Feasibility study and design of a low-energy residential unit in Sagarmatha Park for environmental impact reduction of high altitude buildings

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Abstract:

The project presented in this paper is geographically set within Sagarmatha National Park, a wide area located on the Nepalese mountainside of Everest and declared as World Heritage Site since 1979. In recent years the park was the focus of several studies and initiatives, aimed at improving the management of its many-sided ecosystem, significantly influenced by climate change and increase of human activities and tourism, which occurred from the end of the 1970s, as well as by practices that are harmful both to human health and to our environment (e.g. burn up kerosene or animal excrements in order to obtain heat).

Research work has focused on designing a residential unit that meets population needs, in terms of simplicity of realization, replicability, use of local materials, environmental compatibility and exploitation of available renewable energies. For this purpose a thorough analysis was conducted to identify the housing standard characteristic of reference context and Sherpa people, concerning indoor thermal comfort conditions, construction techniques, availability and skills of local workforce. Data necessary for the design phase were obtained through a collaboration with researchers of Ev-K2-CNR center, active at 5,050 meters a.s.l. in Nepal at the base of Mount Everest with a laboratory/observatory (known as the "Pyramid") for high-altitude meteorological studies since 1989. Climate conditions were registered by specific monitoring stations at certain times (2002-2008); during preliminary stage, these values were considered representative of the local context chosen for the project, that is Namche Bazar, a village located within the park, in a central point both from the logistic and altimetric/weather points of view.

For the residential unit under investigation, two different constructive approaches were selected and compared: earthbags and straw bales. Both techniques have several advantages, in particular availability of raw material (jute bags, soil, straw), simplicity (e.g. earthbag constructions are realized using the ancient technique of pisé, combined with flexible bags or tubes), durability, insulation performance, cost-effectiveness. Through a specific software for calculation of winter/summer thermal loads, different combinations of selections of structure and insulation were examined for both solutions, in order to achieve the optimum for the case study. Furthermore on the base of data monitored on site, a specific assessment was carried out to evaluate the potential of solar and wind resources. Aiming at entirely covering the heat and electric energy needs by exploiting renewable energy sources, various plant configurations were finally assumed.

Every single choice was made to reduce human influence on land resources, such as timber, and to improve internal and external environmental quality.

Keywords:

Energy and Environmental Sustainability, High altitude buildings, Earthbags, Straw bales, Low-energy Residential Unit.

1. Introduction

The present article describes a project started from the cooperation between the Industrial Engineering Department of the University of Perugia and the Ev-K2-CNR Committee in Bergamo.

Ev-K2-CNR is well known for the Pyramid International Laboratory-Observatory, the high altitude scientific facility located on the Nepalese side of Everest at 5050 meters a.s.l. (Fig. 1), which is one of the world’s most important centres for high-altitude meteorological studies since 1990 [1]. The project is geographically set within Sagarmatha National Park, in the region of Kumbu, a wide area located on the Nepalese mountainside of Everest and declared as World Heritage Site since 1979. In recent years the park was the focus of numerous studies and initiatives, aimed at improving the management of its many-sided ecosystem, significantly influenced by climate change and tourism increase, which occurred from the end of the 1970s, which had a considerable impact on the local economy.

The objective of this research work was to design a residential unit that meets the local people’s housing needs, in terms of simplicity of realization, replicability, availability and cost-effectiveness of materials, environmental compatibility and exploitation of available renewable energies. The aforementioned goals are in line with the present management approach of the park, aimed at reducing human impact on that environment. The scarcity of energy resources in some sub-realities of the park, for example, constrains local people to burn kerosene or animals excrements in order to produce heat. This causes very important problems both for the health of inhabitants of the area and for environment, as demonstrated by results of several monitoring campaign.

Climate data were provided by the researchers of the Ev-K2-CNR centre; since the park covers a wide area, climate values were registered by specific monitoring stations during the years 2002-2008. Among different options, the choice was addressed to Namche Bazaar (Fig. 2), a village located within the park, in a central point both from a logistical and altimetric/weather point of view. During the preliminary stage, these values were considered representative of the local context chosen for the project.

