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An Evaluation of Energy and Economic Efficiency in Residential Buildings Sector: A Multi-criteria Analisys on an Italian Case Study

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ABSTRACT

The aim of the paper is to evaluate by means of a multi-criteria analysis (multi criteria decision making [MCDM]) the multiplicity of measures regarding energy efficiency and reduction in consumption of fossil fuels, with relative implementation of integrated renewable energy sources, for planning and renovation of single family residential buildings. The work analize the energy (thermal, electrical) consumed by a building of this type (an Italian case study), and, for the choice of the best technology to adopt for environmental heating (hot sanitary water and cooling), a MCDM model was used, which, in addition to economic evaluation, incorporates too energy efficiency, the reduction of CO_2 emissions, the ease of procurement of raw material and the governative incentives available. Our results underline that the best solution concerns the installation of solar thermal panels combined with the heat pump.

Keywords: Energy Efficiency, Economic Evaluation, Residential Buildings
JEL Classifications: Q410, Q420, L940

1. INTRODUCTION

More than 190 nations have agreed on the need to limit fossil-fuel emissions to mitigate anthropogenic climate change as formalized in the 1992 Framework Convention on Climate Change (United Nations - Framework Convention on Climate Change, 2014). A substantial share of final energy consumption by Italy and the European Community is taken by the construction industry. On the average, 40% of energy consumption can be attributed to buildings that show great inefficiency due to the loss of heat because of poor thermal insulation and, above all, the presence of an inefficient heating system (European Commission, 2003).

On the Italian territory approximately 13,6 milion buildings were identified, of which more than 87% were intended for residential use and the remaining for non-residential use (hotels, offices, hospitals, churches, schools, etc.) (Fouilloux et al., 2015). Of the residential buildings, in 2013, over 60% were built before regulation 376 of 1976, which is the first regulation on energy saving, and of these 25% register annual consumption at a minimum of 160 kilowatt-hour (kWh) for m^2 to over 220 kWh/m^2 (Lannutti and Corsetti, 2012).

Renewable thermal energy sources represent a fundamental element of the Italian strategy to reach the objectives of "20-20-20," thanks to their cost efficiency and their widespread ease of installation. The objective of our country is in effect to develop the production of heat by means of renewable sources (Campisi et al., 2018; Campisi et al., 2017; Morea and Poggi, 2017; Morea and Poggi, 2016; Campisi et al., 2016; Campisi et al., 2015; Stankeviciute and Criqui, 2008).

To stimulate the use of small size renewable thermal energy systems, the Italian Government has presented a ministerial decree which directly subsidizes the installation of dedicated systems, the so called "Conto Termico" or "Conto Termale" (Ministerial Decrees 28 December 2012 and 16 February 2016). By 2020, the "Conto Termale" alone will allow reaching the PAN (so called "Piano di Azione Nazionale") target for thermal energy renewables at an equivalent of 17% of final gross consumption, or rather about 10 milion of tonne of oil equivalent, with an overall commitment to the program of approximately 900 million euro/year, in operation and with coverage on natural gas rates (maximum increase estimated equal to 2.2% on the cost of a cubic metro of gas) (Klessmann et al., 2011).

The present work analyses the possible improvements in order to guarantee appreciable energy savings and the reduction of CO_2 emissions in single family dwellings. Energy saving in the construction industry could be pursued with the integration of active solar panel systems (solar thermal energy and photovoltaic system), or by means of adopting high technology heat generators which respect the environment and reduce the consumption of combustibles and electricity (Mourshed and Quddus, 2009). The market for heat generators offers a wide range of products for the heating and distribution of hot sanitary water. The principal technologies for the production of thermal energy from renewable sources applicable in the residential sector were analyzed and compared in order to highlight which factors are necessary in choosing the the most suitable technology for satisfying the needs of the user. However, every decision with more than one attribute consists of four basic elements, i.e., alternatives, criteria, the state of nature (defined below), and outcomes or consequences. Alternatives are a set of possible options among which the decision maker can choose, while criteria are the attributes against which alternatives are compared (Triantaphyllou, 2000). In order to compare solutions offered by the market, a comparative model was developed, one which was not limited only to the technical characteristics of the possible alternatives, but which also considered factors that were economic, legislative, and last, but not least in importance, the particular needs of those who use the building.

A decision making method falls within the category of multi criteria decision making methods (MCDMs) if it considers more than one criterion in the process of choosing an alternative (Brugha, 2004; Lootsma, 1999). These methods have found many applications within the operational research methods especially in Europe. They have been used to help with decision making in many fields such as agriculture, energy, environment and water management, and transportation (Figueira et al., 2005).

2. BACKGROUND

Energy renovation of buildings is possible thanks to innovative technologies and material available today. Together with careful management of solar energy systems, they allow for a reduction of up to 40-50% on current energy consumption of dwellings and other buildings. Every building shows different characteristics; therefore, there is a solution for each building that allows for improvement in thermal comfort and reduces energy consumption. Interventions for energy renovation regard: System, structural, and management characteristics (Hartungi and Jiang, 2012). In this case, the actions directed to reduce the quantity of energy consumed, and as a consequence the emission of pollutants and climate altering gases, regard the shell of the building a/o the substitution of old boilers with high efficiency systems. Acting on the reduction of heat dispersal by means of thermally insulating non-transparent structures (external walls, attics, basements) and transparent structures (doors and windows) corresponds to obtaining immediate energy and economic savings (Stazi et al., 2013).

