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A New Model to Perform Preliminary Evaluations of Complex Systems for the Production of Energy for Buildings: Case Study

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***Abstract*—**The building sector is responsible, in many industrialized countries, for about 40% of the total energy requirements, so it seems necessary to devote some efforts in this area in order to achieve a significant reduction of energy consumption and of greenhouse gases emissions.

The paper presents a study aiming at providing a design methodology able to identify the best configuration of the system building/plant, from a technical, economic and environmentally point of view.

Normally, the classical approach involves a building's energy loads analysis under steady state conditions, and subsequent selection of measures aimed at improving the energy performance, based on previous experience made by architects and engineers in the design team. Instead, the proposed approach uses a sequence of two well-known scientifically validated calculation methods (TRNSYS and RETScreen), that allow quite a detailed feasibility analysis.

To assess the validity of the calculation model, an existing, historical building in Central Italy, that will be the object of restoration and preservative redevelopment, was selected as a case-study. The building is made of a basement and three floors, with a total floor area of about 3,000 square meters.

The first step has been the determination of the heating and cooling energy loads of the building in a dynamic regime by means, which allows simulating the real energy needs of the building in function of its use. Traditional methodologies, based as they are on steady-state conditions, cannot faithfully reproduce the effects of varying climatic conditions and of inertial properties of the structure. With this model is possible to obtain quite accurate and reliable results that allow identifying effective combinations building-HVAC system.

The second step has consisted of using output data obtained as input to the calculation model, which enables to compare different system configurations from the energy, environmental and financial point of view, with an analysis of investment, and operation and maintenance costs, so allowing determining the economic benefit of possible interventions.

The classical methodology often leads to the choice of conventional plant systems, while our calculation model provides a financial-economic assessment for innovative energy systems and low environmental impact.

Computational analysis can help in the design phase, particularly in the case of complex structures with centralized plant systems, by comparing the data returned by the calculation model for different design options.

***Keywords*—**Energy, Buildings, Systems, Evaluation.

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I. Introduction

THE energy requalification of an historic building has always been problematic due to architectural constraints exist; indeed, on one hand we try to improve the energy performance in order to reduce greenhouse gases released into the environment, on the other hand we need to respect the historical-cultural aspect of buildings. This problem is not new, of course, but its importance has been increasing as the time goes by, especially for increasingly stringent restrictions given by the rules to save energy, both nationally and internationally.

The system Building-Plant needs energy to maintain the internal conditions. Considering that a large proportion of this energy is wasted because of the poor efficiency of the plants and poor energy performance of facilities, it's easy to understand how serious this expense weigh on our network energy consumption is. There is another important aspect: the environmental impact. The more we consume of energy generated by the use of conventional primary sources (gas, oil, etc.), and the more is the amount of pollutants that entered in the environment. Spare energy in buildings is, therefore, the global objective to reach sustainable development of the entire community in the near future.

The classical approach involves an analysis of the energy loads of the structures in steady state, and a consequent design of measures taken from energy requalification of real estate, according to technicians' experience.

Very often the design choices, although adequate, are subject to constraints of various nature and they don't allow the identification of the optimal solution for the absence of a prospective analysis of feasibility that allow you a comparison of energy, environmental and financial data between different design and plant assumptions [1]-[3].

In this study, we propose a procedure that would allow you an optimal configuration of the system to be analyzed.

The integrated use in series of two scientifically validated methods of calculation (TRNSYS and RETScreen [4], [5]), allows a prospective analysis of feasibility; it starts with the determination of the energy loads of the structure in dynamic regime through the TRNSYS, in order to simulate the real needs of the structure, in function of its use. Traditional methodologies, today considered valid, cannot faithfully reproduce the variation of climatic conditions and inertial properties of the structures, given that the calculation runs under steady state. With the TRNSYS is possible to obtain more accurate results that allow you to achieve a correct coupling Building-Plant.

Thus, output data obtained are inserted as an input in the calculation model RETScreen that allows comparing different system configurations from the energy, environmental and financial point of view, with an analysis of investment, operation and maintenance costs that allow determining the economic benefit of intervention. The classical methodology often leads to the choice of a conventional plant system while the RETScreen allows you to get a financial-economic assessment for innovative energy systems and low environmental impact. Especially for complex structures often enslaved by centralized plant systems, computational analysis can help in the design phase, an optimal choice of intervention through comparison of the data returned by the calculation model RETScreen. Thanks to TRNSYS it's possible to get a correct calculation and dimensioning of the energy needs of the structure that allows us to provide a financial and economic analysis more accurate than the traditional model.