Fig. 1. The Pyramid Laboratory-Observatory, Ev-K2-CNR

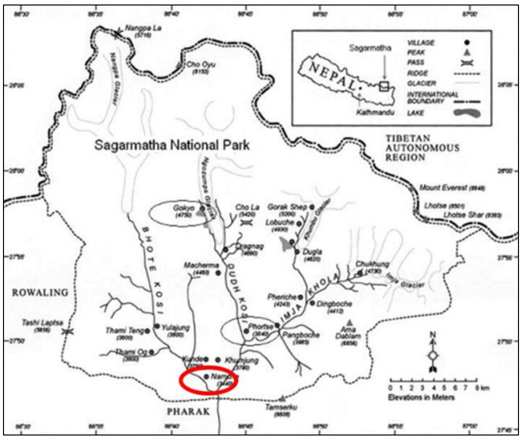

Fig. 2. Namche Bazaar, Sagarmatha National Park, Nepal

2. Site description

Sagarmatha National Park is a protected area in the Himalayas of Eastern Nepal, containing the Southern half of Everest. Sagarmatha is a Sanscrit word meaning “Mother of Universe” and it is the modern Nepali name for Mount Everest. The park lies within an area of 1148 km^2, which is located between 27° 30’ 19” - 27° 06’ 45” N latitude and 86° 30’ 53” - 86° 99’ 08” E longitude, on the border with the Tibet Autonomous Region. It ranges in elevation from 2845 m at Jorsalle to 8848 m at the summit of Mount Everest. Barren land above 5000 m is 69% of the park, while 28% is grazing land and the remaining 3% is forested; most of the park area is very rugged and steep, with its terrain cut by deep rivers and glaciers.

Unlike others, this park can be divided into different climate zones because of the rising altitude. They include a forested lower zone (alpine scrub), an intermediate one including the upper limit of vegetation growth, and the Arctic zone where no plants can grow. The indigenous Sherpa population is about 2500 people, mainly Buddhists, whose economy is based on agriculture and trade. Their properties were legally annexed to the park [2]. Since the first time the Everest summit was reached in 1953, the inflow of tourists was continuously increasing over the years, rising from 1400 visitors in 1972 to 7492 in 1989, to over 20,000 after 2004 [3].

2.1. Conservation management

The National Park and Wildlife Conservation Act (1973), the Himalayan National Park Regulation (1979) and the Buffer Zone Organization Guidelines (1979) provide legal basis for the conservation of flora and fauna. The main objectives of the conservation management plan are to protect animals, waters and grounds, since the park has national and international importance. It is also directed to safeguard the interests of Sherpas, as well as those communities living further downstream.

As for energy consumptions within the park, some elements must be take into account in order to propose effective patterns, which could be adaptable to this territory. Due to low temperatures and atmospheric pressure, the boiling point of water decreases at higher *altitude*. Although a lower energy consumption is necessary to reach the boiling point, cooking is longer due to the lower temperature and the energy consumption is nonetheless higher. The overall energy consumption for heating and cooking is therefore higher. Moreover, there is a different availability of energy resources, such as wood (88%), kerosene (7%), LGP (2%), animal excrements (2%) and sun energy (1%). However, because of its geographic distribution, wood is more consumed by houses located at altitudes between 2500 and 3000 meters than houses at higher altitudes, where wildlife has a lower concentration and combustible materials such as kerosene, excrements and LGP are more used (Table 1). *Income* is another discriminating factor for accessing energy resources, in fact high-income families use quality resources (e.g. LGP), while low-income families are forced to use low-quality materials (e.g. animal excrements). Finally *tourism* led, on the one hand, to the introduction of renewable sources (e.g. solar thermal panels) and, on the other hand, to spread construction techniques based on cement, which are poorly effective in this case, because of too wide glass surfaces, too thin walls and lack of appropriate thermal insulation, with a consequent increase in energy demand [4].

A study concerning the distribution of consumptions among different final uses shows that 56% is associated with cooking, covered mainly by wood and electricity, followed by kerosene and LPG. Wood, animal excrements and electricity are the most used sources for space heating (34%), while LPG and solar thermal systems are more used for heating sanitary water (8%). As previously noted, the use of solar collectors is a prerogative of the hotels with economic resources necessary for their installation [4].

The use of aforementioned fuels, together with bad daily habits (e.g. rooms' inadequate ventilation, which is also favored by an architecture that prefers the use of compact rooms with few openings) and obsolete technologies (e.g. stoves are not connected to a chimneypot, so they emit pollutions directly into the room), cause high levels of indoor air pollution. This reduces the quality of life and determine a number of respiratory diseases especially in elderly people, women and children. A survey carried out by the HKKH Partnership[1] registered, for example, the highest concentration of CO (200 ppm) during cooking hours in the homes with traditional cooking stoves (Fig. 3) [5].

The increase in touristic inflow entailed a greater need for wood as both building material and fuel. Because of the lack of a regulation on the park forests conservation management, since the 1960s there was a progressive deforestation and the consequent alteration of the hydro-geological system, combined with strong impact on Sagarmatha Park's biodiversity and, therefore, on its wildlife balance [4].

