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Solar heating and air-conditioning by GSHP coupled to PV system for a cost effective high energy performance building

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Abstract

Energy requirements for new buildings show the strong direction given by UE Directives to improve energy performance in buildings according to economic feasibility. Nowadays it is possibile to construct new buildings reaching a substancial reduction in energy consumption containing prices and time for the construction. In architectural competitions are always included architectural, energy and economic parameters of quality which are decisive in the success of the project design. A Housing Contest to collect projects with high performance and low cost for residential buildings for the Municipality of Comune di Milano, Italy, and the future construtions in the local area was launched by the to involve architects and professionals on the future development of the urban landscape giving specific requirements to achieve high performance. These requirements were focused on energy quality, acoustic quality, quality of the building site, guaranteed time schedule, prefabrication, economic affordability in comparison with the market trend of costs. The project presented in the paper is one of the chosen building by the Municipality to represent a pilot project for possible future constructions. In the Contest all the design group were in team with a builder to verify and guarantee the costs of the construction. The high energy performance required coupled to the low cost assured by the projects gave the Municipality a good example of how is possible to fulfill quality levels recommended by EU Directives and national regulations. In the Contest a high energy performance for heating was compulsory. The project described in the following paragraphs not only fulfill this energy requirement but also is almost self-sufficiency since it provides the energy for heating, cooling and common electrical demand.

Keywords: Building integration; solar heating and air-conditioning of buildings; renewable energy

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Nomenclature

HVAC	Heating, ventilation, and air conditioning
DHW	Domestic hot water
LCC	Life Cycle Cost
EPH	Primary energy for heating
EPH_{lim}	Limit of primary energy for heating
GSHP	Ground source heat pump
PV	Photovoltaic
ASHP	Air source heat pump

1. Introduction

Reducing primary energy means to minimize the environmental impact associated with generation by traditional sources and move toward the concept promulgated by the European Directive EPBD recast [1] of "nearly" zero energy buildings and supported by local government energy policies [2]. The Directive introduces also the concepts of energy efficiency and suitability, giving furthermore information regarding the plants to be adopted in high performance buildings. Each case will require customized design solutions according to the characteristics of the building, the site, the user profiles and internal loads. The natural lighting and ventilation can usefully been adopted to integrate energy needs of HVAC systems fed by renewable sources and to save a huge amount of energy coupled to economical feasibility as demonstrated in the case study presented.

The technical solutions for energy saving result from the analysis of the relationship between the building and the technical plants, using an approach to establish the interaction between the external environment, the inner space, the building envelope and HVAC systems [3]. The best solution is the one that will achieve a high standard in terms of usability, functionality and cost management, requiring the minimum cost of investment. Energy sustainability is pursued by working on different topics: morphology, construction, architectural technology, systems, focused to guarantee the lowest possible primary energy [4]. The evaluation process is iterative and considers the following parameters: climate data, availability of energy resources, mainly renewable, thermal visual and acoustic comfort levels, morphology and orientation of building, ratio between transparent and opaque envelope surfaces, building technologies and material, plants ensuring the required comfort level with the lowest energy consumption.

The production of almost the total quantity of energy needed for heating, cooling, common electrical consumption and DHW by the same apartment building that use it leads to a great reduction in running costs. In terms of LCC the annual cash flow is positively influenced by the use of renewable energy to feed the building since it can be considered as an income compared with a traditional system and therefore can be equal to the annual mortgage payment to payback the investment cost [5].

2. Project of a low cost and high performance building

2.1. Requirements of the housing contest

The opportunity of the project described in the paper comes from a Housing Contest lunched by the Municipality of the Comune di Milano, Italy, to collect projects marked by high performance and low price. The purpose has been the realization of a feasible stock of solutions for residential buildings which may be chosen and constructed in the Milan area in the next 5 years according with the prices adopted in the projects by the builders of each design team.

The Department of Local Development of the Municipality of Milan decided to set a challenge to designers, construction firms, parts and furnishing manufacturers, by sponsoring the "European competition to form a design directory for high performance, low cost housing". The competition's objective is to gather design proposals for housing with high technical and technological performance, but very low costs and definite time schedule [6].

The proposed residential buildings had to comply structural, energetic, acoustic and economic requirements and the projects presented had to be accompanied by a dashboard communicating synthetically the quality of the building.