II. Case Study

The aim of this study is to evaluate the best plant configuration to be installed in a historic building compound that will be the subject of restoration and preservative renovation.

The building is divided into a basement and three floors with a total area of 3000 square meters.

III. Calculation of Thermal Loads with TRNSYS

The technical and economic convenience in the achievement of a plant requires a specific and accurate analysis of the electrical, heating and cooling loads required by the user. This involves the evaluation of the maximum power demand and daily, monthly and seasonal load curves.

To assess the requirement of thermal power by the compound, it's necessary to estimate the total heat loss from the building during the year. The procedure adopted was as a first step an analysis of all the structural and heat engineering features of the building:

- The geographical position taken
- The values of annual solar exposure
- The climate zone of interest
- The outdoor temperature.

The design conditions adopted in the study are as follows:

External Conditions:

- Summer: 34°C with 50% RH
- Winter: 0°C with 80% RH

Objective -> Internal project condition:

- Summer: 26°C
- Winter: 20°C

Given the restoration projects of the building, it' possible to analyze and implement in the software:

- The surfaces of walls and windows
- The sun exposure of each outer surface during the year
- The volumes
- The stratigraphy of the walls
- The thermal transmittance of each surface.

The outputs of TRNSYS Simultation Studio are presenting in form of graphs and tables that describes a dynamic thermal loads requested by the user. The results of simulation are shown in Fig. 1.

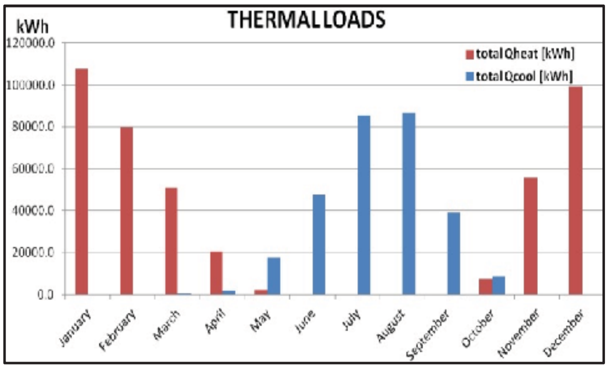

Fig. 1 Monthly thermal loads required by the user

The peak powers required by the compound for heating in winter and cooling in summer are respectively 294,9 kW and 317,4 kW.

Knowing the volumes and heated surfaces, it's possible to estimate the required heat power compared to the square meters of useful surface:

- Heating power to useful surface = 70,2 W/m2
- Cooling power to useful surface = 75,6 W/m2

The annual energy loads are respectively:

- Heating annual load = 422991 kWh/year
- Cooling annual load = 287141 kWh/year
- Heating annual load to useful surface = 84 kWh/year m2
- Cooling annual load to useful surface = 57 kWh/year m2.

In order to evaluate the need for electrical power of the compound luminance levels required in every room and the loads required by the various utilities, taking account of appropriate coefficients of simultaneity and utilization, were considered. The total electric power installed is 340144 W.

The peak powers are shown in Fig. 2.

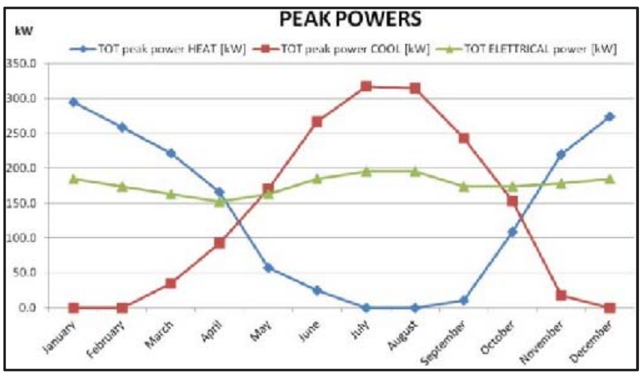

Fig. 2 Required power trend by the user

IV. Feasibility Study with RETScreen

The RETScreen Clean Energy Project Analysis Software (usually shortened to RETScreen) is a software used to determine the feasibility of energy models (including renewable energy systems or high performance) and tools to assess energy efficiency. The software allows the modeling of any power plant for real estate providing output data useful to a technical, economic and environmental analysis for an investment in a 'clean energy' project or cogeneration as in this case. The calculation model has been developed by the Canadian Government in collaboration with other governments with the technical support of an extensive network of industry, institutions and academia experts.