One method for evaluating and promoting sustainable practices in buildings is the application of such rating systems as Leadership in Energy and Environmental Design, Green Globes, GBTool, and the German Sustainable Building Council rating system (DGNB-German Sustainable Building Council, 2014; Fowler and Rauch, 2006). Most rating systems focus more on the economic and environmental dimensions of sustainability, often slighting social sustainability considerations (Lehtonen, 2004).

Some studies have investigated methods to reach a more sustainable design through strategic changes in user behavior (Lilley, 2009). In addition, the way decisions are made in a group (consensus vs single leader decision making) and its influence on design selection tasks have also been studied (Yang, 2010). One effective method for enhancing the sustainability of civil infrastructure projects is the application of decision analysis tools during the planning and design phases of the building cycle (Nikou and Klotz, 2014).

3. METODOLOGY

This work proposes to acquire data and information to utilize in the evaluation of the benefits of applying the MCDM model for the purpose of selecting the most sustainable decisions and to involve the stakeholder more efficaciously in the process.

The work is structured in 3 principle phases:
1. Determination of the thermal energy needs of the building under study: In order to calculate the quantity of primary energy required to cover the energy needs of the building, the annual consumption of heating and the production of hot sanitary water are examined;
2. Construction of a comparison model for the choice of technology: A model of comparison based on multi criteria comparative analysis was developed with the intention to propose a framework of reference for the application of the MCDM to decisions in the phase of planning and renovation of a residential building;
3. Implementation of the methodology in a real situation: The methodology presented was applied to a real case: A residential building in Southern Italy; the typology of the chosen building represents approximately 38% of the total number of dwellings present on the national territory (Istat, 2017).

3.1. Determination of Thermal Energy Requirements

The energy diagnosis was carried out in accordance with the technical specifications of UNI/TS 11300, the Italian reference for the determination of the energy performance of buildings. Particularly, reference is made to UNI/TS 11300-1 for the determination of thermal energy requirements of the building for winter climate control and UNI/TS 11300-2 for the determination of primary energy requirements and for the efficiency of winter climate control and the production of hot water. The energy evaluation carried out is of the tailored rating type, adapted to the user and based on the reading of real consumption (Papadopoulou et al., 2013). To correctly identify the operation to carry out, it was necessary to gather information, such as: Identification of the dimensions and location of the building under examination; use of the building indoor and outdoor climate of the building type of heating system, capacity installed and physical characteristics data (for example if the area is served by the natural gas company).

The cost of energy consumption maintained for heating and the production of hot sanitary water was extrapolated from invoices a/o bills.

Knowing the primary energy requirements for climate control of the building, the quantity of CO_2 emitted by the existing system is established.

The benefit that is derived from the adoption of energy-efficiency measures is not only expressed in the reduction of energy consumption and the lack of carbon dioxide emission, but it can be also assessed in economic terms (Stephan et al., 2013).

3.2. MCDM Model

In the context of building energy renewal, a multidimensional decision-making profile is present (Pohekar and Ramachandran, 2004). MCDM - a well known decision making process - is based on the progression of using methods and procedures of multiple conflicting criteria into management planning processes, whereas, decision support systems (DSS) are considered powerful tools for decision-making (Hsieh et al., 2004).

MCDM is widely used in conjunction with DSS by a large number of decision makers in variety of fields, such as financial analysis, flood risk management, housing evaluation, disaster management and Customer relationship management (Umm-e-Habiba and Asghar, 2009).

Decision makers are often faced with several conflicting alternatives. How do they evaluate trade-offs when there are more than three criteria? To help people make optimal decisions, scholars in the discipline of MCDM continue to develop new methods for structuring preferences and determining the correct relative weights for criteria. A compilation of modern decision-making techniques, multiple attribute decision making (MADM): Methods and applications focuses on the fuzzy set approach to MADM (Gwo-Hshiung and Jih-Jeng, 2011).

The approach of MADM is that to utilize the noted information (factual elements) together with judgement expressed by the decision maker (value elements) to determine a decision by compromise (best compromise solution), or rather the coherent alternative with the structure of preference. A more detailed analysis can be found in the appendix. The problem can be formulated as follows:

$$\max F(x) = [f_1(x),......,f_k(x)]^T \quad (1)$$

s.t. $x \in X \subset R^n$

With:
x = vector of decision variables;
fj (.) = jth objective;
X = set of alternatives eligible.

The assignment of weights to the relative assessment criteria serves to establish an order of importance relative to the latter. From a strictly technical point of view, the weights represent the Marginal Rate di Substitution among the various criteria. The MADM methods assign the weights to each criteria utilizing the information on the importance of the different attributes in terms of importance (Munda, 2004). The decision maker provides a weight to every attribute, to indicate the importance of the attributes themselves. The mechanism for the definition of the parameters of ranking consists in the combination of standardized weights and indicators in respect to every alternative to then carry out a comparison between the alternatives on the basis of obtained values (Li, 2010).