Moreover, progressive worsening of water environmental conditions was registered in Kumbu in recent decades, due to uncontrolled human pressure on natural resources. The proliferation of alpine

[1] The HKKH Partnership Project aims at consolidating the institutional capacity of planning and managing the socio-ecological systems in the regions Hindu-Kush-Karakoram-Himalaya.

tourism generated accumulation of waste along the paths beaten by excursionists, which subsequently fell into torrents and rivers; in addition, organic waste is usually discarded into designated wells or trenches close to houses, and chemicals waste is generated by fertilizers used in agriculture [6].

2.2. Climate data

The data used for this project are based on values measured during CEOP Himalaya experimental project, which provides long-term monitoring of monsoons effects at higher altitudes [7]. Measurements were made every hour during the period from 01/01/2002 to 31/12/2008. Fixed on site station monitors the following parameters at different altitudes (1.5÷5 m): atmospheric pressure (P); air temperature (T); relative (U_r) and specific humidity (U_s); speed (v_V), direction, horizontal and vertical components of wind; rainwater (P_p), incident solar radiation (H_{gh}).

The data shown in table 2 are an average of the measurements made over the period between January 2004 and December 2008. Solar radiation is quite constant over the year, with a maximum value in May; there are also two peaks, which occur in June and September, respectively at the end of the pre-monsoon period and at the beginning of the post-monsoon one. The reason is that in this lapse of time, the rain and an intense cloudiness filter the sun rays , thus provoking a decrease in the measured solar radiation. Regarding the external air temperature, the annual range goes from a maximum of 23 °C to a minimum of -13 °C (punctual values). On the basis of wind speed hourly values, the related duration curve was graphed (Fig. 4); it highlights for how many hours over a year a specific speed is exceeded in the selected site.

Table 1. Daily mean per capita consumption of primary energy sources for each altitude range

Altitude, m	Wood, kg	Kerosene, kg	LGP, kg	Excrement, kg	Electricity, kWh_e
2500-3000	23.46	0.88	6.52	-	2.4
3000-3500	10.93	5.25	7.6	-	23.4
3500-4000	13.31	5.6	1.18	7.48	11.23
4000-4500	16.61	5.77	1.29	8.62	4.5
4500-5000	-	15.66	1.52	14.03	1
>5000	-	9.8	-	9.93	1

Table 2. Monthly mean values of some climatic variables

Month	P, hPa	T_e, °C	U_r, %	U_s, g/kg	v_V, m/s	P_p, mm	H_{gh}, MJ/(m^2day)
J	661.9	-1.27	66	3.24	1.46	10	13.15
F	661.2	-0.54	78	4.26	1.65	20	16.28
M	663.5	2.66	79	5.42	1.79	50	20.21
A	664.8	5.33	81	6.64	1.85	80	23.13
M	663.9	7.89	90	8.96	2.08	110	22.89
J	663.6	10.26	98	11.61	1.92	490	17.30
J	664.0	10.92	100	12.31	1.84	580	15.98
A	663.8	10.88	99	12.21	1.81	520	15.67
S	666.3	9.61	83	9.41	1.66	330	16.32
O	666.6	4.85	90	7.23	1.66	30	18.10
N	665.1	2.93	72	4.97	1.52	10	15.77
D	663.5	2.04	60	3.80	1.29	10	14.27

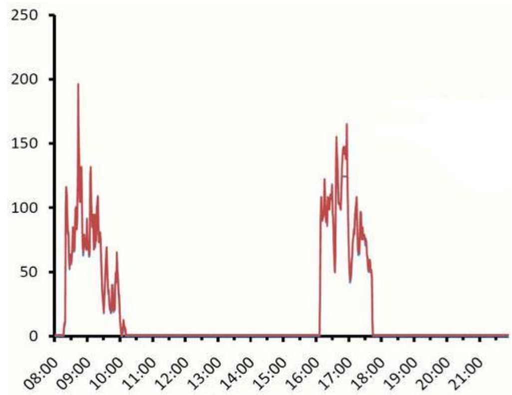

Fig. 3. Average daily trend of CO concentration (ppm)

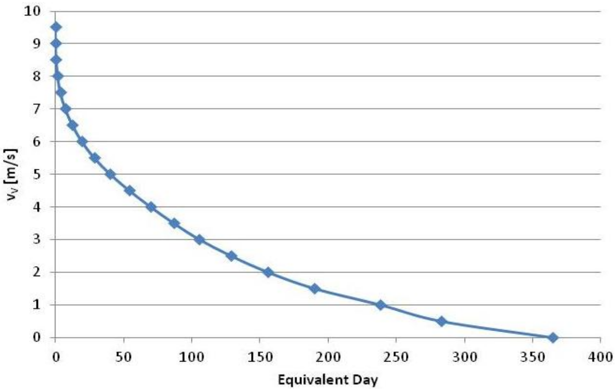

Fig. 4. Duration curve of wind

3. Construction techniques analysed for the residential unit

3.1. Architecture and local construction techniques

Part of the work involved the analysis of the construction types existing on site, in order to design a residential unit sustainable from the energy point of view (including the use of local materials) as well as integrated within the local context.

