertical perimeter wall (PPV) and 4 for the roof) and 4 different materials for the external thermal insulation layer (i.e., wood fiber, sintered expanded polystyrene (EPS), rock wool and glass wool). The different solutions were compared in terms of thermodynamic properties (European Committee for Standardization 2007), energy demand for heating and cooling, primary energy demand, internal surface temperature for south-facing PPV and construction CO_2 emissions.
  To choose the material for the insulation layer of the PPV, the thermodynamic properties of the wall were calculated, increasing or maintaining its thickness with respect to the reference building configuration, to obtain a periodic thermal transmittance (Y_{IE}

measured in [W/m^2K]) less than 0.10 W/m^2K and a time shift (φ measured in [h]) greater than 8 hours. Specifically, to define the thickness of the insulation layer, a parametric analysis was carried out by varying the thickness of the insulation layer within a fixed range with a step of 0.02 m and calculating both the annual energy consumption for heating and cooling and the environmental impact during the operational phase. The thickness of the insulation was varied in a range between the minimum required by current regulations to meet the minimum thermal transmittance (U measured in [W/m^2K]) and a maximum of 0.24 m, which is considered to be the maximum thickness achievable from technological and construction points of view.

- Definition of the systems of new building type. Define the heating system, cooling system, controlled mechanical ventilation system (VMC) and photovoltaic system to produce electricity from renewable sources.
- Validation and verification of a new building type for kindergarten with respect to current energy and emissions regulations. The energy performance [kWh/m^2a] and environmental performance [kgCO_2/m^2year] of the new building type was defined, the typological factors that significantly affect the energy balance were identified and possible and advisable modifications toward low-carbon nursery schools were identified considering different Italian climate zones.
- Drafting qualitative and quantitative guidelines for the construction of zero-emissions nursery schools in Italy.

4. ANALYSES

Regarding the structure/external envelope (point 4 in the methodology section), to define solutions to be outlined in the guidelines for the design of zero-emissions schools in Italy, five technological solutions are considered (Figures 1 and 2). They are described in detail in Appendix A (paragraph A.2).

Several studies and analyses were carried out to validate and verify the new building type for kindergartens with respect to current energy and emissions regulations (point 4 in the methodology section) and to suggest changes in typological factors. The input data for the analyses were detailed in Appendix A (paragraph A.1).

- First, a sensitivity analysis (one-at-a-time step sensitivity analysis) (Ciacci et al. 2020) was carried out to determine which typological factors most influence the primary energy demand [kWh/m^2year] and environmental impact [kgCO_2/m^2year] of buildings during the operational phase. The analysis was carried out for the cities of Florence and Palermo by considering model I1 as the reference model and varying each typological factor and the characteristics of the system (Table A.1) in a precise range, keeping the other factors fixed. Solution 5 was considered to be the structural and technological solution of reference model I1.
- Then, a parametric analysis was performed to identify the appropriate WWR value for each orientation by considering the new typological models (I1, I2, I3) (Ciacci et al. 2019) because the orientation, size and distribution of façade openings inevitably affect the energy and environmental performance of the building The analysis was carried out considering 5 cities (Milan, Florence, Rome, Naples, and Palermo) and by adopting the value required by the current health-hygiene Italian standards as the minimum WWR

FIGURE 1. Stratigraphy of the external walls.

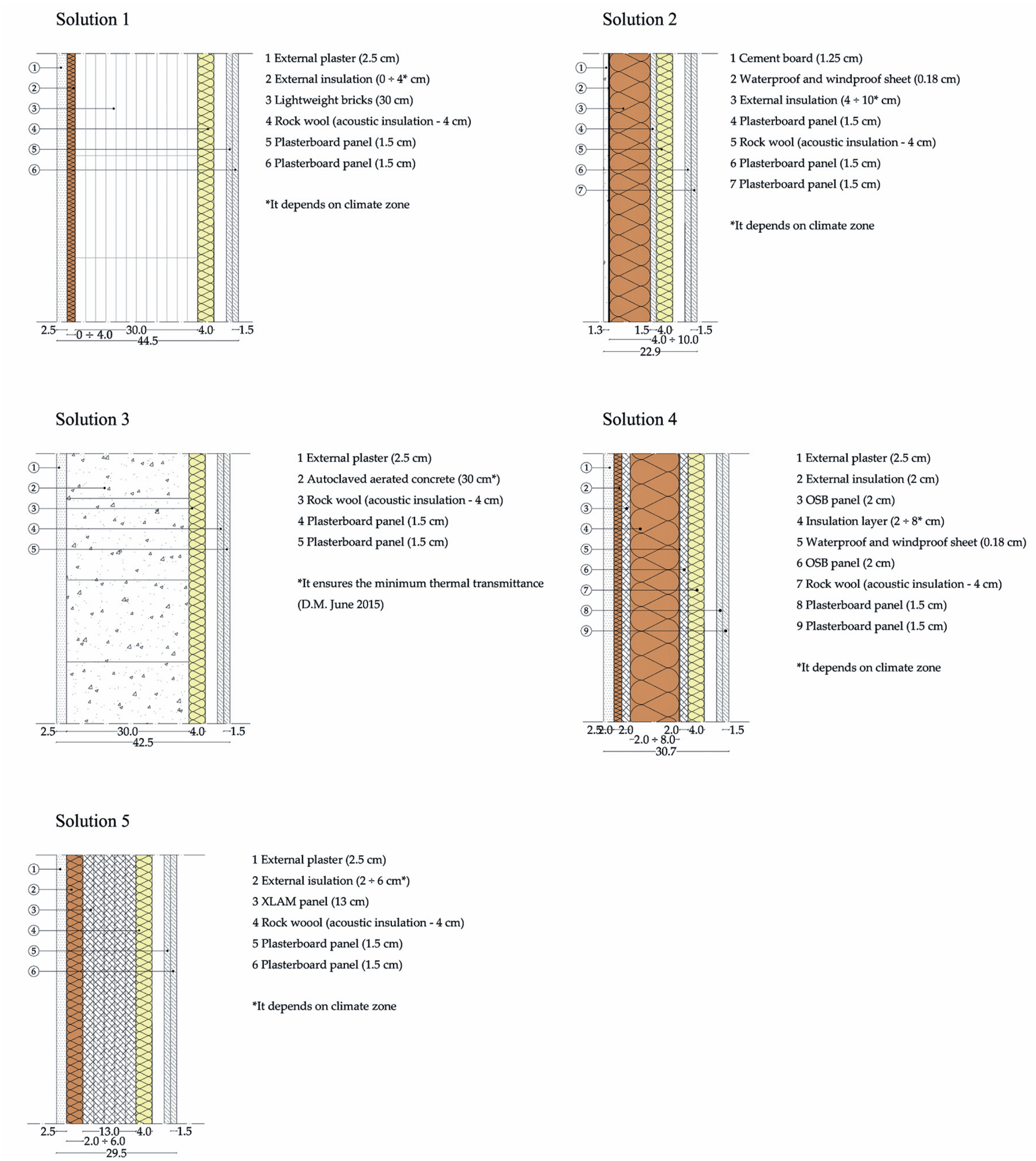
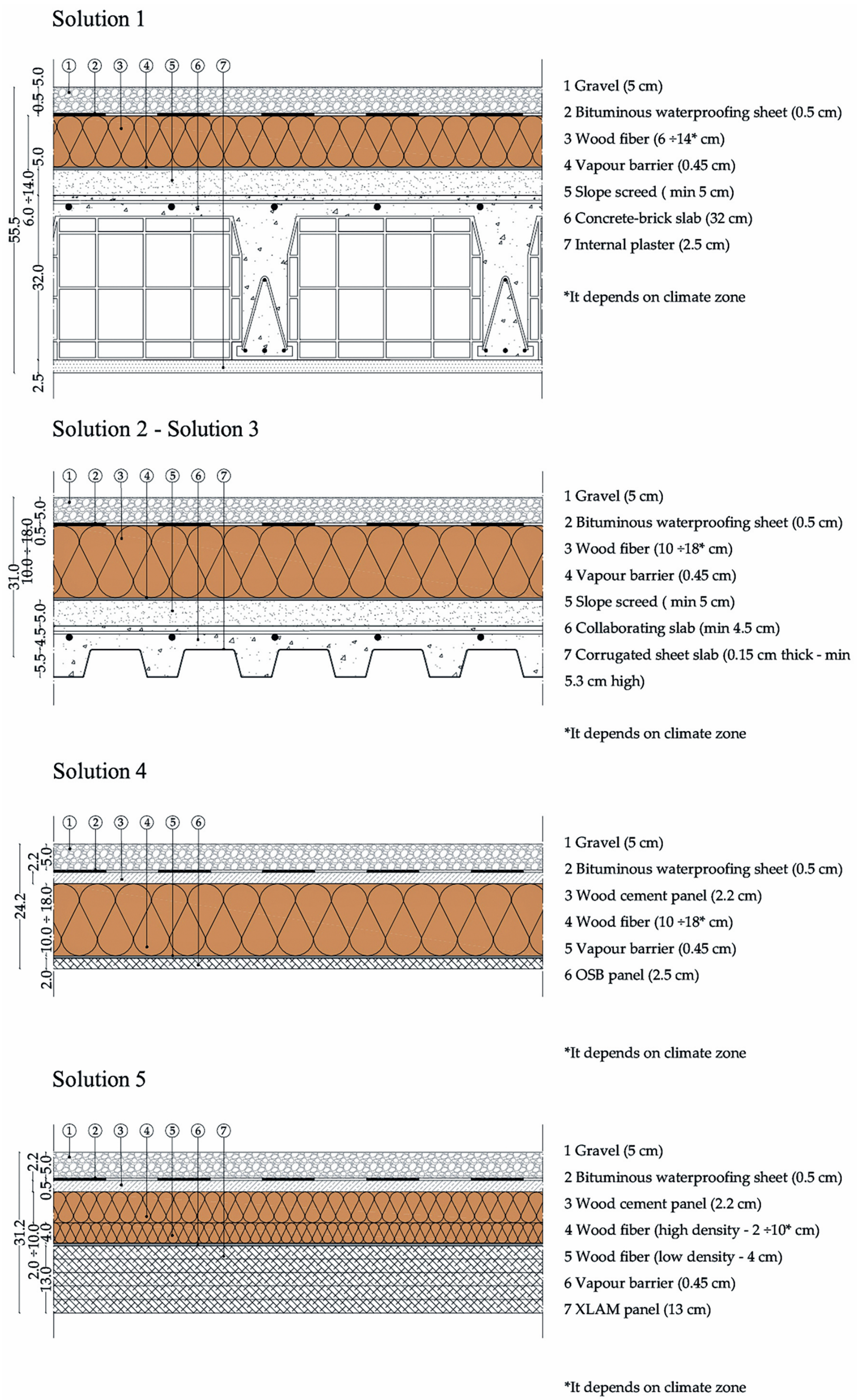


FIGURE 2. Stratigraphy of the roofs.



value and the one achievable inside each functional unit as the maximum, considering the presence of the false ceiling necessary for the ventilation systems. The study was performed by varying the WWR value for one orientation at a time and keeping the others fixed at the minimum value (Table A.2). For the North orientation, the WWR was always kept equal to the minimum value required by current regulations to avoid an increase in dispersion.