3.3. Development of a Model for the Comparison of Heating Solutions

In the establishment of standardization methods necessary for the assignment of points, it is done in a way to associate to every criteria a scale of evaluation with codomain (0.1), with the aim of evening out the weight that the points have in the establishment of the overall evaluation of the diverse technologies, bringing to a single evaluation system all of the criteria, both qualitative and quantitative.

The alternative that the system proposes as a solution will be the alternative which obtained the maximum score.

When a private individual decides to carry out energy rehabilitation of a building, the main critical factors that influence the decision-making process are:

- Capital cost (for this criteria a zero-min standardization is used, with codomain [0.1], in which the maximumum value equal to 1 is assigned to the alternative which shows the lower cost);
- Volume (zero-min standardization is used, in other words the parameter assumes a value equal to 0 in the case of maximum encumbrance and equal to 1 in the case of minimum encumbrance);
- Annual operation (the application field is [0.1] and assumes a value equal to 1 when the number of hours of operation are maximum, otherwise 0];
- Useful life (zero-min standardization is used, in which a point score equal to 1 is assigned to the technology with the greater useful life);
- Efficiency: The ability to convert the energy of the combustibile employed into energy useful for the system represents the efficiency of a heat generator; zero-max standardization is used and the value is equal to 1 if the technology demonstrates a high level of efficiency and equal to 0 when this conversion ability is low;
- Incentives and detractions (a value of 0 is assigned if no subsidies are provided for the technology under examination,

a value of 1 if there are economical incentives for the technology);

- Renewable sources: This factor is considered when the comparative analysis includes technologies powered both by combustible fossil fuels and by renewable energy sources; in this case as well, attribute evaluation is used;
- Flexibility: By flexibility we mean the possibility to integrate the heating system with other production systems or the ability to expand it to satisfy new thermal requirements; the evaluation system is discrete and is of 3 values:
  - 0 if the system is not suitable for future expansion;
  - 0.5 if the system can be expanded over time but demonstrates a limited capacity;
  - 1 if the dimensions of the system can be modified;
- Supply: By supply we mean the ease with which the source materials are found; the values assigned are:
  - 1 if the difficulty to supply is zero;
  - 5 if the difficulty to supply is average;
  - 7 if the difficulty to supply is high;
  - 9 if supply is not possible;

The method of standardization is of type zero-min, with codomain (0.1), in which the minimum value 0 is attributed to the alternative which demonstrates a combustible supply of zero;

- Cleanliness of the equipment (the maximum value is assigned to the alternative that does not require further measures, other than regular maintenance and a value equal to 0 when the daily cleanliness is constant and accurate);
- Supply of the generator (for this criteria, an evaluation scale is adopted with the attributes of:
  - 1 if it is automatic;
  - 0,5 if it is semi-automatic;
  - 0 if it is manual);
- Carbon dioxide emission (a continuous and standardized point scale by means of zero-min is proposed, with codomain [0.1], in which the alternative with the lowest carbon dioxide emission is highlighted).

With the aim of assigning suitable rigor and objectivity to the model, it is necessary to assign a scale of values with which to express judgement on the importance attributed to critical factors. An importance of null can be assigned to the critical factor and choose not to consider the influence of such a factor in the identification of the solution, maintaining however the control of its bearing on different alternatives. In the same way, assigning the maximum critical value of the evaluation scale one chooses to maintain this as a determining criteria for the choice, but not discriminate for this. Such duality is important in that the assignment of maximum points to driver costs should not reduce the multi-criteria analysis to a simple costs/benefits analysis (Brugha, 2004).

For the values to be inserted as input in the comparative model a discrete evaluation system was chosen, mainly utilizing a standardization of zero-max type for quantitative and analytical factors with codomain corresponding to the interval (0.1), while for the qualitative factors discrete and attributional functions were adopted with the aim of obtaining a point scale with the same codomain.

Once a value of importance is attributed to each factor, the points relative to each single criteria are assigned to every solution. The sum of the points that a technology registers in respect to the different factors could be seen as an indication of the overall strength of the solution in respect to the structure of input drivers (Damart et al., 2007).

4. CASE STUDY

The property taken as reference for the typology "residential" is located in the province of Lecce, in Southern Italy. The place in which the property is located comes under climatic zone C, characterized by a number of degree days equal to 1.153. The established period of heating is from the 15th of November to the 31st of March for a maximum of 10 h/day. From this climatic information the maximum number of total hours of operation of the heating system (h_{max}) is calculated:

$$h_{max} = (15+31+31+28+31)*10=1.360 \text{ h} \quad (2)$$

The dwelling is newly constructed and is equipped with an independent heating system of collector type (8 way) with radiant floor panels. The dwelling is extended on one floor and is subdivided into 11 rooms, of which 5 comprise the daytime area and the remaining 6 the night-time area. The overall useful heating surface area (S_u) is equal to 159 m^2, which in volume is 447 m^3.

The useful thermal energy needs are equal to the sum of thermal energy needed for heating the building and for hot sanitary water.