In the Himalayan region the resources used in construction are mainly wood for internal support structure, stone or soil for envelope, according to different installation techniques: compressed clay (gyang) or sun-baked mud bricks (saphang) [8]; dry masonry with different types of foundation according to the substrate type. From the architectural point of view, Sherpa villages have three distinct types of housing, one of which is the basis of the others, characterized by elongated shape, two-levels, ground floor partially adjacent to the side of the mountain. The simplest type (basic module), and consequently the most used by Sherpas, provides a single block, where ground floor is formed of store (for fodder, firewood and agricultural tools) and the stable for livestock, with a wooden staircase which leads to the upper floor, where there is a large space dedicated to domestic and social life of the family (Fig. 5). The other two housing types are obtained by adding two or more blocks to the basic module described above, thus resulting in an even more elongated or L shape house.

Therefore, in Khumbu region houses are mainly made of stone, which is abundantly present throughout the territory and derived from reclamation of agricultural soils or recovery of collapsed material or picked up along rivers, dry laid using techniques that depend on both the region and the stone typology (Fig. 6). External masonry walls are characterized by natural stone veneer facing or may be covered by a soil layer which acts as a plaster; the stone layer should be about 70-80 cm thick, however, this measure may vary within the park, given that it is a self made construction and therefore a standard process guide lacks. Wood, precious material in regions subject to excessive deforestation such as Solukhumbu, is mainly used for load-bearing structures and works of completion; concrete is used only in recent years for commercial and tourist buildings. As for floor, timber joists are disposed perpendicularly to the main girders, overlaid by floorboards; the roof is characterized by the same structural scheme, except for the specific inclination of the pitched roof. Windows have a timber frame and 3-4 mm thick single glasses; the openings are exposed to South-East in order to maximize the light in the house [9].

For the residential unit subject of study, the use of *reinforced concrete* structures was initially excluded; since it is not a technique rooted in the region, it would require the intervention of specialized technicians both in design and construction phases, option economically unattractive. About *steel*, the considerations are nearly similar, although in the design phase it was taken into account for realizing the bearing structure, in replacement of traditional wood; the supply of certain materials in the villages immediately next to the infrastructural network could, in fact, relatively affect the final cost of the work. *Wood* could be a viable alternative, being a material which is already used in the region; however, the aforementioned considerations concerning the deforestation problems make it an unsuitable choice.

Thus, an assessment was carried out on possible sustainable construction techniques in the area described above, from an economic point of view and for the use of local material and labour.

Apart from bamboo, which is available in Nepal but not in the Khumbu region, buildings made of straw bales and earthbags were analysed. Both techniques have several advantages:

- *Material availability*. Straw for insulation is a material widely present in a region based on sheep farming such as the examined area; the same consideration applies to the jute bales, of which Nepal is a leading global manufacturer.
- *Simplicity of construction*. These types of housing may also be made by unskilled people, who do not have specific knowledge of the construction industry; they also have the advantage of being very versatile in terms of shapes, as they are not limited by the geometry of a basic element such as brick.
- *Durability*. If well protected, the filling material is generally not subject to decomposition, nest of worms or fire, therefore it is extremely durable. Some authors argue that the average life of these structures under service loads is 100 years [10].
- *Insulation performance*, through the use of materials such as straw or vermiculite.
- *Cost-effectiveness*, These building types are an inexpensive way to build, given the materials used, and therefore also represent an interesting solution in a context where the population does not have very high incomes [11].

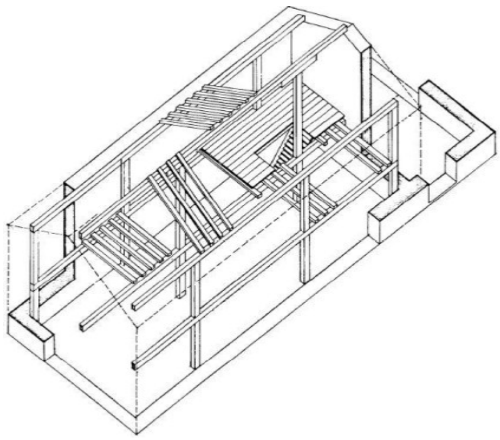

Fig. 5. Typical house perspective view

Fig. 6. Timber and stone house

3.2. Straw bale constructions

Techniques employing raw earth as building material are many and vary depending on the environmental, cultural and geographic characteristics in which they are applied, in particular: adobe, pisè, straw bales, torchis, pressed blocks, bauges [12-14].