- Subsequently, a study was carried out comparing the 4 most common solar shading systems (Table A.3) that can be used in southern functional units as an alternative to the solution used in different building types with a 2.00 m fixed overhang (Bazzocchi et al. 2020). The comparison was conducted by separately considering the energy demand for heating, cooling and artificial lighting. To avoid overheating during summer and to avoid glare, an analysis was performed on the different types of controls that can be applied to an automated internal solar shading system. Finally, both the average daylight factor and the lighting uniformity ratio were verified for the functional unit class. The analysis was performed for 2 of the new typological models (I1, I2) located in 5 different cities (Milan, Florence, Rome, Naples, and Palermo) and considering 12:00 noon on June 21st and December 21st.
- Finally, the production of electricity from renewables through a photovoltaic system was assumed, and a parametric analysis was carried out to define the positioning of the photovoltaic panels on the roof to maximize their energy production (Ciacci et al. 2020). This system not only helps to meet the aim of creating a low-carbon kindergarten but also can be used to create an energy plus building that produces more electricity than it needs; this surplus energy can then be used in other buildings in the neighborhood, which will be common in the near future in smart cities. The factors that were subjected to parametric analysis are as follows: the shape of the building (I1, I2, I3), the orientation of the panels (south-facing or a combination of east- and west-facing) and the tilt angle of the photovoltaic panels (varied between 10° and 80°).

To determine the energy performance of the new building type and to carry out the analyses previously described, energy simulations were conducted in the dynamic regime with hourly steps by using EnergyPlus with Design Builder as a graphical interface. To identify the environmental impact of the new school building type, CO_2 emissions were calculated by evaluating emissions due to the construction of the building using eLCA software (Federal Institute for research on Building, eLCA v0.9.7) (with a useful life of 50 years) and the photovoltaic system (with a useful life equal to 30 years) and those related to consumption during the service phase of the building [$kgCO_2/m^2year$]. A conversion factor of 50 gCO_2/kWh (Khan and Arsalan 2016) was considered for the construction of the photovoltaic system. A conversion factor of 0 $kgCO_2/kWh$ was considered for the evaluation of CO_2 emissions from renewables during the operational phase.

The environmental impact was calculated through the calculation of the Global Warming Potential in [$kgCO_2/m^2year$] and the system boundary for the LCA analysis is the following one: product stage (A1-A3), end-of-life (C3-C4) only for those materials with lower service life with respect to the lifespan of the building (50 years), benefits and loads beyond the system boundary (D1-D4), and servicing during building lifespan (construction phase of the building).

5. FINDINGS AND DISCUSSION

Three new typological models were initially outlined for kindergarten. For general distinguished features and energy and environmental strategies, please refer directly to the qualitative and quantitative guidelines in the study conclusion. For the sake of brevity, only the most significant results related to the analyses carried out to define the new building type for kindergartens and the most appropriate configurations of the main typological factors to obtain a low-carbon school in Italy will be briefly reported.

- From a functional point of view, the major differences between the new typological models outlined and those shown in the 1975 regulation mainly concern the introduction of new functional units (e.g., the agora) and the definition of different areas per student (stud) for the various sections of the building. One of the main differences involves the global net surface index. For the new models, this index equals approximately 14 m^2/stud, while in the current regulation, it equals 7 m^2/stud. For collective activities, which play a key role in children's education, the index is 2.50 m^2/stud for the new models and only 1 m^2/stud for the 1975 regulation. Finally, for the home base, there is an area of 3.40 m^2/student, while the regulation is set to only 1.80 m^2/stud. It is clear that current Italian regulations, and consequently the design manuals, propose typological models with areas that cannot adequately meet the needs of new didactic and pedagogical methods.
- Of the different structural and technological solutions analyzed, solution 1 has the highest surface mass for an insulation layer of any material, mainly due to the high density (ρ) of the lightweight bricks (ρ = 800 kg/m^3). Consequently, this solution guarantees the maximum time shift (> 18 hours). Solution 3 ensures a periodic thermal transmittance of 0.018 W/m^2K and a time shift of more than 15 hours due to the use of the aerated concrete blocks. The other solutions also have suitable thermodynamic properties, in combination with medium- or high-density insulation (ρ > 60–70 kg/m^3).
  Importantly, although solution 2 (dry solution) is characterized by shorter installation times and greater flexibility over time, it has the lowest surface mass (60 kg/m^3 < Ms < 70 kg/m^3) and time shift values because it is mainly composed of materials with reduced thickness. In this case, a change in the insulation material significantly affects the thermodynamic properties of the PPV. To obtain a time shift greater than 8 hours, 0.32 m of EPS insulation (ρ = 35 kg/m^3) (solution 2) are required. Thus, for climatic zones with hot summers, it is advisable to employ a massive technological solution to guarantee appropriate comfortable internal conditions or a solution with a low surface mass combined with medium- or high-density insulation.
  An energy simulation was carried out with the different solutions proposed and applied to the typological models defined, and it is clear that there is no significant difference (~1%) in terms of heating and cooling energy demand and annual primary energy demand (e.g., ~25 kWh/m^2a for I1). Solution 4 has a slightly higher primary energy demand (~2 kWh/m^2a more). Therefore, it can be stated that, in terms of energy, each solution outlined is appropriate and usable for the construction of low-energy consumption kindergartens in Italy.
- The parametric analysis of the insulation thickness showed that the trend of consumption remains the same for each material considered, since the materials have very similar

thermal conductivities (~0.037 W/mK). In addition, the variation in the thickness of the insulation for all 4 materials has a greater impact on the energy demand for heating, and the impact of this factor on energy demand is greater for thinner insulation (<0.14 m) as shown in Figure 3. Figure 4 proves that the increase in CO_2 emissions during construction is proportional to the increase in insulation thickness. The graph shows the technological solutions for solution 1 and solution 4 with wood fiber insulation and EPS, which are the best and worst in terms of environmental impact, respectively. The 5 solutions suggested for the structure and the external envelope, combined with any of the 4 materials considered for the insulation layer, allow a construction phase CO_2 emission value of less than 13 kg CO_2/m^2year to be obtained. Consequently, in terms of environmental impact, the 5 solutions can be considered as valid alternatives for the construction of low-carbon schools in Italy.

- Figure 5 shows the results of the sensitivity analysis. The graph relates the normalized primary energy demand to the reference model (model I1) for Florence and Palermo and the variations of both typological factors and system characteristics.
  The analysis highlights that the ventilation rate of a school building is the most important factor affecting the energy balance, as the hourly air change rate required by current legislation is very high for this intended use. Consequently, for the VMC system, an increase of up to 90% in the efficiency of the heat recovery implies a significant decrease in primary energy demand (approximately 24% for a climate zone with cold winters). The main typological features influencing the primary energy demand of the building are as follows: shape, variation in insulation thickness for climate zone D and variation

FIGURE 3. Energy needs for heating for different technological solutions.

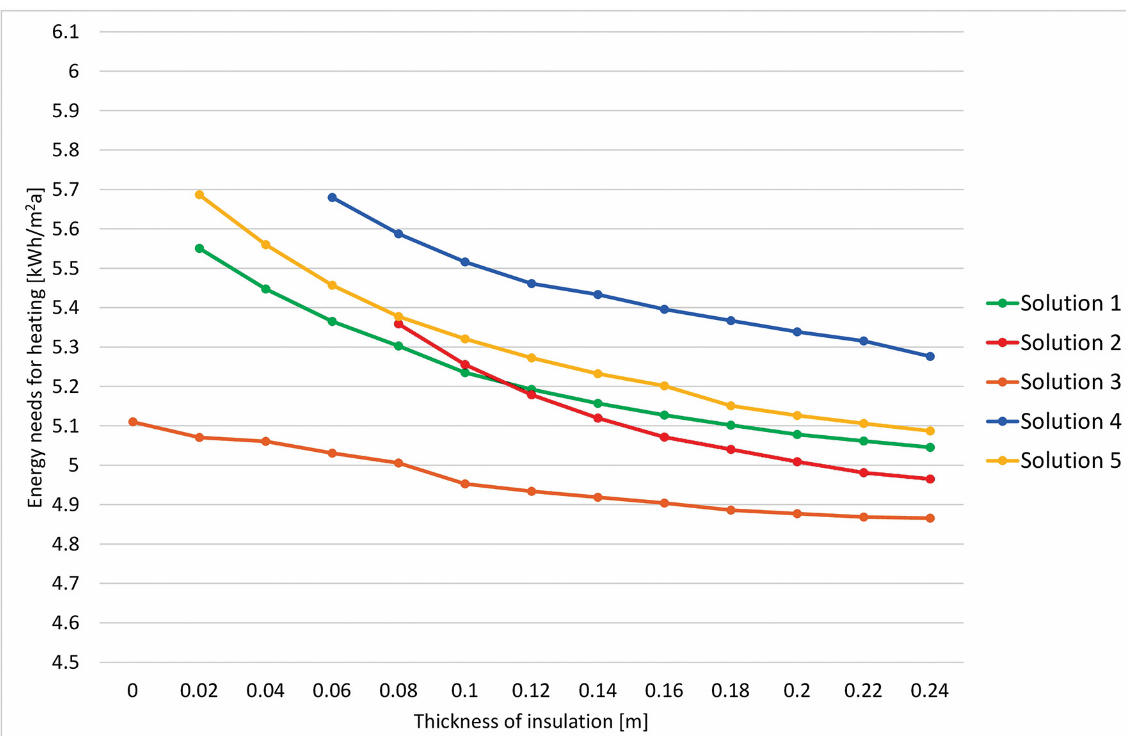


FIGURE 4. CO_2 emissions variation for technological solutions 1 and 4.