The ideal annual energy requirements for heating (Q_h) was calculated as follows:

$$Q_h = (Q_t+Q_v-Q_s-Q_i)=8,773+1,273+0+0=10,045 \text{ kWh/year} \approx 10,000 \text{ kWh/year} \quad (3)$$

The formula takes into consideration thermal exchange by transmission (Q_t), thermal exchange by ventilation (Q_v), internal thermal exchange (Q_i) and solar thermal exchange (Q_s).

The thermal energy needs of Q_h, equivalent to 10,000 kWh/year, is the useful energy needed to guarantee a temperature of 20°C in the dwelling, the net of renewable energy contribution or other means of generation.

The specific annual thermal energy need of the house is 62,89 kWh/m^2.

The thermal energy required to produce hot water for sanitary use (Q_{hsw}) is:

$$Q_{hsw}=47.9*Su^{-0.2356}*Su=47.9*159^{-0.2356}*159=2.307 \text{ kWh/year} \approx 2.000 \text{ kWh/year} \quad (4)$$

The volume of hot water required is conventionally referred to at an output temperature of 40°C and at an input temperature of 15°C.

The required useful thermal energy needs for heating the building and the production of hot sanitary water (Q_{useful}) is equal to:

$$Q_{useful} = (Q_h+Q_{hsw})=10{,}000\ kWh/year+2{,}000\ kWh/year =12{,}000\ kWh/year \quad (5)$$

To guarantee the quantity Q_{useful} energy, the system must produce just as much primary energy Q.

The quantity of primary energy (Q) is given in the relation:

$$Q = (Q_{useful}/\eta_{global}) \quad (6)$$

With η_{global} as the global output of the system.

Output efficiency (η_e): A floor system with insulated panels shows an output efficiency equal to 0.97.

Distribution efficiency (η_d): An independent collector system shows an η_d equal to 0.99.

Regulation efficiency (η_r): An on-off apartment regulator only for room temperature shows an efficiency η_r equal to 0.92.

The input data is summarized in the following Table 1.

4.1. Analysis of Alternatives

4.1.1. Heating system with an liquid petroleum gas (LPG) condensing boiler

The use of a condensing boiler powered by LPG together with radiant heat panels, guarantees the best energy savings currently available. The condensing boiler differs from traditional ones because they have a special exchanger that captures the heat of the exhaust fumes in order to take advantage of the latent heat trapped in the water vapour. The recovery of latent heat allows the condensing boiler to function at a lower operating temperature and therefore adopt the radiant floor as a terminal of the climate control system.

According to the calculation methodology of norm UNI/TS 11300, the production output (η_p) is 0.95. The global output of the system is equal to:

$$\eta_{global} = (\eta_p*\eta_e*\eta_d*\eta_r)=0.95*0.99*0.97*0.92=0.84 \quad (7)$$

The annual quantity of primary energy consumed or that which is required for winter climate control and hot sanitary water is equal to the relation of the useful thermal energy need for the global efficiency of the system.

$$Q = (Q_{useful}/\eta_{global})=12{,}000/0.84=14{,}286\ kWh/year \quad (8)$$

The price of liquefied petroleum gas is 0.92 €/l, estimated by the market.

The boiler powered by natural gas or condensing LPG is not supported, at this time, by any subsidies or tax deductables.

The operational cost (amortization costs, maintenance costs, annual heating costs, etc.) are equal to 2,430 €/year, estimated by the market.

The equivalent amount of CO_2 emitted by combustible fossil fuels for the production of 14,286 kWh/year is:

$$CO_{2(emissions)}=(Fem_{LPG}*Q)=(0.31*14{,}286)=4{,}428\ kg\ CO_2/year \quad (9)$$

4.1.2. Heating system with a gas oil boiler (non condensing)

This technology is by now obsolete but is taken into consideration as regards locations where the building is not yet serviced by distribution of natural gas.

According to the calculation methodology of norm UNI/TS 11300, the efficiency of a non condensing gas oil boiler is estimated at an output equal to 0.87.

The global efficiency of the system is equal to:

$$\eta_{global}=(\eta_p*\eta_e*\eta_d*\eta_r)=0.87*0.99*0.97*0.92=0.77 \quad (10)$$

The annual quantity of primary energy is equal to:

$$Q = (Q_{useful}/\eta_{global})=12{,}000/0.77=15{,}584\ kWh/year \quad (11)$$

The price of gas oil for heating is 1.60 €/l, estimated by the market.

The conventional gas oil boiler does not benefit from any incentives a/o tax deductions.

The operating expenses are equal to 2,931 €/year, estimated by the market.

The quantity of equivalent CO_2 emitted by the combustible fossil fuel for the production of 15,584 kWh/year is:

$$CO_{2(emissions)}=(Fem_{DIESEL\ FUEL}*Q)=(0.30*15{,}584) =4{,}675\ kg\ CO_2/year \quad (12)$$

4.1.3. Heating system using pellets

The pellet boiler is a heat generator fueled by biomass which provides indoor home heating as well as producing hot sanitary water.