Specifically, the straw bale technique considers the construction of a primary wall in bales of straw, supported by a timber or metal light structure, which is then covered with a layer of soil-based plaster, paying particular attention that this does not penetrate the straw; actually, the aim is to leave inside empty spaces, responsible for its insulating capacity. The technique of the soil-based plaster consists in proceeding by successive layers, with progressively finer granulometry; at the end of the process there can be a phase of smoothing and compacting of the surface. Given the predisposition to shrinkage, an adequate presence of fibers is expected for internal plasters not subject to rain and atmospheric agents; in case of exterior plasters, it is always preferable to add a binder material such as lime and cement, which gives more stability and increases resistance to humidity and rain water [15].

3.3. Earthbag constructions

The idea of building walls with dry stacked sandbags was started about a century ago in military and civil defense; the first uses of this technique was designed to control flooding and create military trenches (temporary facilities or barriers). A leader in this field is the German architect and researcher Gernot Minke who, since 1976, began to look for solutions for using sand and gravel instead of concrete. Later, around the beginning of the 1980s, the notion of permanent houses built in bags became popular thanks to Nader Khalili, an Iranian architect, who created the technique of "Superadobe", which consists in filling the bags with a mixture of clay, sand and water that, once dry, would have constituted the bearing structure [16-17].

The bags are filled in with soil of different granulometries, which should have a 30% clay component, characterized by a low tendency to expand when subjected to humidity (i.e. kaolinite) [15]. Alternatively, in case of filling with incoherent material, this should be added with a binder, such as lime and cement. The first bags were in natural materials such as canvas or jute, while more recently polypropylene is used; they offer excellent resistance against expansion, but are subject to damage by long-term exposure to UV rays, so they must be properly protected by a plaster layer.

4. Design choices

The analysis carried out in the present study does not consider the structural aspects of the module. The possible solutions in terms of materials are represented by wood and steel; at present, it is not possible to say which is the best, since some parameters are unknown such as cost, transportability, on site workers' skills, study of loads with related impact on the structural element sizes. From an environmental point of view, due to the increasing deforestation, steel would limit the timber use in constructions.

On the basis of what is described in the previous section, it was possible to define the dimensions of an elementary residential unit (Fig. 7), for which two different design criteria were also assumed for building envelope. Given the difficulty in finding specific information about doors and windows typically used in the houses, a qualitative assessment was necessarily based on the photographic available material. The front door is supposed to be in raw fir wood (0.9 m x 2 m, 2.041 W/m^2 K), as well as windows, with double glazing 4-12-4 (no. 1, 1.5 m x 1.5 m, no. 2, 0.9 m x 1.5 m, South-facing; 2.684 W/m^2 K). Particular attention should be paid planning these elements, because it is not possible to act subsequently in a non-destructive way.

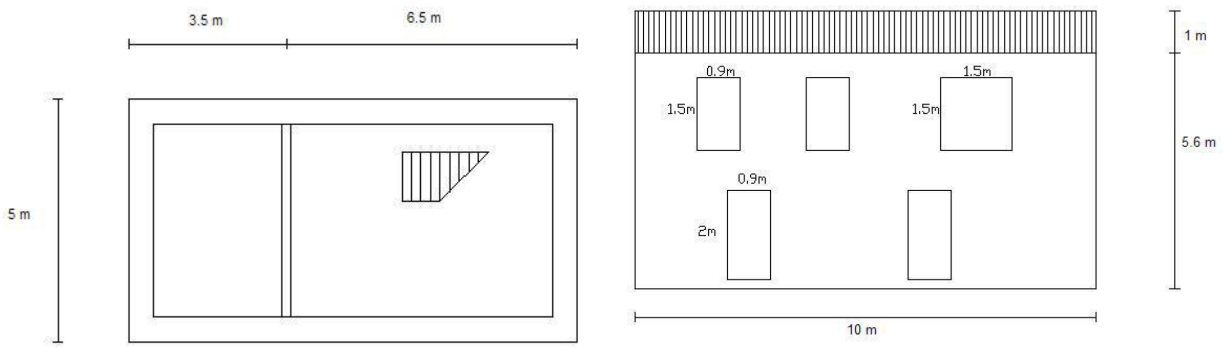

Fig. 7. Dimensions of the analysed residential unit

4.1. First design assumptions for the building envelope (S1)

The technique of straw bales requires a drying period for expelling the water contained inside. In order to evaluate the possibility to apply this technique in the Solukhumbu region, it is necessary to assess what is the most suitable period for the construction phase, depending on drying (and therefore on humidity) and on raw material workability (and thus on temperature). Based on the recorded parameters, the most binding constraint is the relative humidity, which, in the monsoon season (between June and August), reaches 100%; this forces to choose September and October as drying period, characterized by temperatures ranging between 5 °C and 12 °C and wind speed that, even if not so high, facilitates drying.