The classical methodology often leads to the choice of a conventional plant system whereas the peculiarities of the RETScreen is the possibility to assess the feasibility of complex, innovative and low environmental impact systems such as trigeneration, which requires an energy diagnosis deepened. The software performs a comparison between a base case, typically the conventional technology or measure, and a proposed case; this has a very important implications for the way in which the user specifies the costs: RETScreen does not consider the absolute costs but the incremental costs, that is the cost of the proposed case that are in excess of those of the base case. An analysis of the reduction of greenhouse gas emissions adheres to the same approach: RETScreen shows the reduction of emissions associated with the change of technology from the base case to the proposed case.

In the case study was considered a complex system, with a request energy variable in function of the end use. Through the output data obtained from the TRNSYS and shown in the previous section, we could build with RETScreen the models of plant configurations suitable to our case study.

In Table I are shown the reference data used in the conventional scenario for the exanimated building.

TABLE I
CONVENTIONAL SCENARIO OF ENSLAVEMENT OF RESIDENTIAL OR SCHOOL USERS TAKEN AS REFERENCE

Heating project	value	u.m.
Heated area of the building	5038	m2
Type of fuel	Natural Gas	/
Seasonal efficiency	300	%
Thermal loads of the building	70.2	W/m2
Request of domestic hot water	20	%
Total heating demand	677	MWh
Peak heat load	353.7	kW
Annual Fuel Consumption	23923	m3
Fuel Price	0.180	€/m3
Fuel Cost	4360	€
Heating project	value	u.m.
Cooled area of the building	5038	m2
Type of fuel	Electricity	/
Seasonal COP	3.00	/
Cooling loads of the building	75.6	W/m2
Total cooling demand	1056	MWh
Peak cooling load	380.9	kW
Annual Fuel Consumption	352	m3
Fuel Price	0.212	€/m3
Fuel Cost	74652	€

Once you have entered the weather data you need to set the necessary electrical and thermal loads to satisfy the user throughout the year, specifying the heated surface and above all the specifications relating to the conventional reference case that we will use such as parameter to define the validity of our new configuration. Some specification of the conventional case will be implemented in software:

- the type of fuel used
- the cost of fuel and electricity required by the load
- the efficiency of heating and cooling plants used.

The reference case, therefore, in this case, is the conventional scenario of enslavement of residential or school users:

- Consumption of electricity taken from the network
- Production of thermal energy for heating via a gas boiler.

Production of thermal energy for cooling through a compressor system is powered by electricity.

Once modeled thermal, electrical, and cold production plant through conventional configurations, we made a comparison with calculation models that use innovative technologies with a low energy impact by implementing an alternative energy model of the case study, with the aim of obtaining a energy savings and a consequent reduction of greenhouse gas emissions; for the case study were considered three possible configurations of trigeneration plant:

1. *Trigeneration with an Internal Combustion Engine*
2. *Trigeneration with Gas Turbine*
3. *Trigeneration with Fuel Cells*

Once implemented the energy model we introduced all cost items, such as initial, management and annual maintenance costs. From these specifications, it was possible to evaluate year to year savings attributable to each type of plant compared to the reference, also taking into account the incentives imposed by law.

The financial plan is rated for a project life of 15 years, taking into account the current financial parameters (inflation rate, discount rate and rate of indexation of fuel). The financial incentives which you can use for this type of cogeneration plant (> 200 kW) are [6], [7]:

- White Certificates
- Credit for reduction of greenhouse gases.

Recalling that in Italy all cogeneration plants with an "high efficiency" for electric power up to 200 kW, can take advantage of the service “Net metering”. Plants with a capacity greater than 200 kW can still sell electricity to the grid at favorable conditions laid down under the “Withdrawal dedicated”.

It’s important to specify that, in this type of plant, the electrical tracking is not advisable due to efficiency losses of almost two percentage points. In this user where there is a great variety of energy needs, characterized by a teleheating plant, we have verified that it is more rational to fully meet the thermal requirements for never having to lose the useful thermal power output downstream of the plant with the result that the system sells or consume electricity of the network to which it is connected.