Table 1: Residential building: Input data (source: Own elaboration)

Year of building	2014	Heating requirement (KWh/year)	10,000
Climate zone	C	Electricity requirement (KWh/year)	4,000
Heating period	15.11-31.03	Energy requirement for hot water production (KWh/year)	2,000
Degrees day (°C)	1,153	Efficiency emission (%)	97
Total area (m^2)	189	Efficiency distribution (%)	99
Floor area to heat (m^2)	159	Total working annual hours heating	1,360
Net volume heated (m^3)	447	Regulation efficiency (%)	92

The pellet is an ecological combustible because it is made from wood sawdust, whose combustion is in balance with the environment.

Biomasses are part of renewable energy sources as the CO_2 emitted for the production of energy does not represent an increase in carbon dioxide present in the environment, but the same that plants have first absorbed in development and returned into the atmosphere at their death by means of normal biodegrading processes of organic substances. The use of biomasses therefore accelerates the return of CO_2 into the atmosphere rendering it newly available to plants. Substantially, these emissions are part of the normal carbon cycle and are in balance between CO_2 emitted e absorbed.

According to the calculation methodology of norm UNI/TS 11300, the estimated efficiency of the biomass boiler is equal to 0.86.

The global efficiency of the system is equal to:

$$\eta_{global} = (\eta_p*\eta_e*\eta_d*\eta_r)=0.86*0.99*0.97*0.92=0.76 \quad (13)$$

The annual quantity of primary energy is equal to:

$$Q = (Q_{useful}/\eta_{global})=12{,}000/0.76=15{,}789 \text{ kWh/year} \quad (14)$$

The price of certified pellets in 15 Kg bags is 0.33 €/Kg, estimated by the market.

The operating costs are equal to 1,645 €/anno, estimated by the market.

4.1.4. Heating system with a heat pump

The type of heat pump proposed is the air-water pump, which draws heat from outdoor air and transfers it to the interior of the environment to be heated. This new technology is particularly indicated for heating systems with floor distribution, which require much lower temperatures in respect to old radiators.

The combination of heat pump and floor systems not only guarantees greater residential well-being and lower heating costs, but also allows the cooling of the dwelling during the hotter months.

However, the heat pump shows some limitations regarding the generation of hot water for the water and sanitary system. The temperature of the hot water produced by the current technology is quite low. For this reason it is necessary to adopt an added system which supplies sanitary water at a higher temperature (60/70°C). Therefore a traditional electric water heater at a cost of 150 € is proposed.

The efficiency of the heat pump has an output efficiency (COP) equal to 3.11%. The global efficiency of the system is equal to:

$$\eta_{global} = (\eta_p*\eta_e*\eta_d*\eta_r)=3.11*0.99*0.97*0.92=2.75 \quad (15)$$

The annual quantity of primary energy is:

$$Q = [(Q_h/\eta_{global})+Q_{hsw}]=(10{,}000/2.75)+2{,}000 =5{,}636 \text{ kWh/year} \quad (16)$$

The cost of electric energy is assumed to be 0.25 €/kWh, estimated by the market.

The operating costs are 1,980 €/year, estimated by the market.

The equivalent quantity of CO_2 emitted for the production of 5,636 kWh/year is:

$$CO_{2(emissions)} = (Fem_{ELETT.}*Q)=(0.4464*5{,}636) =2{,}516 \text{ kg } CO_2\text{/year} \quad (17)$$

4.1.5. Heating system with heat pump and solar thermal energy

The low temperature of sanitary water is a critical and undesirable factor for the user, a problem which can be overcome by installing a solar thermal panel system.

The combination of solar thermal energy with the air-water heat pump creates a complete thermal energy system and is almost completely powered by renewable energy. This solution, furthermore, guarantees coverage of energy needs for both environment heating and for the production of hot sanitary water, without needing to install other auxiliary sources of heat.

With the aim of carrying out the estimated cost evaluation for each solution the following hypotheses were made:

- The solar energy system uses collectors exposed southward and inclined 60°;
- Estimate of the capture surface: 1 m^2 of panel every 10 m^2 of dwelling.

In our case, the dwelling has a useful heatable surface equal to 159 m^2, therefore it calls for an installation of 8 panels of 2 m^2.

The quota of coverage of the solar thermal energy system for heating is 40%.

The quota of coverage of the solar thermal energy system for hot sanitary water is equal to 70%.

The output efficiency (COP) is equal to 3.11%.

The global output of the system is equal to:

$$\eta_{global} = (\eta_p*\eta_e*\eta_d*\eta_r)=(3.11*0.99*0.97*0.92)=2.75 \quad (18)$$

The annual amount of primary energy is:

$$Q = [(Q_h/\eta_{global})-Q_{sol.}+Q_{hsw}]=(10{,}000/2.75)-1{,}455+600 =2{,}781 \text{ kWh/year} \quad (19)$$

The expense paid by the private individual for the installation of solar thermal energy collectors is subsidized by the so called "Conto Energia Termico" (CET): The Ministerial Decree of 16 Febbruary 2016, called "Conto Energia Termico," is a support program for small size interventions for the production of thermal energy by renewable sources and for the improvement of energy efficiency. The incentive is substantially a contribution to expenses incurred for the realization of the intervention and is given in annual installments for a variable duration (from 2 to 5 years) in function of the work carried out (Gestore Servizi Energetici - GSE, 2017a).