The technical specifications included in the brief have been:

- Energy performance calculated with reference to regional energy regulation [7] at least equal to the minimum required to take advantage of the provisions of paragraph 1 ter of art. 2 of Regional law [8]: $EPH \leq 0.9\ EPH_{lim}$;
- Passive noise requirements at least equal to the class III of the acoustic classification of UNI 11367 [9,10,11];
- Compliance with the standards of earthquake [12], fire [13,14] and accessibility [15,16,17]

The typologies of buildings accepted could be apartment tower building or residential slab.

2.2. Performance of the project presented

The project presented is a tower building which reaches higher goals in comparison with the requirements of the brief. The building is zero energy counting air conditioning both in winter and summer. In table 1 the features of the designed building are resumed.

Table 1. Features of the project as presented in the dashboard required in the Contest Brief.

Energy requirement		
Energy label	-	Class A+
Costs and surfaces		
Construction cost	€	1.558.343,46
Finishing cost	€	6.387.180,57
Total cost	€	7.387.524,04
Gross floor area	m^2	5.000,00
Cost / m^2 of gross floor area	€/ m^2	1.589,10
Commercial area	m^2	6.278,68
Cost / m^2 of commercial area	€/ m^2	1.265,48
Schedule span		
Schedule span	months	20
Typological features		
Flats with double facing	N. 48	66,67%
Flats equipped with balcony	N. 72	100,00%
Acoustic requirements		
Acoustic performance	UNI 11367	Class I

2.3. Results of the housing contest

The Contest has collected more than a hundred proposals from architectural studios and engineering and it allows creating a stock of possible projects classifiable in the two typologies: tower building and residential slab. In Fig. 1 are listed the results for the tower building typology showing the construction cost (€/m^2 of gross floor area) and the construction schedule (months). The complete results for all the projects are published [18].

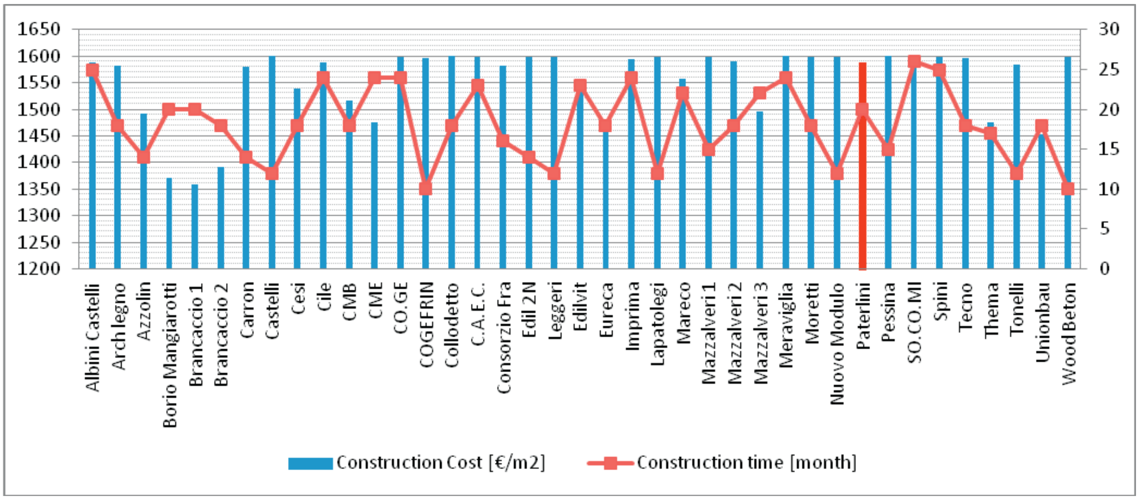

Fig. 1. List of competitors tower buildings at the Housing Contest; red mark is the Tower Building presented

3. Strategies for the tower building presented

3.1. Architectural and structural features

The building is a square and compact tower with a symmetrical structure to the outer perimeter wall, consisting of 12 plans for housing and 2 common spaces for users' activities. The building ensures the highest energy and acoustic performance. The square, rigid and symmetrical plant, driven by structures optimization, is in contrast and balanced by the use of curved finishing elements. The square plant with gross floor area under 500 m^2 can be reached by a single staircase and two elevators. Six apartments different in dimensions are located in each floor to meet the required mix of two storey type X and Y. The X floor is repeated 8 times and the Y floor 4 times with a total of 72 apartments. Their vertical alternation was studied to obtain a varied composition of the façade openings and parapets.