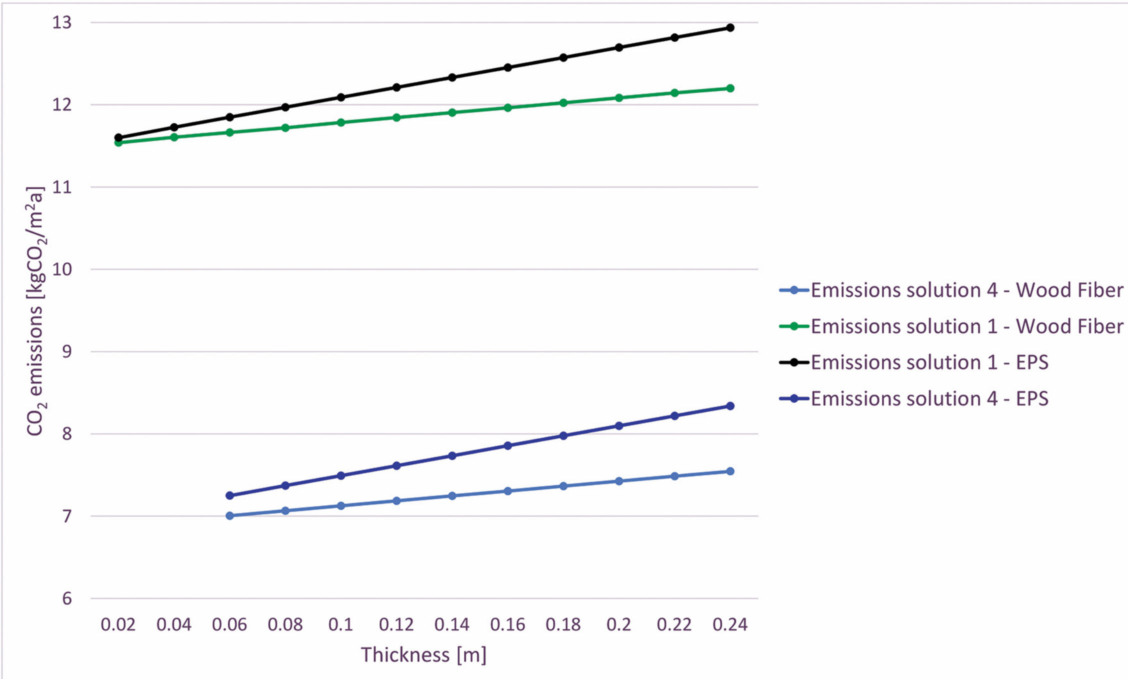
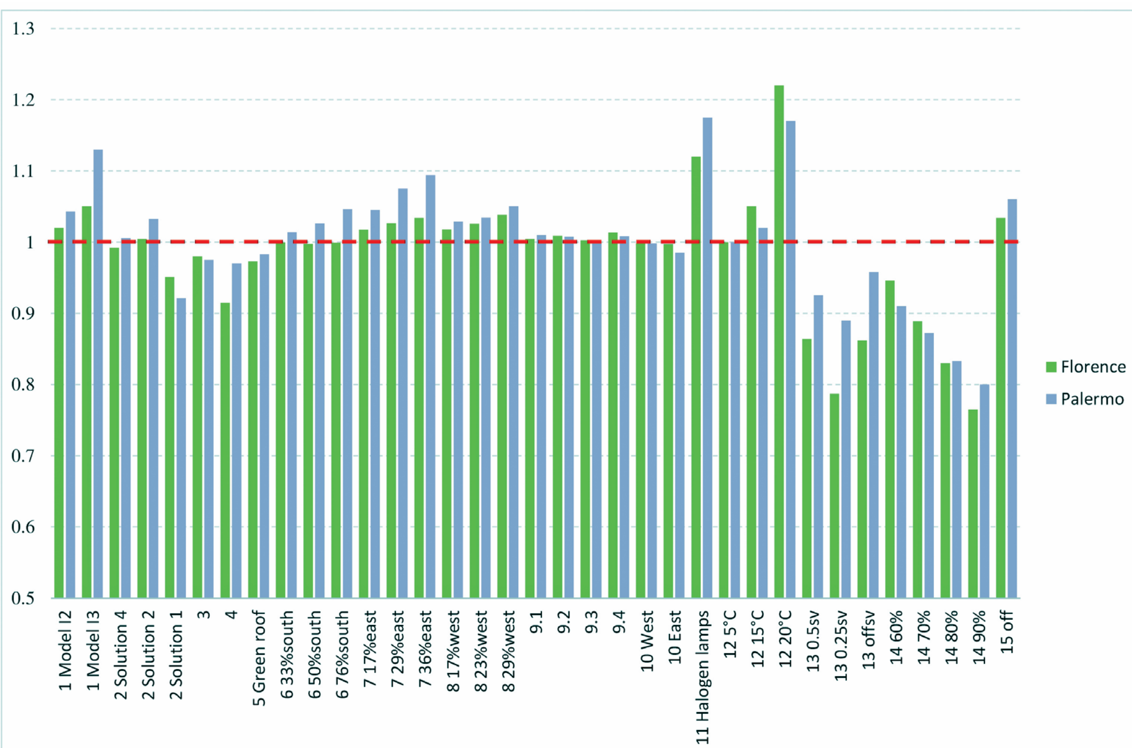


FIGURE 5. Sensitivity analysis results.



in WWR for climate zone B, especially for the east- and west-facing orientations. For instance, the compact shape with internal courtyard (model I1) most significantly reduces the primary energy demand, with differences of 5% and 13% compared to model I3 with 6 classes for Florence and Palermo, respectively. The increase in the thickness of the roof insulation for climate zone D leads to a decrease in the primary energy demand of the building of approximately 8.50%, which is related to the decrease in energy demand for heating. In addition, for Florence, the use of a technological solution with a green roof involves a decrease in energy demand for cooling by approximately 8% due to the reduction in surface temperature. For both Florence and Palermo, this solution results in a decrease in primary energy demand of approximately 2%.

- Regarding the parametric analysis conducted for the WWR, the most significant results are listed below (Ciacci et al. 2019) (Table A.3).
  - For the southern front, considering model I1, it is possible to demonstrate that a variation from 25% to 50% of the WWR value for climate zones E and D implies a decrease in energy demand for heating of 5% (Figure 6). For climate zones C and B, an increase in WWR on this front leads to a considerable increase in energy demand for cooling by approximately 22% (Figure 7). Models I2 and I3 perform similarly but are characterized by a decrease in energy for heating (climate zones E and D) and an increase in energy for cooling (climate zones C and B) because the prevailing orientation of the building is along the East-West axis.
  - For the east-facing and west-facing façades for all models and for each climate zone considered, the change in the WWR value does not significantly affect the energy

FIGURE 6. Final energy demand for heating with respect to South WWR variation for model I1.

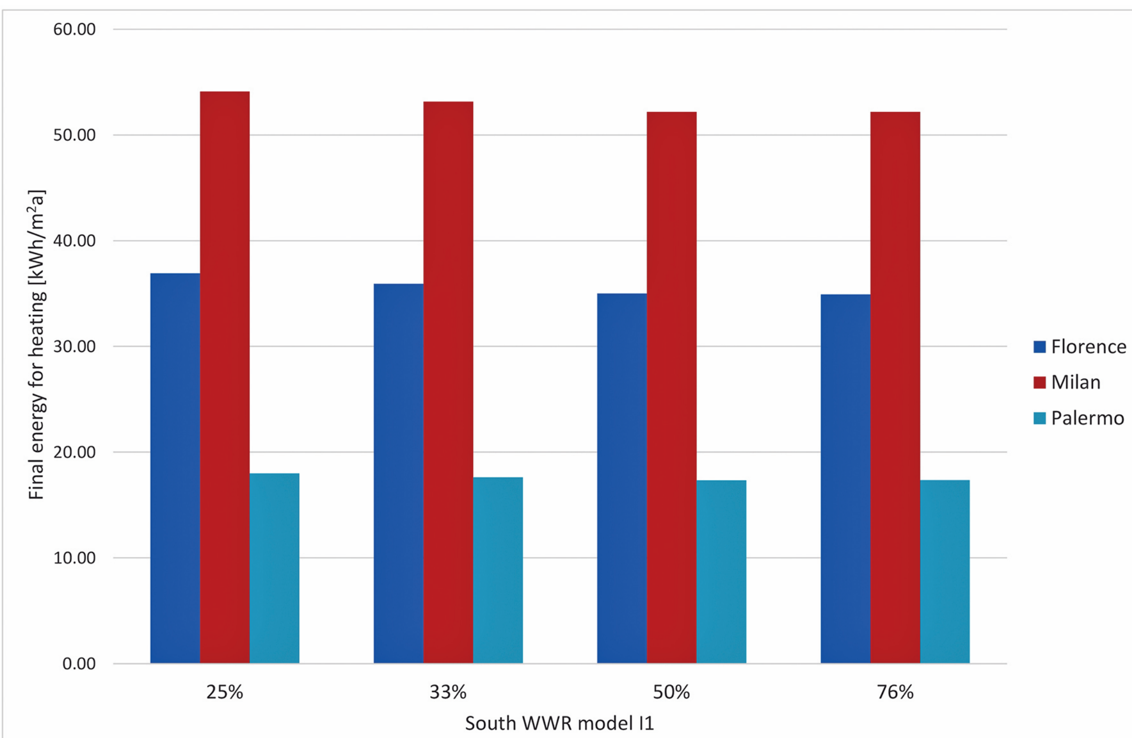
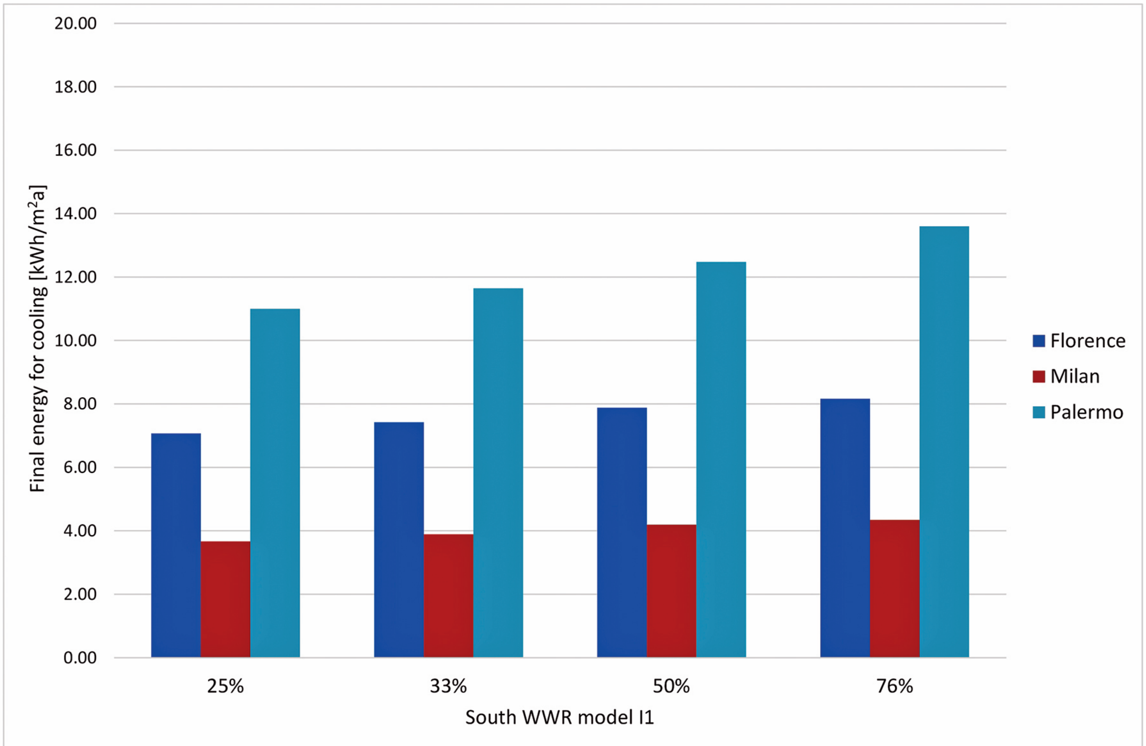