The operating costs are 1,583 €/year, estimated by the market.

The utilization of solar energy does not involve carbon dioxide emissions and the heat pump further contributes to reducing them. Therefore the quantity of equivalent CO_2 emitted by electricity for the produzione di 5,636 kWh/anno is:

$$CO_{2(emissions)}=(Fem_{ELETT.}*Q)=(0.4464*2{,}781)=1{,}241\ kg\ CO_2/year \quad (20)$$

4.1.6. Heating system with a heat pump and photovoltaic system

The proposed alternative is an electrical system in which a photovoltaic system of 3 kilowatt-peak (kWp) augments the heat pump. The excess energy produced by the photovoltaic system is used by the heat pump to guarantee the heating of the dwelling. The hot sanitary water is instead guaranteed by the installation of the electric water heater.

In special cases, the photovoltaic system of 3 kWp can produce on average 4,000 kWh/year. Pertaining to the Region of Puglia, a production equal to 1,350 kWh is estimated.

The photovoltaic system in question is connected to the network. This means that a part of the electrical energy produced is utilized immediately and directly to satisfy the consumption of the dwelling in which they are installed, while the remaining energy is emitted to the national electric network. The selling price of the energy emitted to the network is not equal though to the cost of the energy.

With the aim of carrying out the evaluation of estimated annual cost for every solution the following hypotheses were made:

- Basic electrical need, excluding possible consumption for heating, equal to 4000 kWh/year;
- Quota of coverage by the photovoltaic system for heating equal to 25%; quota of coverage by the photovoltaic system for hot water equal to 40%;
- Peak power of 3 kW and 12 photovoltaic system modules;
- Producibility, average/year, of electrical energy from the system is 4,000 kWh/year;
- Quota of auto-consumption of the energy produced by the photovoltaic (excluding the quota for hot water and heating) equal to 50%;
- Value of the energy sold to “Gestore Servizi Energetici” (GSE), exchanged on the spot, equal to 0.04 €/kWh (Gestore Servizi Energetici - GSE, 2017b).

For the heat pump output efficiency (COP)is determined equal to 3.11%. The global output efficiency of the system is equal to:

$$\eta_{global} = (\eta_p*\eta_e*\eta_d*\eta_r)=(3.11*0.99*0.97*0.92)=2.75 \quad (21)$$

The annual amount of primary energy is equal to:

$$Q = [(Q_h/\eta_{global})-Q_{sol.}+Q_{hsw}]=(10{,}000/2.75)-1{,}013+1{,}200 =3{,}823kWh/year \quad (22)$$

The operating costs are equal to 1,841 €/year, estimated by the market.

The amount of equivalent CO_2 emitted by electricity for the production of 3,824 kWh/year is:

Table 2: MCDM: Evaluation of the alternatives (source: Own elaboration)

Alternative CRITERIA	Importance of the criteria [0;5]	LPG heating		Gas oil boiler heating		Heating with pellets		Heating with heat pump		Heating with heat pump+solar thermal energy		Heating with heat pump+photovoltaic system	
Investiment cost	5	0.70	3.50	0.69	3.45	0.60	3.00	0.57	2.85	0.00	0.00	0.16	0.80
Operating costs	3	0.19	0.57	0.00	0.00	0.54	1.62	0.42	1.26	0.67	2.01	0.57	1.71
Renewable energy	1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Production efficiency	3	0.31	0.93	0.28	0.84	0.28	0.84	1.00	3.00	0.70	2.10	0.60	1.80
Subsidy	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.52	0.52
Temperature reduction	2	0.00	0.00	0.00	0.00	0.00	0.00	1.00	2.00	1.00	2.00	1.00	2.00
Help hot sanitary water	4	1.00	4.00	1.00	4.00	0.00	0.00	0.00	0.00	1.00	4.00	0.00	0.00
Volume	3	0.00	0.00	0.00	0.00	0.00	0.00	1.00	3.00	1.00	3.00	1.00	3.00
Working life	0	0.80	0.00	0.80	0.00	0.80	0.00	1.00	0.00	1.00	0.00	1.00	0.00
Provision	3	1.00	3.00	1.00	3.00	0.50	1.50	1.00	3.00	1.00	3.00	1.00	3.00
Cleaning equipment	3	1.00	3.00	1.00	3.00	0.00	0.00	1.00	3.00	1.00	3.00	1.00	3.00
Power source	2	0.50	1.00	0.50	1.00	0.50	1.00	1.00	2.00	1.00	2.00	1.00	2.00
CO_2 emission	2	0.05	0.10	0.00	0.00	1.00	2.00	0.46	0.92	0.73	1.46	0.63	1.26
	Sum	5.55	16.10	5.27	15.29	5.22	10.96	9.45	22.03	11.10	24.57	9.48	20.09
	Total	16.10		15.29		10.96		22.03		24.57		20.09	

MCDM: Multi criteria decision making, LPG: Liquid petroleum gas

$$CO_{2(emissions)} = (Fem_{ELETT.}*Q)=(0.4464*3,824) =1,707 \text{ kg } CO_2/\text{year} \quad (23)$$

4.2. MCDM: Evaluation of the Alternatives

The heating system most suitable for the user's needs was identified by adapting the multi-criteria comparative model which is summarized in the following Table 2.