V. PLANT TRIGENERATIVE

A plant trigenerative is able to simultaneously satisfy the requirement of electric, heat and cooling power. In fact, as shown in Fig. 3, in this type of plant the waste thermal energy is recovered downstream of the process to produce cooling energy, in other words chilled water for air conditioning or for industrial processes [8]. The possibility to couple to a cogeneration plant a classical absorption machine shows the many possibilities and prospects for these new systems. The applications for the trigeneration plant are the same as cogeneration, with particular reference to those users where is a constant demand for energy in all its forms (heat, electricity, cold). [9]

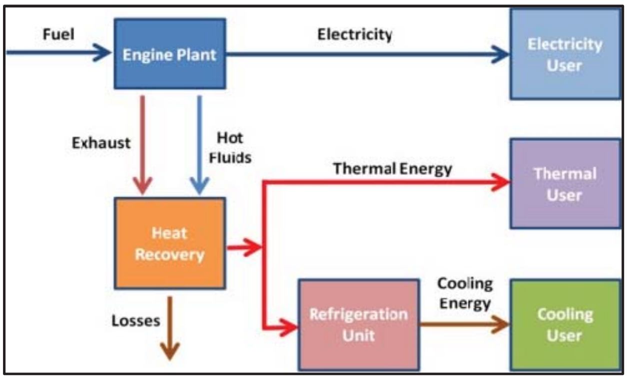

Fig. 3 Block diagram of the trigenerative plant

Technological progress, thanks to constant research in the field, has resulted trigeneration plants afford to offer an efficiency superior to 90%, low environmental impact, low noise and, thanks to electronics, greater ease of use and management [10]. The fundamental performance of a cogeneration plant are expressed through its electrical efficiency, the ratio between the net electricity produced and the energy of the fuel used, and its thermal efficiency, the ratio between the useful thermal energy and the energy of the fuel used [2]. The sum of the two efficiencies expresses the overall performance of the cogeneration plant and represents the portion of the fuel energy converted into useful energy [9].

$$\eta_{cogen} = \frac{E_{electricity} + E_{thermal}}{E_{fuel}} = \eta_{el} + \eta_{th} \quad (1)$$

CHP is a technological alternative to the conventional plant that is more frequently present in the civil sphere. In fact, the conventional solution that is currently most prevalent in urban areas to satisfy the energy needs of civilians [11] is represented by the connection to the electricity grid, to meet the demand for electricity, and the use of centralized or autonomous boilers, to meet the demand of thermal energy relative and the production of domestic hot water [9]. The diffusion of cogeneration technologies in domestic residential requires that these are effectively convenient from the energy, economic and environmental point of view.

The basic types of plant to generate electric power and useful thermal energy at the same time are [8], [12]-[18]:

- Internal combustion engines
- Gas turbines
- Steam turbines
- Combined cycle gas-steam
- Stirling Engine
- Fuel Cells
- TR.E.BIO.S - Renewables (Low Impact). Innovative ENEA solar technology, characterized as supply chain TR.E.BIO.S (Trigeneration with Renewable Energy: Biomass and Solar Power).

Each of them presents some unique characteristics that make it suitable for particular configurations and performance classes. The relationship between thermal and electrical energy consumed guide in choosing the type of installation.

VI. Analyzed Configurations

The first scenario is assumed starting from a use of a combustion engine with a total recovery, which concern the exhaust gas, recovered heat from the coolant and the recovery of the lubricating oil, as shown in Fig. 4. Through this heat recovery in output from the engine, there are many types of cogenerators that can reach value of efficiency greater of 60% [1], [19].

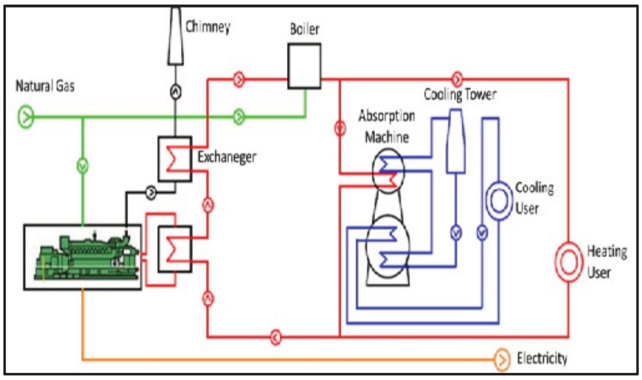

Fig. 4 Diagram of trigeneration

In our system the engine represents the cogenerator, which through a full recovery will take advantage of the thermal energy output at different temperature levels [1]. In the moment when the electricity demand exceeds the availability provided by the cogenerator, the system is able to exchange and then receive energy from the electricity grid. As for the thermal energy peak load, the system has assumed a gas boiler relief (installed power of 498kW) and refrigeration compressors (installed power of 104 kW with seasonal COP of 3.87) regarding the application of cold. The total power of the engine is equal to 852kW, 330kW than electricity while the recoverable at 120 °C equal to 358kW. With this model we are able to achieve an overall efficiency of 81% tri-generation.