This type of external masonry veneer wall presents a good degree of insulation, according to the thickness of straw, but a reduced thermal inertia, due to the low density of straw and the thin soil layer. To solve this problem, the two properties can be separated, using the stone of the Himalayan areas in order to protect the exterior layer from atmospheric agents, thereby increasing the thermal inertia of wall assembly. The chosen solution among those analysed provides the following stratigraphy from the outside inwards: stone (30 cm), soil (2 cm), straw (45 cm), soil (2 cm), internal plaster (1 cm), for a total thickness of 80 cm and a transmittance of 0.186 W/(m^2 K). For its construction, the procedure consists in building a frame that wraps the straw bales previously stacked up. The frame, made in wood or in any material that could perform the same function, remains internal to the wall once the soil is laid mud and it is usually presented as a grid having a 50 cm pitch in both directions. A layer of soil with a high clay component is distributed on both sides, so as to close the internal straw walls; then a stone wall is built, which rests against the outer face, and finally the interior plaster is laid.

It is necessary to consider that the formation of internal condensation can cause the humidification of raw earth and for this reason vapor barriers should be used, that may inhibit the passage and avoid the wall degradation. Whereas, the exterior stagnation of rain water should be avoided by appropriate removal systems as small trenches and by raising the supporting basement. Another problem is the water rise from the foundation; in this case it may be convenient to create a draining wall plate made of sand or gravel, and create an overlying waterproof layer.

As for roofing, the chosen solution among those analysed provides the following stratigraphy from the outside inwards: board (2 cm), waterproof layer, layer of cellulose fiber such as leaves or straw (30 cm), vapor barrier, board (1 cm), for a total thickness of 33 cm and a transmittance of 0.297 W/(m^2 K).

The traditional buildings of the Khumbu region are characterized by floor made of timber joists and floorboards; the proposed solution plans of maintaining the above system, adding a lower board and filling the air gap with insulating material (e.g. 30 cm thick straw).

4.2. Second design assumption for the building envelope (S2)

The earthbag constructions have different shapes corresponding to specific needs. A dome shape gives self-bearing capacity to the structure, but it is not typical of the Solukhumbu region. Then for this case study a structure with vertical walls was considered, where the earthbags are used for the external masonry, while the roof is made of wood.

The earthbags usually provide high thermal inertia, but are characterized by a low insulating effectiveness. A possible solution is to couple them with straw layers, which determines an increased thickness of the wall structure (70-80 cm). The selected alternative, already indicated by Owen Oyger [18], consists in dividing the bag into two compartments, of which the exterior part filled in with insulation, and the interior part with soil, according to the following stratigraphy (from the outside inwards): plaster of soil and lime (1 cm), polypropylene (5 mm), soil (15 cm), polypropylene (5 mm), perlite (15 cm), polypropylene (5 mm), plaster of soil and lime (1 cm), for a total thickness of approximately 33 cm and a transmittance of 0.220 W/(m^2 K).

For this technique, specific types of foundation were tested, which could be used on site, in addition to traditional ones in lightened concrete; these are based on stabilization of the soil, already used for filling bags, through the addition of binding materials, usually cement, asphalt emulsifiers or lime [19-20]. Even in this case it is necessary to emphasize the importance of creating something able to prevent capillary rise; this barrier can be made using commercial products or, alternatively, local materials: two alternating rows of flat stones, for example, can be laid between the foundation and the first layer of earthbags. If soil does not provide a proper drainage, a foundation trench filled with small stones, gravel or cement debris has to be created; the first row of bags is placed, paying attention that each bag is well covered by the former. Common work tools are used for tamping, which are characterized by a flat base sufficiently large to cover half bag. Generally barbed wire must be placed at every level of bags, in two rows running parallel to the direction of the wall, spaced one each other by 20 cm; this has a velcro joint effect the prevents lateral expansion due to vertical compression. In order to improve the structural solidity, the bags must be installed vertically staggered.