The solution considered to be the best, and therefore that characterized by a highest point analysis, was that of the heat pump and solar energy system, followed by that of the simple heat pump and the combination of the heat pump and the photovoltaic system. The choice that results as the least economical is that of the Pellet, surely because of the difficulty related to the supply and modest efficiency.

The model proposes, therefore, as the optimum solution, the heating system with the heat pump combined with the solar thermal energy system. The installation of solar thermal panels combined with the heat pump represents the greatest economic investment among those considered, but guarantees significant annual savings and a return time of about 4 years. With this intervention a reduction of approximately 80% in combustibles consumption is expected, with consequent annual savings of 2,111,90 €. Furthermore the dwelling becomes almost energetically self-sufficient, which minimizes dependence on traditional energy sources.

5. CONCLUSIONS

Multi Criteria Decision Analysis methods have become increasingly popular in decision-making for sustainable energy because of the multi-dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems. This article reviewed the corresponding methods in different stages of multi-criteria decision-making for sustainable energy, i.e., criteria selection, criteria weighting, evaluation, and final aggregation. The criteria of energy supply systems are summarized from technical, economic, environmental and social aspects (Wang et al., 2009; European Commission, 2003).

From the study it was revealed that the use of combinations of diverse renewable energy sources of high efficiency for the production of hot sanitary water a/o the integration of the existing heating system helps the user to reduce energy expenses and to improve living comfort in the home, and the State to meet the binding objectives established by the European Union and to greater cover the national energy needs with the production of energy derived from renewable sources. Between the quantity di carbon dioxide per metro squared (kg CO_2/m^2) produced in the pre-intervention situation and that of post- intervention of the case study, a reduction of 73,44 % is obtained. The study provides the public decision maker with an analysis typology hat is structured and complex, regarding the decision making process that involves the planning and renovation of single family residential uildings, directed towards energy efficiency and the reduction of the consumption of combustible fossil fuels, all thanks to a multi-criteria methodology that correlates different typologies of renewable resources integrated among themselves."

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APPENDIX

Multi-criteria decision making (MCDM) methods deal with the process of making decisions in the presence of multiple objectives. A decision-maker is required to choose among quantifiable or non-quantifiable and multiple criteria. The objectives are usually conflicting and therefore, the solution is highly dependent on the preferences of the decision-maker and must be a compromise. In most of the cases, different groups of decision-makers are involved in the process. Each group brings along different criteria and points of view, which must be resolved within a frame work of understanding and mutual compromise (Pohekar and Ramachandran, 2004).

A difficulty in decision making is that reaching a general consensus in a multidisciplinary team can be very difficult to achieve. By using MCA the members don't have to agree on the relative importance of the criteria or the rankings of the alternatives. Each member enters his or her own judgements, and makes a distinct, identifiable contribution to a jointly reached conclusion (Köksalan and Sagala, 1995).

MCDM is a well known branch of decision making. It is a branch of a general class of operations research models which deal with decision problems under the presence of a number of decision criteria. This major class of models is very often called MCDM. There are several methods in each of the above categories. Priority based, outranking, distance based and mixed methods are also applied to various problems. Each method has its own characteristics and the methods can also be classified as deterministic, stochastic and fuzzy methods (Gal and Hanne, 1999).

These methodologies share common characteristics of conflict among criteria, incomparable units, and difficulties in selection of alternatives. In multiple objective decision making, the alternatives are not predetermined but instead a set of objective functions is optimized subject to a set of constraints. The most satisfactory and efficient solution is sought. In this identified efficient solution it is not possible to improve the performance of any objective without degrading the performance of at least one other objective. The best alternative is usually selected by making comparisons between alternatives with respect to each attribute (Pohekar and Ramachandran, 2004).

Weighted Sum Method (WSM)

The WSM is the most commonly used approach, especially in single dimensional problems. If there are M alternatives and N criteria then the best alternative is the one that satisfies the following expression:

$$A^*_{WSM} = Max \sum_i^j a_{ij}\, w_j \qquad for\, i = 1,2,3,M \tag{24}$$

Where A^*_{WSM} is the WSM score of the best alternative, N is the number of decision criteria, a_{ij} is the actual value of the i[th] alternative in terms of the j[th] criterion, and w_j is the weight of importance of the j[th] criterion. The total value of each alternative is equal to the sum of products. Difficulty with this method emerges when it is applied to multi-dimensional decision-making problems. In combining different dimensions, and consequently different units, the additive utility assumption is violated (Solnes, 2003).

Weighted Product Method (WPM)

The WPM is very similar to WSM. The main difference is that instead of addition in the model there is multiplication. Each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion.