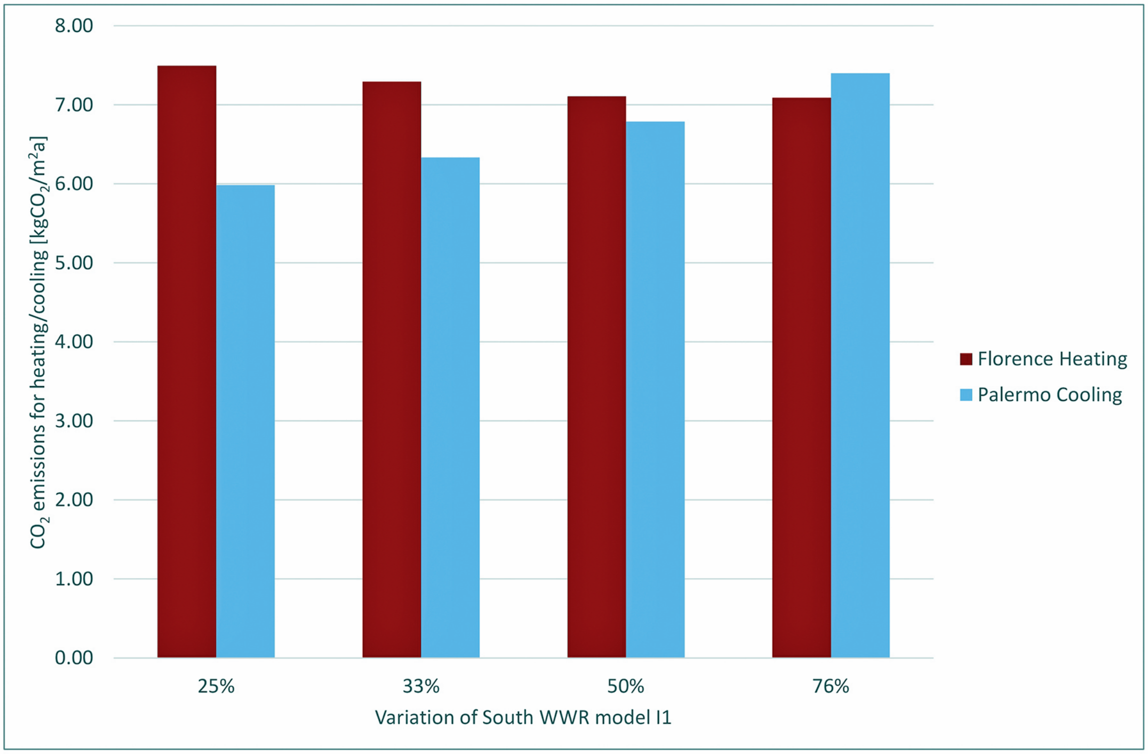
FIGURE 7. Final energy demand for cooling with respect to South WWR variation for model I1.



demand for heating, while for the energy demand for cooling, it is necessary to analyze the results with respect to the climate zone. For Milan (climate zone E) and Florence and Rome (climate zone D), an increase in WWR of up to 36% for the eastern front and 29% for the western front does not significantly impact energy consumption for cooling, while for Naples (climate zone C) and Palermo (climate zone B), an increase in WWR on the eastern front causes a percentage increase in energy demand for cooling comparable to the one for the southern front. For models I2 and I3, the variation in WWR on the eastern and western fronts does not influence the energy demand of the building. This result is mainly related to the internal functional distribution of the two models (on these fronts, there are no main functional units).

To reduce the primary energy demand for the new building type, it is necessary to have a WWR value equal to 50% for the southern front for climate zones with cold winters (E and D) to exploit free solar gains during winter and to maintain the minimum values required by the current health-hygiene regulations for all other orientations. For the climate zones characterized by very warm summers (C and B), it is advisable to keep the minimum WWR for each orientation to limit the energy consumption related to cooling. These WWR values are also confirmed by evaluating the environmental impact in terms of CO_2 due to the energy demand for heating and cooling. As for the environmental impact, considering model I1, a southern WWR value equal to 50% for Milan, Florence and Rome results in a reduction of emissions due to heating by approximately 5% compared to the minimum configuration required by Italian health-hygiene standards (Figure 8). In contrast, for Naples and Palermo, if the southern WWR

FIGURE 8. CO_2 emissions for energy demand for heating and cooling for Florence and Palermo.

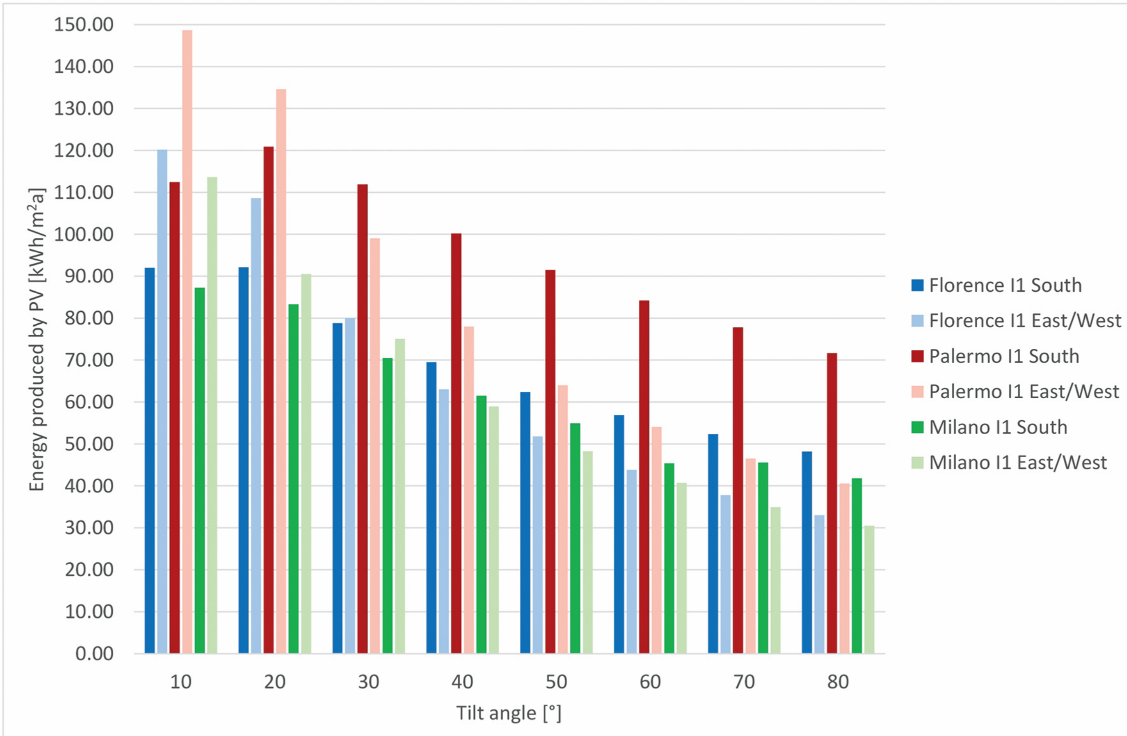


value varies from 26% (minimum) to 76% (maximum), there is an increase in CO_2 emissions due to cooling of 1207 $kgCO_2$/year (Figure 8).