The thermal energy required to satisfy the hygrometric comfort of users in winter is transformed, in the summer, in cooling energy thanks to absorption machines. The installed power of the absorption machine (single-effect), in this trigenerative plant, is equal to 348kW with a seasonal COP of 0.7.

The second case analyzed with RETScreen is characterized by a cogeneration plant based on gas turbine [20]. Regarding the production systems of electricity and heat energy is considered to use the same machines in the previous case. The heat recovery is possible thanks to the high temperature of exhaust gases leaving the turbine [1]. Also in this case were analyzed energy parameters relevant to the evaluation of the model were calculated investment, operating and maintenance costs and have been estimated annual pollutant emissions (tCO2 / MWh). In this case, we calculated an installed power of 1330kW, an electric power of 400 kW and a power recoverable at 280 °C equal to 358kW. So it was necessary to use an installed capacity greater than the internal combustion engine because a significant reduction in power has greatly increased the initial investment costs, which for turbines raise almost exponentially [21]-[24]. The values of efficiency, achieved in this configuration, are equal to 71%.

TABLE II
COMPARISON OF THE DIFFERENT TRIGENERATION PLANTS

	ICE	GAS TURBINE	FUEL CELLS
Overall trigenerative efficiency	**81%**	**71%**	**87%**
Annual energy saving [MWh]	1661	1022	2503
White certificates [tep]	200	123	301
Wc*86,98€/tep per years [€]	17.396	10.702	26.218
Wc incentives in 15 years [€]	260.940	106.228	393.269
Ire	25%	18%	44%
Pes	0,25	0,155	0,29
Lt	0,526	0,536	0,458
FUEL USED [m^3]	533221	595711	614773
Total initial costs [€]	**1.529.598**	**2.377.242**	**3.914.733**
Annual cost of fuel gas [€]	124.316	115.780	
Design life [years]	15	15	15
Van [€]	4.022.500	2.694.881	2.357.429
Total costs per year [€]	124.136	141.080	156.859
Return on investiment	**4,8**	**7,8**	**9,7**
Tir net taxes	22,8	11,3	6,9
ANNUAL GREENHOUSE GASES REDUCED [tonnes of CO_2]	115	**-8,4**	378
DATA REFERENCE OF ITALY⇒0,483 tonnes of CO_2/MWh			
Annual revenue reducing of greenhouse gases [€]	2.291		17.267
Annual electricity sales revenue [€]	65.152	63.150	132.700

TABLE III
ENERGY SAVING FROM THE TRADITIONAL TO THE INNOVATIVE MODEL

	TRADITIONAL MODEL [MWH]	INNOVATIVE MODEL [MWh]	**ENERGY SAVING [MWh]**
Ice	6560	4899	1661
Gas turbine	8067	7045	1022
Fuel cell	8229	5726	2503

If you wish to satisfy the hygrometric comfort of the university complex through a "Low-Impact" configuration, you can introduce a fuel cell at high temperature as cogenerator of trigenerative plant. In this case, the aim is to increase the overall efficiency to reduce consumption of fuel and greenhouse gases. The FuelCell Energy (FCE) operates in the field of Molten-Carbonate Fuel Cells (MCFC) and has developed a technology known commercially as DFC, Direct Fuel Cells, which the process of reforming the fuel (natural gas, biogas, coal gas) occurs within the cell [25]. The program of the FCE is projected on products development for the distributed power generation market for applications below 40 MW. In the case of cogeneration applications are achieved total efficiencies that can exceed 80%. The fuel used in this case study is the methane gas [4]. Using these high-temperature cells, the initial and annual costs will be increased compared to the other configurations, as you will need a replacement of the stack after only four or five years of operation [4]; this issue is caused by corrosion and high thermal stress where the stack is subjected during its life cycle. The installed capacity is equal to 1064kW, the electricity equal to 500kW while the recoverable downstream of the electrolytic process is 423kW. With this configuration you get an overall trigeneration efficiency of 87%.

The results are shown in Tables II and III.

VII. ANALYZED CONFIGURATIONS

The analyses made have shown that the most suitable solution for the trigenerative plant is the use of an internal combustion engine (ICE). This conclusion was reached with the aim of finding a meeting point between the technical, economic and environmental analysis performed. With this configuration, you can reach values an overall cogeneration efficiency of 81%. From an economic and financial point of view, this choice would result in a low initial investment compared to the other configurations and also an economic return on investment after only 5 years. The chosen configuration has the property of conjugate perfectly with the balance between electricity and thermal required by the user (the relationship between electrical energy and thermal energy equal to 0.7); also, this layout, can effectively meet the demand of thermal energy at a low temperature (<120°C) required for ambience heating.