The plant is free from the structure and from constrains due to the HVAC distribution. Therefore there are several possible organizations of the interior space with plants opened with no changes while maintaining the facade and the divisions between the units. Mergers, divisions and combinations of units without changing facades are possible (Fig. 2).

The building is equipped with 2 levels of common spaces which can be used according to the demands of the users and their changing needs over time: from micro-nursery to play area, relax and green spaces at the 8th floor or at the ground floor, in continuity with the garden.

The building has the following geometric characteristics: height 46 m (with the structure supporting the PV plant is 49 m); the distance between ceiling and floor is 3,20 m; the plant is 26x26 m, the number of floors is 14. The foundation and supporting structure (columns, beams and "core") are reinforced and concrete over in situ, the floors are slabs in predalles. The structural analysis, conducted with a finite element model, was carried out in accordance with the national regulations.

The possibility to change the configuration of the plant of the building will stretch the useful life adapting the inner space to the extensions and contractions of the space needs. However it must be pointed out that the flexibility of the spaces and consequently of the number and typology of the users may have a dramatic effect on energy consumption. The goal of a zero energy building can be reach only in certain configurations. However in a residential building it is highly improbable that the variation may lead to a substantial change in global energy need and usually with the ageing of the building and the people living in there usually the energy consumption tend to be lower. In Fig.2 is shown the analysis on flexibility of the free plant and the possibility to assembly different units.

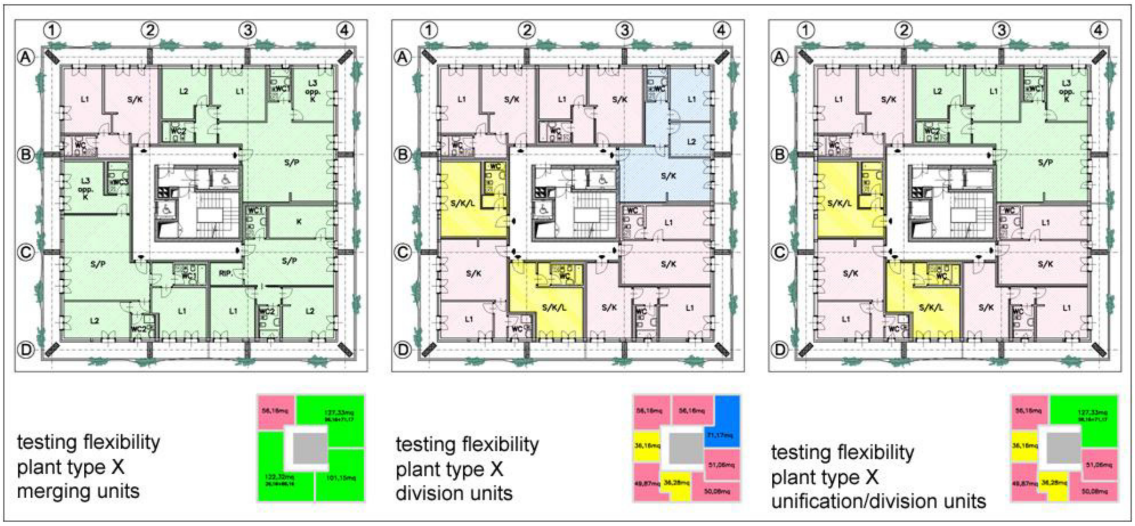

Fig. 2. Analysis on the flexibility of the building plant

In table 2 the typological availability of the apartments according with the Contest brief and the presented project are compared. The data resumed are number and dimensions of the flats and the percentage of gross floor area (GFA) designed to the flat typology in the building.

Table 2. Mix of apartment in the project of the Tower Building

		Housing Contest requirements			Design flat mix		
		N. of flats	m^2/flat	% GFA	N. of flats	m^2/flat	% GFA
A	One-room flat	8	35,00	5	8	36,16	5,79
B	Two-roomed flat	23	55,00	25	28	56,16	31,45
C	Three-room flat	11	70,00	15	12	71,17	17,08
D1	Three-room flat			25	8	86,16	27,31
D2	Three-room flat	15	85,00	25	4	83,31	27,31
D3	Three-room flat			25	4	85,73	27,31
E	Four-room flat	5	100,00	10	8	101,15	16,18
	TOTAL	62			72		

It is possible to evaluate how the project can implement the number and dimensions of the flats adding variety to the apartment mix. The interior spaces have high quality levels considering flexibility, acoustic and thermal comfort.