For the roofing, the selected solution among those analysed provides the following stratigraphy from the outside inwards: joists and roof tiles (3 cm), waterproof membrane, perlite layer (20 cm), Kraft paper, timber layer (3 cm), lime and cement plaster (2 cm), for a total thickness of 28 cm and a transmittance of 0.22 W/(m^2 K). Regarding the floor, the choice is an insulation based on the use of a perlite layer in the assembly, according to a stratigraphy similar to the one used for the roof.

5. Energy analysis

The energy assessment of the module was performed using STIMA 10 TFM software, which aims at calculating winter and summer thermal loads, on the basis of climate and geographic parameters and all technical data related to the designed structure [21]. The studied residential unit was modeled to be calculated by the software, reporting each room size, doors and windows orientation, stratigraphies of the structural elements defining the heated volume (integrating the existing library). The energy analysis was also carried out on the basis of the assumptions described in the next paragraph.

5.1. Calculations

In the Solukhumbu region, district which includes the Sagarmatha Park, for the first time an experimental campaign was recently promoted, aimed at studying thermal control methods of residents, estimating their neutral temperature and evaluating thermal comfort conditions in inner spaces. The survey campaign was conducted by giving the inhabitants a questionnaire to complete concerning comfort levels of the housing, in relation to certain internal temperatures [22]. The study brings out the following results:

- winter conditions: average recorded internal temperature 6.5 °C; comfort temperature 13.4 °C;
- summer conditions: average recorded internal temperature 17.8 °C; comfort temperature 21.1 °C.

The external design temperature was set at -13 °C, while for the ground-floor rooms (unheated) the temperature of a "cellar with doors and windows closed" (5 ° C) was assumed.

Another assumption concerns the number of people inhabiting the module upper floor, assumed equal to 6 (based on the average number of children in each Nepalese family); this figure influences the definition of the air volume exchange rate and the internal heat gains (300 MJ/month). The average daily electricity consumption was assumed about 5 kWh_e [4].

The lack of homogeneity in materials such as soil, straw, or mixture of soil and straw does not allow the definition of unique values for quantities such as thermal conductivity or density. Not knowing accurately geological features of the specific site, the authors preferred to characterize the materials with average values that can be identified in the literature (Table 3) [13, 15].

5.2. Energy balance and preliminary design

Since it is not necessary to install summer air conditioning, only the energy demand for heating in the provided configurations S1 and S2 was determined during the heating months (from October to

April) as shown in table 4. A demand of 75 MJ per day of hot sanitary water was estimated, by considering a temperature in the incoming and outgoing water respectively equal to 5 °C and 45 °C, and an average daily consumption of 37 liters per capita.

In the preliminary phase, a study was carried out about the energy generation from solar photovoltaic panels (polycrystalline silicon, 180 W_p, 1.31 m^2, 13.7% efficiency) and thermal collectors (vacuum, 12 tubes, 1.92 m^2, 63% overall efficiency), as a function of the irradiation values recorded on site. Similar considerations also involved the wind resource; the integration of the duration curve with the selected generator power curve (2 kW_e, 4 blades, 1.3 m rotor diameter, 2 m/s cut-in speed) allowed to estimate an average annual generation of 920 kWh_e.

In relation to the different design solutions to cover the maximum thermal demand (January), it is expected:

- S1: 750 liters storage of heat generated from the solar system; in particular 12 panels are installed on a total gross surface of 26.5 m^2 out of 31 available, flush mounted to the roof pitch (37°).
- S2: 800 liters storage of heat generated from the solar system; it consists of 13 panels on a total gross area of 28.7 m^2 out of 31 available, flush mounted to the roof pitch (37°).

In accordance with the issues related to indoor air quality, an electric stove is planned in place of traditional wood-burning ones, which are source of air pollution in homes. It was chosen with an electrical rating of 1.5 kW_e [23], determining an average daily total consumption of electricity equal to 8.75 kWh_e. The electricity demand is covered by a photovoltaic system composed of 8 panels (10.5 m^2 of gross surface, outside of the Southern pitch of the roof, almost completely occupied by the solar thermal plant) and by a single wind generator (8 m hub height). In any case, since the module is designed to be autonomous and not grid-connected, electrical energy storage solutions were considered (8 batteries, 12 V, 100 Ah).

Figure 8 shows the comparison between energy demand (heating and hot sanitary water) and supply via thermal solar system, both for S1 and S2 assumptions . Besides figure 9 plots electricity demand and supply via photovoltaic and wind generators, considering that the average monthly wind speed is characterized by a distribution fairly constant throughout the year.