- Southern solar shading is currently required by Italian energy legislation because, depending on the ratio between the equivalent summer solar area of the building and the useful surface of the building, it ensures that the external envelope performs appropriately during summer (Governo Italiano 2015). According to the study of different types of solar shading, the one with a 2.00 m fixed overhang combined with an internal venetian blind with automated horizontal slats and external temperature control (>24°C), allows CO_2 emissions to be reduced for new building type during operation. This result is valid for each climate zone evaluated. Furthermore, this configuration ensures adequate values of the average daylight factor, illuminance uniformity and low levels of glare (discomfort glare index (DGI) < 22) in class functional units in which visual tasks are performed (Bazzocchi et al. 2020).
- Finally, a low-carbon school must be designed with consideration of the use of renewable energy on site, as such energy sources significantly reduce CO_2 emissions during the service phase. Figure 9 shows the electrical energy production of the photovoltaic panels for model I1 in relation to the variation of the tilt angle for both panel orientations.

The parametric analysis shows that, in Italy, for all climatic zones considered, it is possible to maximize the producibility of the photovoltaic system by considering an East-West

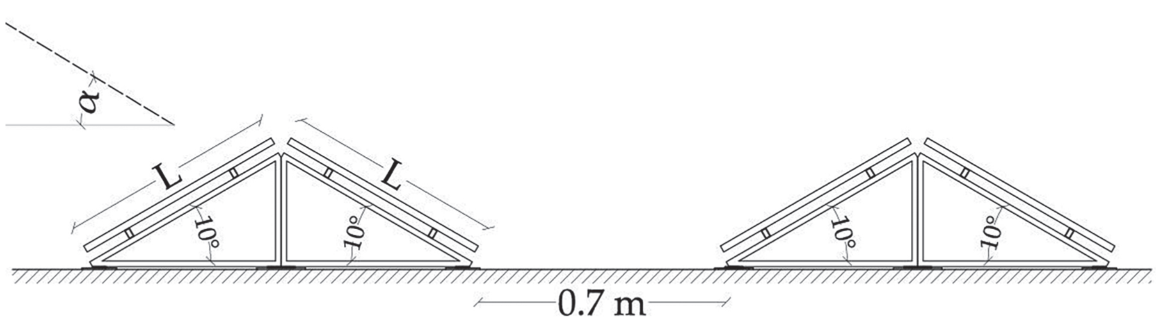
FIGURE 9. Energy produced by the PV system (model I1).



orientation (Figure 10) and a tilt angle of 10°. This result is mainly related to the East-West orientation of the photovoltaic panels that maximizes their area on the roof because the distance required to avoid shadows between one row and another is less than that in the southern configuration (Ciacci et al. 2020).

Therefore, this photovoltaic panel configuration avoids the increased production of CO_2 emissions, and it ensures that a greater amount of electricity (that can be hypothetically stored and used when solar radiation is not available) is produced and fed to the grid to be exploited by neighboring buildings. By comparing the most common configurations used in Italy for

FIGURE 10. Photovoltaic panels configuration.



the installation of photovoltaic panels (south-facing orientation; tilt angle = 30°) and the one previously defined for model I1 in Palermo, it was found that the difference in surplus electricity production is 38 kWh/m^{2}a; consequently, emissions are reduced by approximately 57142 kgCO_2.

5.1 Low-carbon kindergartens guidelines

Qualitative and quantitative guidelines can be outlined as the main result of the study. These guidelines can be considered as a cultural reference to support the designer during the preliminary phase of the design process for the construction of zero-emission, low-energy kindergartens in Italy. They define a new building type for kindergartens and propose solutions and configurations for the main typological factors characterizing the building to reduce energy consumption and environmental impact.

General characteristics

The modern school is a civic center and a place of reference for the community that is directly connected with the surrounding environment and the city through an efficient infrastructure system; it is a place open to everyone. The functional units for collective activities (e.g., canteen and agora) can also be used during extracurricular hours by the neighborhood. They are designed in such a way that they are completely independent not only from an architectural point of view (in terms of access and exit systems) but also from an installation point of view. The division between the school environment and the city is disappearing, and this change can be seen in many aspects. For instance, the presence of large windows in classrooms ensures that continuous visual contact is maintained with the surrounding natural environment so that the environment becomes an extension of the space used for teaching activities via educational gardens, outdoor sensory pathways, play areas, educational greenhouses, and accessible green roofs. In addition, the entrance to the school building is developed into an agora, which is a key functional area of a modern school building, where the children's families are free to enter and be in direct contact with the school environment. In kindergarten, this functional area is essential since it allows parents to stay with the children according to their needs. As far as the internal functional distribution is concerned, it is necessary that each school building ensures the integration and interoperability of the main functional areas. In addition, the flexibility and adaptability of the space to teaching needs are fundamental in a modern school. Movable partitions and furniture are used so that the spaces and available equipment can be divided according to the number of pupils participating in teaching activities or to carry out intercycling and cooperation activities even between students of different ages. This use is also reflected in the modularity of the structure and the layout of the system, which must adapt to the constantly evolving needs of didactics.

Finally, a school built based on sustainability with zero-emissions strategy must be considered a real 3D textbook (Gulay 2015) from which both children and the neighborhood can learn about and develop respect for the environment and the principles of sustainability and thus acquire greater awareness of these aspects.

Energy strategies

To reduce the primary energy demand during winter season in climate zones with cold winters (climate zones D and E), where the contribution of the energy demand for heating prevails, the following energy strategies are recommended:

- low aspect ratio (<0.55 m^{-1}), i.e., the ratio between the dispersing surface of the building (S) and its volume (V) (S/V), expressed in [m^{-1}], obtained through the construction of empty areas (internal courtyards) and recesses, built in the geometry of the building;
- orientation prevailing along the East-West axis to exploit solar gains during winter; this orientation is possible if the surrounding urban context does not create shade;
- southern functional band characterized by a depth greater than the northern one in a ratio of at least 2:1, considering an average depth of the south-facing functional band of approximately 9.30 m;
- a main functional area, which includes the home base, that holds more people in the area facing the South during school to exploit solar gains, with all ancillary rooms, as well as the kitchen and the teachers' area, which occasionally hold people during the school day, to the North;
- southern WWR value of 50%, which is much greater than the minimum required by current health-hygiene regulations, for cities in climate zones E (e.g., Milan) and D (e.g., Florence); on the northern front, the WWR should equal the minimum required to limit dispersion;
- heat recovery efficiency related to the VMC system of at least 65%.

In climate zones characterized by extremely warm and humid summers (climate zones C and B), where the energy demand for cooling is high, the following strategies are advisable:

- WWR value equal to the minimum required by health-hygiene regulations for each orientation;
- use of additional solar shading systems for southern-facing functional units to avoid both overheating during summer and glare in areas where visual tasks are performed;
- use of green roofs to decrease the surface temperature since such roofs absorb less solar radiation than traditional solutions, enabling them to maintain a lower indoor air temperature.

For all climate zones, the use of fixed shading with a 2.00 m overhang and movable automated solar shading with an internal venetian blind with external temperature control (>24°C) is advised.

Environmental strategies

To minimize the environmental impact and thus reduce greenhouse-gas emissions, the following strategies are recommended:

- use of natural (or CAM-compliant) materials for the main technological and structural solutions used in the building to decrease global warming potential due to building construction;
- use of materials produced close to the construction site to reduce the environmental impact of construction by reducing transport distances and therefore CO_2 emissions;
- use of renewables for on-site energy production to meet the building's energy demand and to produce energy that can be stored or used by surrounding buildings; the installation of a photovoltaic system on roofs with East-West orientation and a tilt angle of 10° or the use of other solar, wind or geothermal energy systems is suggested.

External layout

The external area next to the building is a space for learning activities that can possibly be organized into different thematic areas. Many collective and learning activities should be organized in the outdoor garden to keep the children in contact with the natural environment. Classes should be directly connected to the outdoor garden to connect students with nature. Although these guidelines do not go into detail regarding the design of the external area, here are some useful suggestions:

- the main entrance to the construction site must be reached from secondary arterial roads for the safety of the children;
- public transport stops should be less than 200–300 m away; an area with rubber flooring should be provided so that children can safely board and alight;
- the parking area should be located outside the garden; it should be reserved for external staff and teachers and directly connected to the secondary entrance of the building along the North side, and the parking area should be at least 1 m^2 per 10 m^3 of construction;
- at least 25% of the external area must be permeable (e.g., lawn, external self-locking floors);
- the outdoor play area should be constructed with finishes that do not cause injury to children (e.g., sand or rubber flooring) or cultivated for educational gardens, sensory pathways or educational greenhouses.

A study of shadows over the school caused adjacent buildings should be carried out for at least the solstices and equinoxes.

Geometry

New typological models for kindergartens are developed on a single ground floor due to the age of the children inside the building, and therefore, they do not have vertical connections. Possible planimetric shapes that can be used for a nursery school in Italy to follow the new didactic and pedagogical methods and to obtain the appropriate energy and environmental performance are listed below:

- compact shape with internal courtyard (model I1) (Figure 11);
- linear shape with 3 classrooms (model I2) (Figure 12);
- linear shape with 6 classrooms (model I3) (Figure 13).

Table 1 shows the main geometric characteristics of the configured typological models, including the length (C), depth (B), internal height (H_{int}), area (A), volume (V), aspect ratio (S/V), number of students (NS), global net surface index (S_{stud}), orientation (O), number of classes (NC) and class size (E width; D depth).

Building organization

With respect to the internal functional organization, the advisable configurations for each defined shape (model I1, model I2, model I3) are as follows:

- model I1 (compact shape) is organized according to 5 longitudinal functional bands of different sizes, with a ratio between the southern and northern functional bands of 1.70;

TABLE 1. Geometrical characterization of typological models for neutral-carbon kindergartens.

	Building						Students		Classrooms			
	C [m]	B [m]	H_{int} [m]	A [m^2]	V [m^3]	S/V [m^{-1}]	NS	S_{stud} [m^2/stud]	O	NC	E [m]	D [m]
I1	37.80	29.80	4.4	1036	6008	0.53	78	14.44	South	3	12.6	10.0
I2	75.60	14.90	4.4	1064	6172	0.51	78	14.44	South	3	12.6	7.90
I3	100.8	19.50	4.8	1631	10116	0.46	156	12.60	South	6	12.6	11.0

- model I2 and model I3 (linear shape) are organized with 3 longitudinal functional bands with a central band taken up by the horizontal distribution system and a ratio between the south- and north-facing functional bands of 1.8.