3.2. Technological plants

The project uses a centralized HVAC system producing hot and cold fluids through a GSHP (110 kW_{th}) that maximize the coefficient of performance and minimizes the consumption of electricity. The energy demand is supplied by an integrated photovoltaic system (85 kW_p) that feeds the thermal plant to provide heating and cooling demand and other common utilities, i.e. lifts, stair lights, water pumps, etc. The heat exchangers for the heat pump are installed in the horizontal structures in the basement, such as garages and cellars, using structure spaces where probes can be placed with almost no additional cost.

DHW production is also provided by individual ASHP placed into the bathrooms as traditional boilers however achieving a 70% of energy reduction compared to electric water heaters with an economic payback time less than 4 years. The internal terminals adopted for heating and cooling are radiant ceilings, using plasterboard components. The mechanical ventilation guarantees a renewal internal air stream and is combined with dehumidifiers for each unit, minimizing cost and complexity of the plant while preserving air quality and comfort. In modern building, almost air tight, renewal is strongly recommended since condensation in building elements causes a severe reduction in performance and signs of deterioration may take place in presence of strong envelope insulation with low permeability, high production of vapour, specific materials characteristics and variations in temperature.

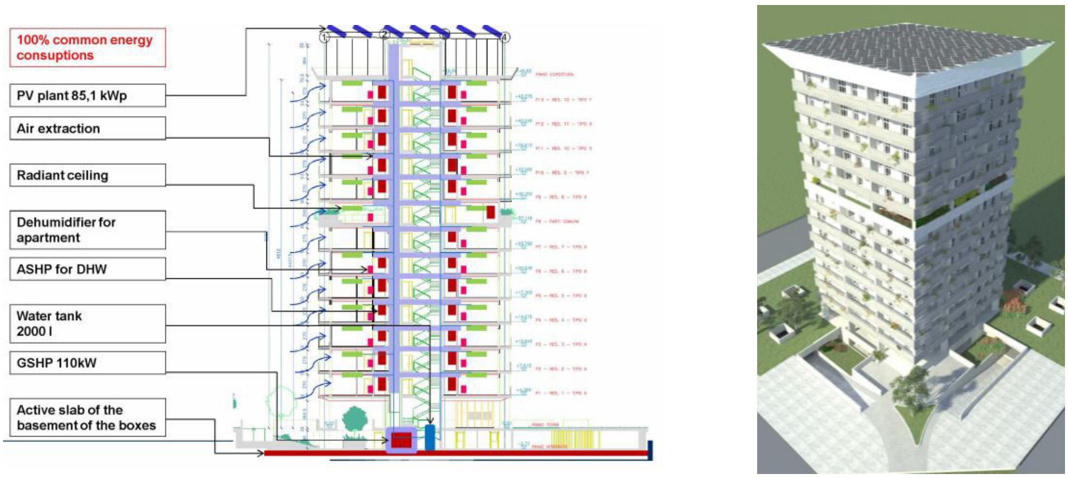

Fig. 3. Layout of the plants and rendering of the building; the PV plant is located on the rooftop

4. Energy performance

The building has a high insulated envelope (thermal transmittance of the opaque envelope 0,18 W/m^2K and 1,1 W/m^2K for the windows) and achieves a Class A+ in the local regulation scheme [19] with a primary energy consumption for heating of 11.42 kWh/m_2 year, with a reduction of nearly 80% of local energy threshold for new construction ($EPH = 0,22\ EPH_{lim}$) The cooling demand achieved is a Class B with 16.7 kWh/m^2 year.

The PV plant produces 95,3 MWh/year which covers the total energy required for air-conditioning, the electrical demand for common uses and the 45% of DHW demand. The Italian Feed in Tariff scheme to promote electrical PV production [20] guarantees an economic income of 18.000 €/year. The building represents a replicable high standard performance level in housing comfort: the average daylight factor in the indoor living spaces is 7,2% [21], the shading in summer period is above 50%, reaching 70% by movable devices, and the acoustic classification is the upper quality class (Class I) complying the national standards. The building doesn't use traditional fuel; even the kitchens are equipped with induction plates.

In high performance buildings which minimize heating and cooling loads, it is possible to provide these amounts of energy using solar systems; differently from traditional buildings the most relevant consumption is due to electrical domestic equipments, as shown in Fig. 4.