Regarding the emission values, although the ICE is not the choice for a lower environmental impact compared to other layout, however it have a good compromise compared to the configuration with the Gas Turbine. Using an Internal Combustion Engine in Total recovery mode you get to reduce the CO2 emissions of about 115 tonnes compared to the Italian average reference that takes account of a traditional model of enslavement [7].

Furthermore trigeneration plant is a new technology that can spread in the residential and tertiary sector of medium and small scale. If at first this new technology could be considered only for systems of large scale (with specific powers in excess of installed MW), nowadays this technology can become a part of the residential, commercial and industrial scope for medium and small power. Instead, the residential sector, which falls more properly within the micro cogeneration, still has great untapped potential but it can sustain its growth only if he can find a great compromise with the essential requirements in this type of plant [4]:

- high operating hours;
- high and constant demand for electricity and heat;
- request for heat and electricity simultaneously.

In the residential scope, these requirements are difficult to meet if you evaluate the thermal and electrical satisfaction of each building in a single and separate approach [23]; if we consider the possibility of no longer meet the hygrometric comfort of each building with a single plant, but to use one medium power for most buildings, the situation is different. In the near future, hand in hand with a new low energy design and building, it will be possible to size a single heating and electricity production for a residential area, neighborhood or group of buildings then enslaved by a district heating system. This new concept could lead to several advantages:

- much higher efficiency than any other heating plant;
- specific fuel consumption reduced;
- significant environmental benefits due to a lower CO_2 emissions than the national average, but especially in the urban context;
- greater environmental benefits if you use a renewable fuel such as biogas instead natural gas (and so consequently there is the possibility of access to the Green Certificates [6]);
- operating and maintenance costs are shared with many users.

The study undertaken, as well as the optimal plant configuration for the complex, has allowed us to analyze a new method for sizing and design of thermo-mechanical systems. In this new approach we must first define the input data relating to the user: calculation of surfaces and volumes, physical properties, stratigraphy and sun exposure. Following, through the program TRNSYS, is possible to derive the required heat loads from the utility that, once introduced into the RETScreen software, you get the comparison between a traditional model of subservience and a new concept one which leads to an analysis of technical, economic and environmental feasibility. This new approach is schematise in Fig. 5.

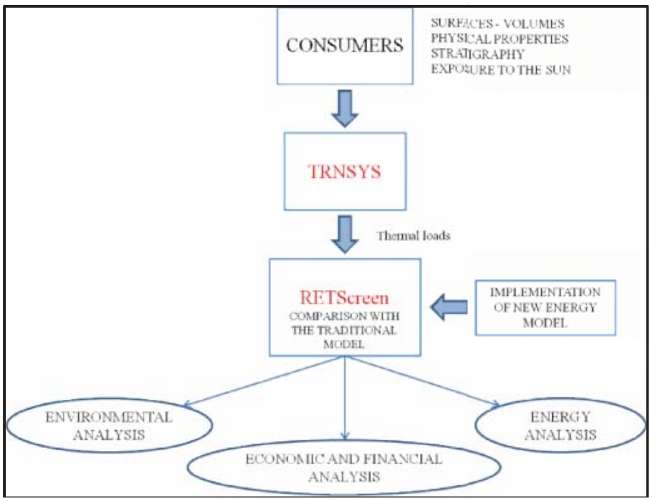

Fig. 5 Logic of the new design methodology

Thanks to the two software used in series (TRNSYS and RETScreen) it was possible to obtain the following results:

1. New method to estimate the economic and environmental feasibility of a power plant.
2. Preparation and study of complex and newly developed plants through a graphical interface.
3. Evaluation of the economic and financial prevision with an immediate feedback in numerical software.
4. Economic and financial plan at different levels of accuracy: more detail requires more knowledge of the input data (all types of costs or credits acquired).
5. Thanks to the software TRNSYS you can perform a dynamic analysis and accurate thermal loads dispersed by the user during the course of the year (assuming an heat flow dynamic, the ventilation losses, the ground losses, the internal heat gains and the solar gain due to different exposure of the surfaces).
6. Energy and environmental assessment and preliminary design is quite flexible and accurate thanks to the RETScreen software.

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