The functional units within a kindergarten are as follows: the home base, organized in 4 main areas with different uses (practical activities,such areas includes bathrooms), learning activities, collective activities, and rest), an area for collective activities (FA) that is flexible and adaptable to teaching needs, the kitchen and canteen area (C/K) with movable furniture to provide a multifunctional space (the canteen may not be necessary due to the age of the children, and meals may be consumed in the classroom or in the collective activities area) and the care area (CA), which includes an area for teachers.

The functional organization of each typological model is detailed in the following table (Table 2) that highlights the depth of the horizontal functional band (Functional $\text{bands}_{\text{Horizontal}}$) with respect to the orientation (South/center/West), the percentage of each functional unit with respect to the total area (functional units), the ratio between the depth of the southern and northern functional bands (R) and the area per student (HB).

Orientation

- Typological model I1 does not have a prevailing orientation from a geometrical point of view, as it is characterized by a compact shape. However, the functional band that includes the home base is oriented toward the South.
- Typological models I2 and I3 have a prevailing orientation along the East-West axis because the ratio between the two dimensions of the building (depth and length) is

TABLE 2. Functional characterization of typological models for carbon-neutral kindergartens.

	Functional $\text{bands}_{\text{Horizontal}}$ [m]			Functional units [$\%_{\text{TOTAL}}$]					R	HB
	South	middle	North	HB	FA	C/K	CA	C	S/N	m^2/stud
I1	10	9.00	5.80	38.3	10.3	22.4	9.5	14.8	1.7	4.85
I2	7.9	2.50	4.50	37.4	14.2	16.7	14.8	18.6	1.8	5.10
I3	11	2.50	6.00	44.3	14.5	21.4	8.0	11.7	1.8	5.33

FIGURE 11. Model I1 for kindergarten.

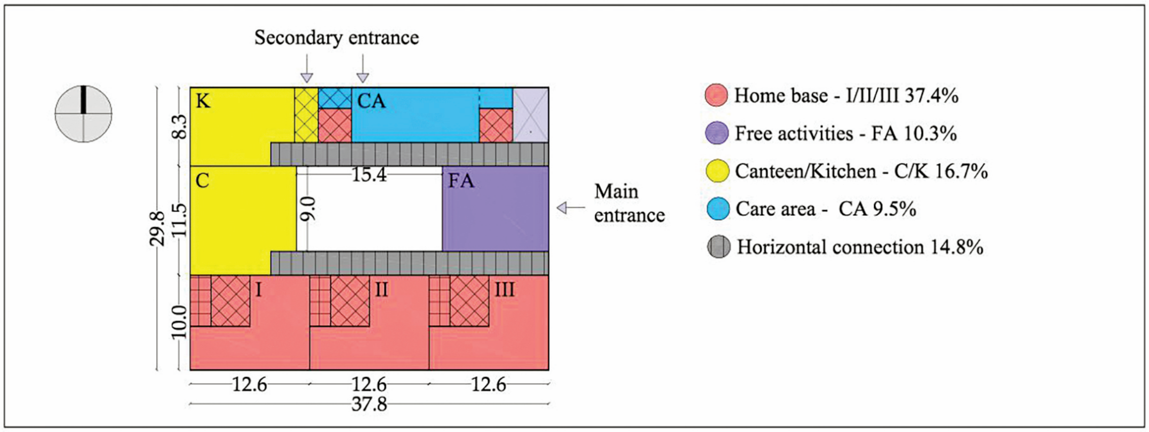


FIGURE 12. Model I2 for kindergarten.

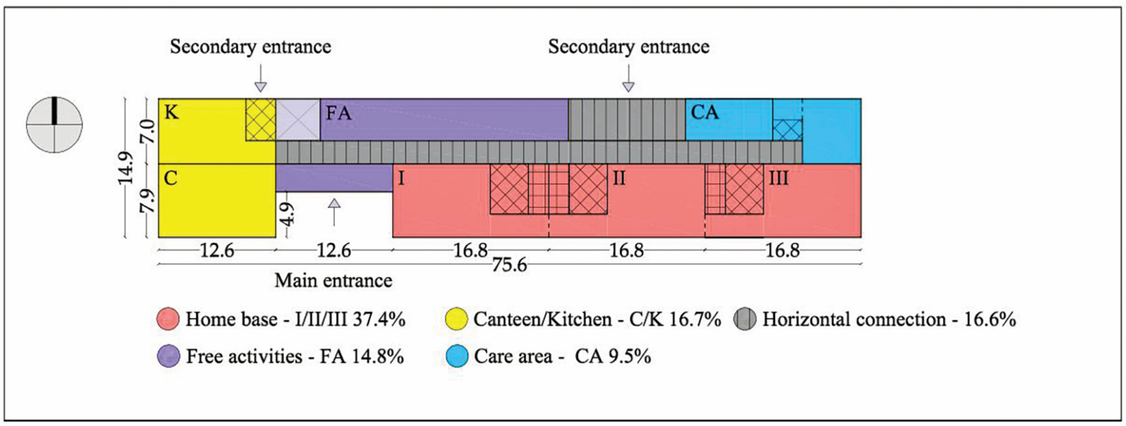
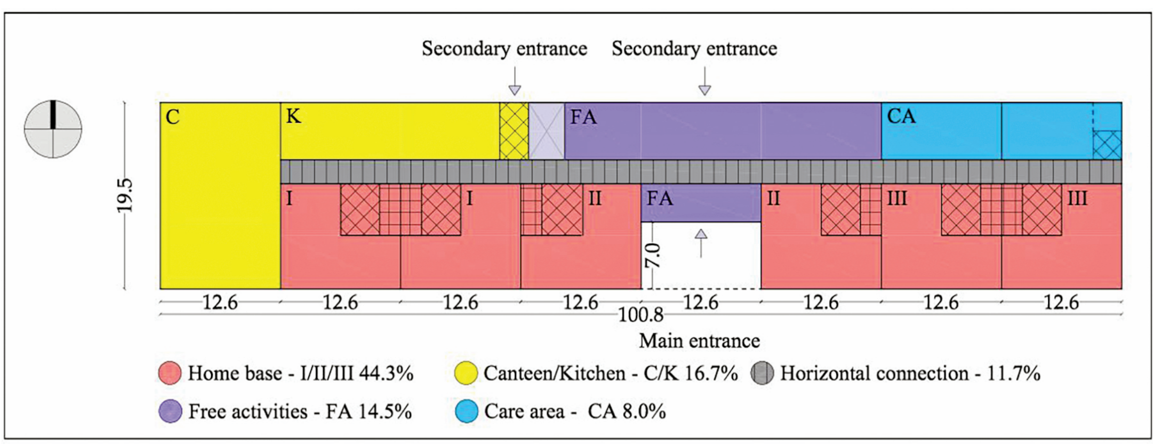


FIGURE 13. Model I3 for kindergarten.



1:5. In this case, the home base, the canteen and part of the area dedicated to collective activities are developed in the main functional band oriented toward the South.

Structural solutions

For foundation elements, a reinforced concrete structure is recommended. For a vertical load-bearing structure, possible solutions are as follows:

- wooden structure with a 5-layer XLAM panel (at least 130 mm thick) as the construction system;
- wooden structure with a platform frame as the construction system with a double OSB panel (panel thickness of 20 mm; e.g., a structure with 50 mm × 100 mm wooden columns);
- reinforced concrete structure;
- steel structure.

For the ground floor, plastic disposable formworks completed by a reinforced concrete structural slab are recommended.

For the horizontal roofing structures, 4 different solutions can be used depending on the choice of the vertical load-bearing structure:

- a wooden floor made with 5-layer 130-mm-thick XLAM panel for the vertical structure with the XLAM construction system;
- a wooden floor with a platform frame construction system with wooden beams and 20-mm-thick OSB panel for the vertical structure with the platform frame construction system;
- brick slab, including reinforced concrete slab (with a total thickness of at least 250–320 mm), for the vertical reinforced concrete structure;
- corrugated metal sheet (at least 1.5 mm thick and 53 mm high) with reinforced concrete slab (at least 50 mm thick).

The choice of the structural solution depends on the environmental impact and energy performance as well as the traditions of the construction site and the locally available materials.

External envelope technological solutions

For the floor slab, it is preferable to adopt a solution with a disposable plastic formwork, a 0.08 m screed, an insulation layer of expanded polystyrene (EPS) with a variable thickness depending on the climatic zone (E and D = 0.04 m; B and C = 0.02 m) and the same material (or wood fiber) for the radiant floor system (0.05 m), a 0.04 m lightened screed for laying the flooring and an internal wooden floor (0.015 m). The recommended thermal transmittance value for the floor slab is approximately 0.25 W/m^{2}K for climate zones E and D and 0.30 W/m^{2}K for climate zones C and B. It is not necessary to increase the insulation thickness of the floor slab as dispersions are limited. Typically, the ground is considered to be at a temperature of 15°C.

For the technological solution for PPV, it is possible to use any of the 5 alternatives suggested in the study combined with one of the 4 materials for the insulation layer. The recommended thermal transmittance for PPV is between 0.17 W/m^{2}K and 0.20 W/m^{2}K for climate zones E and D and equal to 0.25 W/m^{2}K for climate zone C and 0.40 W/m^{2}K for climate zone B. An increase in the insulation thickness for PPV to above 140 mm does not allow for a significant decrease in the building's primary energy demand. For climate zones C and B, it is advisable to maintain a low insulation thickness in the façade, as excessive insulation leads to a significant increase in energy demand for cooling during summer.

For the windows, an aluminum thermal break profile (U_f = 1.7 W/m^{2}K) and double glazing (the properties of which depend on the thermal zone considered) are recommended. The advisable properties of the glazing for each climate zone are as follows (thermal transmittance, U_g; solar factor, g; solar transmittance, T_L):

- climate zone E: U_g = 1.1 W/m^{2}K; g = 52%; T_L = 75%;
- climate zones C and D: U_g = 1.2 W/m^{2}K; g = 50%; T_L = 74%;
- climate zone B: U_g = 2.5 W/m^{2}K; g = 69%; T_L = 78%.

For Palermo, which is in climate zone B, to further reduce the energy consumption for cooling, it is possible to use a glaze with a solar transmission of approximately 0.4%.