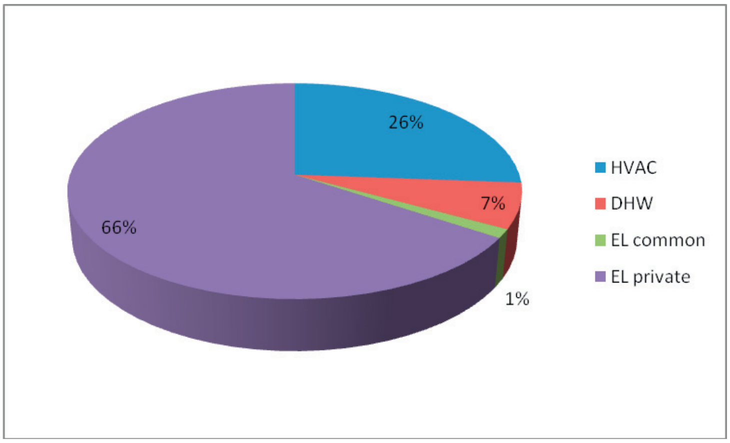

Fig. 4. Distribution of electric consumption in the tower building

The possible configurations of the solar roof, maintaining the extension into the footprint of the building and the maximum allowable building height to guarantee the goal of zero energy building are evaluated.

5. Economic aspects

The cost of the building had to be lower than 1.600 €/m^2, the average value of the tower projects presented to the Housing Contest was 1.554 €/m^2. The project presented in this study achieves the high performance result with a cost of 1.589 €/m^2.

5.1. Economic, energetic and environmental parameters

The results achieved in energy saving and environmental impact reduction due to the strategies used in the projects have not led to a substantial increase of construction costs, showing that high efficiency is consistent with low cost.

In table 3 are shown economic and environmental parameters of the Tower Building in comparison with the same project without the PV plant, often considered as an excessive extra cost, and the building with the same high quality features for the envelope but fed by a standard thermal system consisting of a condensing boiler for heating and DHW production and a ASHP for the cooling demand. It is possible to verify how the project achieves a 16% of primary energy reduction, and accordingly of running costs, with the advanced thermal plant described in Section 3.2 even without considering the PV plant.

The energy saving reaches the 42% adding the contribution given by the solar electricity. As result, using a GSHP for heating and cooling purpose and ASHP to provide DHW instead of gas for energy supply it is possible decrease the carbon dioxide emissions of 16%. Accounting the electricity of the PV plant the global reduction amounts to 42%.

A simpler thermal system that meets heating and cooling demand doesn't have a lower cost in comparison to the system designed for the Tower Building without the PV plant which has (table 3) a cost reduced by 1%. The real extra cost of the Tower Building with the PV plant is 2%, therefore it is possible to assume that energy efficiency, in this case, is really convenient.

Table 3. Comparison between a standard building and the project with and without the PV plant

Parameters	Units	Tower building with standard thermal system	Tower Building without PV plant	Tower Building
Primary Energy	kWh	794.472	667.455	463.625
Carbon dioxide emissions	kg CO_2	158.152	132.633	92.129
Yearly running costs	€	54.971	45.926	31.900
Total cost of the buildings	€	7.822.774	7.732.774	7.945.524
Payback time	Years	-	-9,9	5,3

5.2. Economic pay-back

The investment costs to realize the PV plant is strongly variable according to the market evolutions [22] and variations of prices. The cost considered in the project amounts to 212.750 € (2,500 E/kW$_p$) but recently the prices have shown a substantial reduction and it is possible to make a prediction that the cost in 5 years (i.e. the time considered by the Housing Contest) could be less than 80.000 € (940 €/kW$_p$).

Considering the cost of electricity as 0,15€/kWh [23] subjected to a annual medium increase of 2% and a Feed-in Tariff of 0,3 €/kWh for PV produced electricity it is possible to calculate the net present value (NPV) of the PV plant. By this economic parameter it is possible to understand if the investment is profitable in the long term period, when the NPV is positive. The NPV value is calculated as formula 1:

$$NPV = -\frac{TCI}{(1+r)^{-1}} + \sum_{t=0}^{24} \frac{F_t}{(1+r)^t} \tag{1}$$

Where:
- TCI is the investment total costs, expressed in €;
- F_t is the cash flow, i.e. the annual income of the system, expressed in €;
- r is the national interest rate;
- t represents the progressive number of the year.