Table 3. Materials characteristics

Material	λ, W/(m K)	μ	ρ, kg/m³	c, kJ/(kg K)
Raw earth (Adobe)	0.635	7.5	1650	1
Raw earth (Pisè)	1.02	10.5	1950	1
Mixture of soil and straw	0.28	6	750	0.9
Straw	0.09	3	130	0.6
Fir wood	0.12	44	450	2.7
Perlite	0.04	9	150	0.84
Polypropylene	0.035	170	25	1.25
Plaster of raw earth and lime	0.8	8	1500	1.25

Table 4. Primary energy demand for heating

Month	S1, MJ	S2, MJ
O	1230	1318
N	1570	1708
D	1917	2124
J	3377	3838
F	2778	3136
M	2099	2327
A	1319	1428
Total	14,290	15,878

6. Conclusions

The work presented in this paper aimed to a preliminary study of a residential unit that allows to reduce the environmental impact of buildings at high altitude in the Nepali Sagarmatha National Park, meeting local people's needs, in terms of construction simplicity, replicability, availability and cost-effectiveness of materials, environmental compatibility and exploitation of available renewable energies. A series of obstacles were encountered due to the complexity of gathering reliable data during the study, especially with regard to diversity of Nepali reality from a social/cultural point of view, characterized by a specific concept of housing, both in terms of construction techniques and subjective conditions of climate comfort.

Thinking of a residential unit for a different context than European one implied a thorough analysis of the existing reality, in order to design an element sustainable in terms of energy, as well as integrated within the local context. After a survey of on-site characteristics, available resources and their conservation management, straw bales and earthbag buildings were selected between the construction techniques, sustainable from an economic point of view and for the use of local material and labour.

Through the use of a specific software, several configurations for the residential unit envelope were examined; on the basis of recorded data concerning solar radiation and wind on site, a preliminary assessment was also performed to evaluate the potential generation associated with the solar and wind resources. With the purpose of achieving full coverage of heating and electricity demands by using renewable energies, different plant configurations were then assumed, which allow to reduce the use of combustibles such as wood, animal excrements and fossil fuels.

Further future developments of the project may concern an in-depth examination of structural, plant and especially economic elements of the proposed residential unit and a verification of possible solutions for partial coverage of energy demands and/or centralized management of users within the settlements, in the perspective of a dual LCA/LCC assessment.

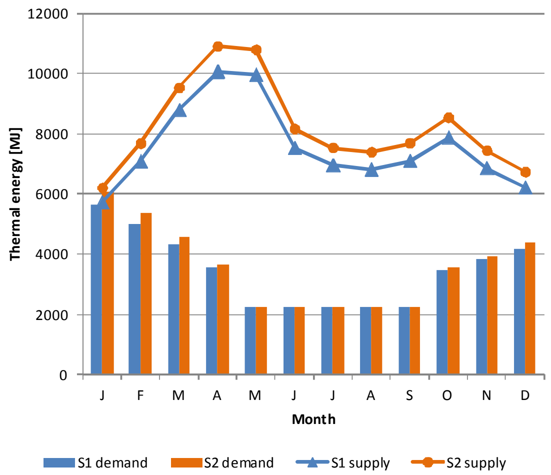

Fig. 8. Thermal energy demand vs. supply via solar system

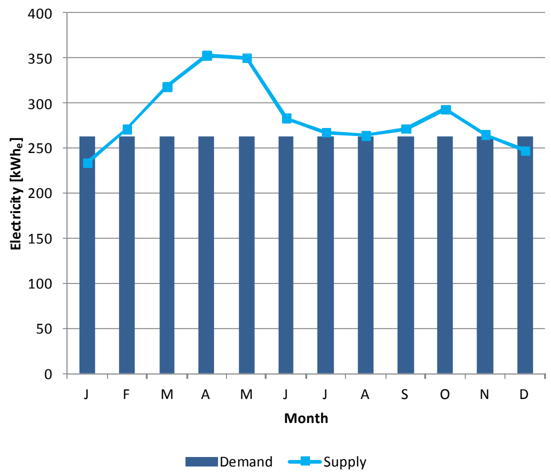

Fig. 9. Electricity demand vs. supply via photovoltaic and wind systems

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Nomenclature

c	Specific heat capacity, kJ/(kg K)
H_{gh}	Incident solar radiation, MJ/(m^2 day)
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LGP	Liquefied petroleum gas

ppm Parts per million

P Atmospheric pressure, hPa

P_p Rainwater, mm

T Air temperature, °C

U_r Relative humidity, %

U_s Specific humidity, g/kg

v_V Wind speed, m/s

Greek symbols

λ Thermal conductivity, W/(m K)

ρ Density, kg/m^3

μ Resistance to steam passage

Subscripts

e Electric

p Peak

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