For the roof, it is possible to use any of the solutions previously proposed with an insulation layer in wood fiber, EPS or extruded expanded polystyrene (XPS). However, it is important to verify the compression load that the insulating material can bear. The recommended value for thermal transmittance for the roof is between 0.12 W/m^{2}K and 0.13 W/m^{2}K for climate zones C and D and equal to 0.15 W/m^{2}K for climate zones C and B. The maximum insulation thickness to be used for climate zones with cold winters (E) is 240 mm, which is considered to be the maximum achievable from a technological point of view. For climate zones with warm summers, it is possible to use green roof technology.

Window-to-wall ratio

The WWR value for each functional unit must be equal to at least the minimum required by the current health-hygiene regulations in Italy (Table A.2). However, to improve the energy and environmental performance of the new building type defined for kindergarten, the following recommendations should be considered:

- in all climate zones, maintain the minimum value for the northern orientation according to current health-hygiene regulations to reduce dispersion during winter;
- in all climate zones, do not increase the size of windows facing East or West, as it does not result in any advantage in terms of energy or environmental performance;
- for climate zones D and E, provide a WWR value for the south-facing orientation of 50% to exploit solar gains during winter and save energy for heating; an increase above this value does not lead to any advantage (on the contrary, it could increase the energy required for cooling). In addition, to obtain a better value for the uniformity of natural light in the classrooms, it would be advisable to have 2 windows per classroom;
- for climate zones B and C, keep the WWR value for each orientation equal to the minimum required by the regulations to avoid overheating and, consequently, an oversized cooling system.

Solar shading system

The recommended sun-shading configuration for all south-facing functional units is a 2 m fixed overhang combined with an automated internal venetian blind (made of horizontal slats of a material with a high reflection coefficient) with outside temperature control (>24°C). For climate zones D and E, DGI > 22 can be used as an alternative, while for climate zones B and C, cooling control is recommended. For east- and west-oriented functional units, if the internal design functional distribution is similar to the new typological models identified, then no solar shading systems are required.

Internal partitions and finishes

The internal partitions can be made with a dry system consisting of a metal substructure and plasterboard panels with rock wool insulation in the cavity when necessary for acoustic insulation. For the interior finishes, it is advisable to use wood to ensure adequate environmental quality in terms of the emissions of harmful substances into the environment to protect the students and reduce the environmental impact of construction.

System

The recommended configurations of the systems of a kindergarten are as follows:

- Heating system:
  - generation system: heat pump with COP equal at least to 3.6;
  - distribution system: radiant floor panels for each functional unit.
- Cooling system:
  - generation system: heat pump with EER equal at least to 3.2;
  - distribution system: radiant floor panels for each functional unit.
- Ventilation system: air handling units with sensitive heat recovery an efficiency of at least 65%.

To maximize the production of electricity, for all climate zones in Italy, the recommended configuration for the installation of photovoltaic panels on the roof should have an East-West orientation and a tilt angle of 10°. The minimum distance between one row of panels and the other should be at least 70 cm to ensure the necessary space for maintenance and to avoid shading between rows of panels.

Three summary tables (Tables 3, A.5, A.6) for Florence and Palermo are reported to show the 3 different solutions for the structure and external envelope (solutions 5, 2 and 1, respectively). The tables also show the energy and environmental performance of the new building type (i.e., the typological models defined) and the appropriate changes to the typological factors. It is demonstrated that, for all 3 models and in both cities, the primary energy demand is less than 33 kWh/m^{2}year, and CO_2 emissions during both construction and operation are less than 20 kgCO_2/m^{2}year.

6. CONCLUSION

In conclusion, qualitative and quantitative guidelines to build new, environmentally friendly kindergartens in Italy were outlined. They can be considered as a reference during the preliminary phase of the design process for building a new school, taking into account both new teaching and pedagogical methods and recent regulations on energy savings and emissions reduction to tackle climate change. They define both the environmental and technological system for a new building type for kindergarten considering general characteristics, energy

TABLE 3. Example of application of guidelines with solution 2 for Florence [FI] and Palermo [PA] for all models.

	Model I1		Model I2		Model I3	
City	FI	PA	FI	PA	FI	PA
Structural solution	Steel frame structure					
Technological solution for wall	Solution 2					
Insulation material	Wood fiber					
Thickness of insulation for wall [m]	0.14					
Wall thermal transmittance [W/m^{2}K]	0.127					
Thickness of insulation for roof [m]	0.24	0.20	0.24	0.20	0.24	0.20
Roof thermal transmittance [W/m^{2}K]	0.142	0.167	0.142	0.167	0.142	0.167
Type of glass—Florence	66.2A(12)44.2A; solar factor = 50% – light transmittance = 74%					
Type of glass—Palermo	66.2A(20)44.2; solar factor = 69% – light transmittance = 78%					
Glass thermal transmittance [W/m^{2}K]	1.2	2.5	1.2	2.5	1.2	2.5
Window frame thermal transmittance [W/m^{2}K]	1.7					
South WWR	50%	25%	50%	19%	50%	20%
North WWR	8%		9%		13%	
East WWR	7%		7%		—	
West WWR	7%		8%		15%	
South solar shading—Florence	Fixed overghang (2.00 m) + automated internal venetian blinds with control on external temperature > 24°C or on discomfort glare index (DGI) > 22					
South solar shading—Palermo	Fixed overghang (2.00 m) + automated internal venetian blinds with control on external temperature > 24°C or on cooling					
East/West solar shading system	Not necessary					
Mechanical ventilation system	Air handling unit with free cooling on enthalpy (15 vol/h) with sensible heat recovery with efficiency 65%–Air change per hour based on UNI 10339					
Heating system COP	3.6	3.6	3.6	3.6	3.6	3.6
Cooling system EER	3.2	3.2	3.2	3.2	3.2	3.2
Primary energy demand [kWh/m^{2}year]	24.38	24.47	28.60	28.16	30.94	32.15
PV panels configuration	Orientation: East/West Tilt: 10° Minimum distance between panels rows: 0.70 m					
PV panels surface [m^2]	547.93		681.56		1271.5	
PV surplus energy production [kWh/m^{2}a]	95.79	124.18	91.57	141.42	94.30	122.07
Avoided CO_2 emissions [kgCO_2/m^{2}year]	52.11	67.55	49.81	76.93	51.30	66.41
Total amount CO_2 emissions	14.70	15.50	14.53	15.98	13.30	14.58

and environmental strategies, external layout, geometry, building organisation, orientation, structural and external envelope technological solutions, window-to-wall ratio, solar shading system, internal partition and finishes and system. They suggest and recommend solutions to choose the proper strategies, directly during the preliminary phase of the design process, to obtain a low-carbon school but also to size the school to make it comfortable for children. These guidelines are based on an interdisciplinary approach that consider many topics (architecture, energy, and environment), and consequently suggest the most suitable solutions to outline the building type for building a carbon neutral kindergarten. These guidelines offer an integrated approach that could help designers develop new school buildings in the context of obtaining a carbon-free economy by 2050. Finally, the method applied to define the guidelines described in the paper could be used to outline school building types in different climates because the methodology is absolutely applicable to other contexts.

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APPENDIX A

A.1 Input data for energy simulations (Design Builder)

For the energy simulation, the following design parameters for each single functional unit (thermal zone) were considered: (i) occupancy (persons/m^2) according to Appendix A of UNI 10339, (ii) minimum air flow rate according to the same legislation in Table III, (iii) heating setpoint of 20 °C during activity periods and 10 °C during the rest of the day in accordance with UNI/TS 11300-1, (iv) cooling setpoint temperature of 26 °C during activity periods and 36 °C at other times in accordance with UNI/TS 11300-1, and (v) internal gains according to UNI/Technical Specification (TS) 11300-1. Regarding the systems, the following equipment was initially considered for the energy simulations in the dynamic regime: for heating, a system with a gas condensing boiler with an efficiency of 90% with radiators; for cooling, a heating pump with an energy efficiency ratio (EER) of 2.5 with fan coil units; a mechanically controlled ventilation system with sensitive heat recovery with an efficiency of 50% to guarantee the hourly air exchange rates. Subsequently, the use of a photovoltaic system (0.15 kWp/m^2) installed on the roof was evaluated to guarantee the production of electricity from renewables on site. The photovoltaic system is on-grid, so electrical energy can be used from the public grid when the solar radiation is unavailable. However, electrical energy storage for the building is provided. Consequently, in this case, a heating pump system with a coefficient of performance (COP) of 3.6 and an EER of 3.2 with radiant floor panels and a VMC system with sensitive heat recovery with an efficiency of 65% were considered.

TABLE A.1 Range of the considered parameters for on-a-time step sensitivity analysis.

N.	Parameter	Range
1	Shape	2 types (Model I2 and I3)
2	Type of structure	3 types (sol. 4–sol. 2–sol. 5)
3	Façade thermal transmittance (D)	0.275 W/m^2K–0.104 W/m^2K
	Façade thermal transmittance (B)	0.145 W/m^2K–0.104 W/m^2K
4	Roof thermal transmittance (D)	0.249 W/m^2K–0.120 W/m^2K
	Roof thermal transmittance (B)	0.340 W/m^2K–0.177 W/m^2K
5	Green roof technological solution	use it—not use it
6	South WWR	33%; 50%; 76%
7	East WWR	17%; 29%; 36%
8	West WWR	17%; 23%; 29%
9	Type of solar shading (South)—table A.3	4 types
10	Vertical solar shadings	West–East orientation
11	Lighting efficiency	120 lm/W (LED); 22 lm/W (halogen lamps)
12	Attenuation temperature for heating	5°C; 10°C; 15°C; 20°C
13	Air change per hour	standard value (sv); 0.5 sv; 0.25 sv; off sv
14	Heat recovery efficiency	50%–90%
15	Free cooling	on—off

A.2 Technological solutions for both external envelope and roof

- In solution 1, the building has a reinforced concrete frame structure, with a PPV consisting of lightweight bricks (0.30 m), an external insulation and an internal false wall of 0.10 m composed of a double plasterboard panel (0.07 m air cavity and 0.015 m thick panels) and rock wool insulation (0.04 m) to ensure the acoustic insulation requirements from the regulations. The roof is made with a brick slab (0.32 m) with slope screed (minimum 0.05 m), a vapor barrier (0.00045 m), a wood fiber insulation, a bituminous waterproofing with double reinforcement (0.005 m) and a gravel layer (0.05 m).
- For solution 2, the building has a steel frame structure, a PPV (dry solution) made of external cement board (0.0125 m), a waterproof and windproof sheet (0.0018 m) that is permeable to vapor, an insulation layer, a plasterboard panel (0.015 m) and an internal false wall, as in solution 1. The roof is made with a corrugated steel sheet slab (0.0015 m thick and 0.053 m high) with collaborating slab (0.045m), slope screed (minimum 0.05 m), a vapor barrier (0.00045 m), wood fiber insulation, bituminous waterproofing sheet with double reinforcement (0.005 m) and a gravel layer (0.05 m).