In Fig. 5 are shown the results of the calculation. The higher NPV with the shorter payback time of less than 4 years is related to the lower cost of the PV plant (2017 scenario), considering the decrease of the incentive tariff of 2% for each year. In the more expensive case (2012 scenario) (blue line), we have a lower NPV and a payback time of 9 years, compatible with the lifespan of the plant and the building.

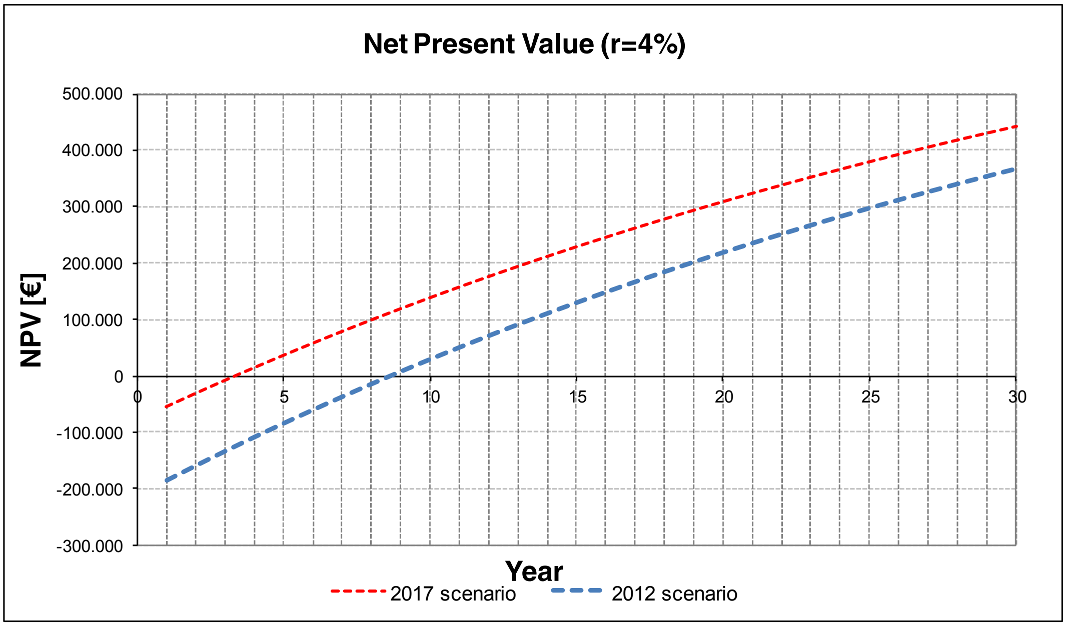

Fig. 5. Curves NPV for the two assumed cost of the PV plant

6. Conclusions

The strategy of solar heating and air-conditioning to supply energy to residential building has to be related to the possibility of feed efficient thermal systems as GSHP with PV systems to obtain a annual net zero energy balance. This result can be achieved by an integrated work on architectural and constructive features, thermal systems and renewable energy powered systems in the early phase of design. The process of design for high energy quality needs to connect and match different skills and to evaluate during the development of the project all the instances in a iterative trial of improvement. As stressed in the EPBD Directive the cost effectiveness of technological solution is a primary focus to allow the market penetration of such technologies and the review of the cost to guarantee economic feasibility has to be updated every 5 years. Therefore, the costs calculated for a solution of today has to be updated with the future costs derived by the market trend evolution. For that reason we calculate the economic advantage and payback time for the PV plant in the two cost scenarios. For air conditioning it is possible to stress that the cost of this kind of solutions is not higher than gas powered thermal systems coupled with low performance plant for summer air conditioning, which is the simplest system used in a wide range of buildings in Italian cities. Promoting a new way to design and construct building is an important step to lower energy needs related with buildings. The energy of this type of construction is almost 20 times lower than buildings constructed during the '70s or before. This means that a substantial renewal of all existing building according to these new standards will lower by a factor of 20 the primary energy demand of the town under analysis. That is to say that Milan which is a 1.5 million people city may use the same energy of a small town of no more than 75.000 people, not counting the reduction in pollution that can be achieved. This scenario however may not be easily achieved since many energy providers will not be happy with this situation because the annual income may be reduced by the same factor of 20. This energetic and economic decrease must be carefully governed by the politics otherwise the market itself will never easily allow such a huge reduction of profit.

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