- For solution 3, the building has a steel frame structure, a PPV with autoclaved aerated concrete blocks (0.30 m) and an internal false wall, as in solution 1. The insulation layer is not present because the low thermal conductivity of the autoclaved aerated concrete blocks allows the required transmittance to be obtained without insulation. The technological solution is the same as that used for the roof in solution 2.
- For solution 4, the building has a wooden structure with a platform frame with 0.05 m × 0.10 m columns organized 0.60 m apart, a PPV made with a single oriented strand board (OSB) (0.02 m), an insulation layer with a waterproof and windproof sheet (0.0018 m) that is permeable to vapor, a single OSB panel (0.02 m) and an internal false wall, as in solution 1. The roof consists of a platform frame structure with a single OSB panel (0.02 m), a vapor barrier (0.00045 m), a wood fiber insulation, a wood cement panel (0.022 m), a bituminous waterproofing sheet with double reinforcement (0.005 m) and a gravel layer (0.05 m).
- For solution 5, the building has a wooden structure with 0.13-m-thick 5-layer cross-laminated timber (XLAM) panels, a PPV with external insulation applied directly on the XLAM panel and an internal false wall, as in solution 1. The roof has a wooden structure with a XLAM panel (0.13 m), a vapor barrier (0.00045 m), a wood fiber insulation (low density; 0.04 m), wood fiber insulation (high density), a wood cement panel (0.022 m), a bituminous waterproofing sheet with double reinforcement (0.005 m) and a gravel layer (0.05 m).

TABLE A.2 Minimum value of WWR for each typological model and variation step each orientation.

Model	Orientation	Minimum WWR	Variation step
I1	North	8%	—
	South	25%	33%; 50%; 76%
	East	7%	17%; 29%; 36%
	West	7%	17%; 23%; 29%
I2	North	9%	—
	South	19%	33%; 50%; 76%
	East	7%	17%; 30%
	West	7%	17%; 23%; 60%
I3	North	13%	—
	South	20%	30%; 51%; 77%
	East	No windows	—
	West	7%	17%; 23%; 60%

TABLE A.3 Final energy needs for heating and cooling for Florence (FI), Milan (MI) and Palermo (PA). The data shown are referred to Model I1. The North WWR is fixed and equal to 8%.

Model—City	Orientation	WWR	Final energy needs for heating [kWh/m^{2}year]	Final energy needs for cooling [kWh/m^{2}year]
I1—FI		20%	36.92	7.07
		33%	35.92	7.42
		50%	35.01	7.88
		76%	34.93	8.16
	East	7%	36.92	7.07
		17%	36.92	77.17
		29%	36.74	8.29
		36%	36.67	8.57
	West	7%	36.92	7.07
		17%	36.58	7.88
		23%	36.44	8.41
		29%	36.35	8.91
I1—MI	South	20%	54.11	3.66
		33%	53.15	3.89
		50%	52.18	4.19
		76%	52.19	4.34
	East	7%	54.11	3.66
		17%	54.29	3.97
		29%	54.40	4.25
		36%	54.45	4.39
	West	7%	54.11	3.66
		17%	53.58	4.29
		23%	53.34	4.71
		29%	53.16	5.10
I1—PA	South	20%	18.00	11.00
		33%	17.62	11.64
		50%	17.34	12.48
		76%	17.35	13.60
	East	7%	18.00	11.00
		17%	17.92	12.71
		29%	17.65	14.22
		36%	17.45	15.36
	West	7%	18.00	11.00
		17%	17.60	12.29
		23%	17.67	12.31
		29%	17.52	13.25

TABLE A.4 Different type of solar shading systems analyzed during the research.

Type of solar shading system	
1	Automated internal blind with horizontal slats with high reflection and control on solar radiation (120 W/m^2)
2	Combination of fixed overhang of 2 m and automated internal blind with horizontal slats with high reflection and control on solar radiation (120 W/m^2)
3	Horizontal louvres
4	External blind with horizontal slats with high reflection and control on solar radiation (120 W/m^2)

TABLE A.5 Example of application of guidelines with solution 5 for Florence [FI] and Palermo [PA] for all models.

	Model I1		Model I2		Model I3	
City	FI	PA	FI	PA	FI	PA
Structural solution	Wooden structure—XLAM panel (0.130 m)					
Technological solution for wall	Solution 5					
Insulation material	Wood fiber					
Thickness of insulation for wall [m]	0.10	0.02	0.10	0.02	0.10	0.02
Wall thermal transmittance [W/m^{2}K]	0.190	0.323	0.190	0.323	0.190	0.323
Thickness of insulation for roof [m]	0.22	0.14	0.22	0.14	0.22	0.14
Roof thermal transmittance [W/m^{2}K]	0.138	0.162	0.138	0.162	0.138	0.162
Type of glass—Florence	66.2A(12)44.2A; solar factor = 50% – light transmittance = 74%					
Type of glass—Palermo	66.2A(20)44.2A; solar factor = 69% – light transmittance = 78%					
Glass thermal transmittance [W/m^{2}K]	1.2	2.5	1.2	2.5	1.2	2.5
Window frame thermal transmittance [W/m^{2}K]	1.7					
South WWR	50%	25%	50%	19%	50%	20%
North WWR	8%		9%		13%	
East WWR	7%		7%		—	
West WWR	7%		8%		15%	
South solar shading—Florence	Fixed overhang (2.00 m) + automated internal venetian blinds with control on external temperature > 24°C or on discomfort glare index (DGI) > 22					
South solar shading—Palermo	Fixed overhang (2.00 m) + automated internal venetian blinds with control on external temperature > 24°C or on cooling					
East/West solar shading system	Not necessary					
Mechanical ventilation system	Air handling unit with free cooling on enthalpy (15 vol/h) with sensible heat recovery with efficiency 65 %–Air change per hour based on UNI 10339					
Heating system COP	3.6	3.6	3.6	3.6	3.6	3.6

TABLE A.5 *(Continued)*

	Model I1		Model I2		Model I3	
City	FI	PA	FI	PA	FI	PA
Cooling system EER	3.2	3.2	3.2	3.2	3.2	3.2
Primary energy demand [kWh/m^{2}a]	24.75	25.51	29.17	28.91	31.64	32.88
PV panels configuration	Orientation: East/West Tilt: 10° Minimum distance between panels rows: 0.70 m					
PV panels surface [m^2]	547.93		681.56		1271.5	
PV surplus energy production [kWh/m^{2}a]	95.42	123.40	107.93	140.67	93.60	121.34
Avoided CO_2 emissions [kgCO_2/m^{2}year]	51.91	67.13	58.71	76.53	50.92	66.01
Total amount CO_2 emissions	14.36	15.17	10.41	15.45	9.31	14.10

TABLE A.6 Example of application of guidelines with solution 1 for Florence [FI] and Palermo [PA] for all models.

	Model I1		Model I2		Model I3	
City	FI	PA	FI	PA	FI	PA
Structural solution	Reinforced concrete structure					
Technological solution for wall	Solution 1					
Insulation material	Wood fiber					
Thickness of insulation for wall [m]	0.08	0.00	0.08	0.00	0.08	0.00
Wall thermal transmittance [W/m^{2}K]	0.190	0.324	0.190	0.324	0.190	0.324
Thickness of insulation for roof [m]	0.22	0.18	0.22	0.18	0.22	0.18
Roof thermal transmittance [W/m^{2}K]	0.138	0.163	0.138	0.163	0.138	0.163
Type of glass—Florence	66.2A(12)44.2A; solar factor = 50% – light transmittance = 74%					
Type of glass—Palermo	66.2A(20)44.2A; solar factor = 69% – light transmittance = 78%					
Glass thermal transmittance [W/m^{2}K]	1.2	2.5	1.2	2.5	1.2	2.5
Window frame thermal transmittance [W/m^{2}K]	1.7					
South WWR	50%	25%	50%	19%	50%	20%
North WWR	8%		9%		13%	
East WWR	7%		7%		-	
West WWR	7%		8%		15%	
South solar shading—Florence	Fixed overghang (2.00 m) + automated internal venetian blinds with control on external temperature > 24°C or on discomfort glare index (DGI) > 22					
South solar shading—Palermo	Fixed overghang (2.00 m) + automated internal venetian blinds with control on external temperature > 24°C or on cooling					

TABLE A.6 *(Continued)*

	Model I1		Model I2		Model I3	
City	**FI**	**PA**	**FI**	**PA**	**FI**	**PA**
East/West solar shading system	Not necessary					
Mechanical ventilation system	Air handling unit with free cooling on enthalpy (15 vol/h) with sensible heat recovery with efficiency 65 %–Air change per hour based on UNI 10339					
Heating system COP	3.6	3.6	3.6	3.6	3.6	3.6
Cooling system EER	3.2	3.2	3.2	3.2	3.2	3.2
Primary energy demand [kWh/m^{2}a]	24.71	25.22	28.90	28.73	31.29	32.72
PV panels configuration	Orientation: East/West Tilt: 10° Minimum distance between panels rows: 0.70 m					
PV panels surface [m^2]	547.93		681.56		1271.5	
PV surplus energy production [kWh/m^{2}a]	95.46	123.43	108.20	140.8	93.95	121.50
Avoided CO_2 emissions [kgCO_2/m^{2}year]	51.93	67.14	58.86	76.62	51.11	66.10
Total amount CO_2 emissions	18.59	19.58	18.12	19.36	16.43	17.71