In general, in order to compare the alternatives A_K and A_L the following product is obtained:

$$R\left({A_K}/{A_L} \right) = \sum_{J=1}^{N} \left({a_{kj}}/{a_{lj}} \right)^{w_j} \tag{25}$$

Where N is the number of criteria, a_{ij} is the actual value of the i[th] alternative in terms of the j[th] criterion, and w_j is the weight of importance of the j_{th} criterion. If R (A_K/A_L) is greater than one, then alternative A_K is more desirable than alternative A_L (in the maximization case). The best alternative is the one that is better than or at least equal to all the other alternatives (Triantaphyllou, 2000).

Analytical Hierarchy Process (AHP)

The essence of the process is decomposition of a complex problem into a hierarchy with objective at the top of the hierarchy, criterions and sub-criterions at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy.

Elements at given hierarchy level are compared in pairs to assess their relative preference with respect toeach of the elements at the next higher level. The verbal terms of the Saaty's fundamental scale of 1–9 is used to assess the intensity of preference between two elements. The value of 1 indicates equal importance, 3 moderately more, 5 strongly more, 7 very strongly and 9 indicates extremely more importance. The values of 2, 4, 6, and 8 are allotted to indicate compromise values of importance. Ratio scale and the use of verbal comparisons are used for weighting of quantifiable and non-quantifiable elements. The method computes and aggregates their eigenvectors until the composite final vector of weight coefficients for alternatives is obtained. The entries of final weight coefficients vector reflect the relative importance (value) of each alternative with respect to the goal stated at the top of hierarchy. A decision maker may use this vector due to his particular needs and interests. To elicit pair wise comparisons performed at a given level, a matrix A is created in turn by putting the result of pair wise comparison of element i with element j into the position a_{ji} as below.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{21} & \cdots & a_{2n} \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{26}$$

After obtaining the weight vector, it is then multiplied with the weight coefficient of the element at a higher level (that was used as criterion for pair wise comparisons).

The procedure is repeated upward for each level, until the top of the hierarchy is reached. The overall weight coefficient, with respect to goal for each decision alternative is then obtained. The alternative with the highest weight coefficient value should be taken as the best alternative. One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision maker's inconsistency and randomly generated index. This index is important for the decision maker to assure him that his judgments were consistent and that the final decision is made well. The inconsistency index should be lower than 0.10.

Although a higher value of inconsistency index requires re-evaluation of pair wise comparisons, decisions obtained in certain cases could also be taken as the best alternative (Pohekar and Ramachandran, 2004).

Preference Ranking Organization Method for Enrichment Evaluation (Promethee)

This method uses the outranking principle to rank the alternatives, combined with the ease of use and decreased complexity. It performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteriab (Brans et al., 1986).

The method uses preference function Pj (a, b) which is a function of the difference dj between two alternatives for any criterion j, i. e. d_j = f(a,j) – f (b, j), where f(a, j) and f(b, j) are values of two alternatives a and b for criterion j. The indifference and preference thresholds q' and p' are also defined depending upon the type of criterion function. Two alternatives are indifferent for criterion j as long as dj does not exceed the indifference threshold q'. If dj becomes greater than p', there is a strict preference. Multi-criteria preference index, π (a, b) weighted average of the preference functions P_j (a, b) for all the criteria is defined as:

$$\pi(a,b)=\frac{\sum_{j=1}^{J} w_j P_j(a,b)}{\sum_{j=1}^{J} w_j} \quad (27)$$

$$\Phi^+(a)=\sum_A \pi(a,b)$$

$$\Phi^-(a)=\sum_A \pi(b,a)$$

$$\Phi(a)=\Phi^+(a)-\Phi^-(a)$$

Where wj is the weight assigned to the criterion j; Φ^+ (a) is the outranking index of a in the alternative set A; Φ^- (a) is the outranked index of a in the alternative set A; Φ(a) is the net ranking of a in the alternative set A. The value having maximum Φ(a) is considered as the best (a outranks b iff Φ (a) > Φ (b), a is indifferent to b iff) (Pohekar and Ramachandran, 2004).

The Elimination and Choice Translating Reality (Electre)

This method is capable of handling discrete criteria of both quantitative and qualitative in nature and provides complete ordering of the alternatives. The problem is to be so formulated that it chooses alternatives that are preferred over most of the criteria and that do not cause an unacceptable level of discontent for any of the criteria. The concordance, discordance indices and threshold values are used in this technique. Based on these indices, graphs for strong and weak relationships are developed. These graphs are used in an iterative procedure to obtain the ranking of alternatives (Roy, 1985). This index is defined in the range (0–1), provides a judgment on degree of credibility of each outranking relation and represents a test to verify the performance of each alternative. The index of global concordance Cik represents the amount of evidence to support the concordance among all criteria, under the hypothesis that Ai outranks Ak. It is defined as follows:

$$C_{ik}=\sum_{j=1}^{m} W_j\, c_j \frac{A_i A_k}{\sum_{j=1}^{m} W_j} \quad (28)$$

Where Wj is the weight associated with jth criteria. Finally, the ELECTRE method yields a whole system of binary outranking relations between the alternatives. Because the system is not necessarily complete, the ELECTRE method is sometimes unable to identify the preferred alternative. It only produces a core of leading alternatives. This method has a clearer view of alternatives by eliminating less favorable ones, especially convenient while encountering a few criteria with a large number of alternatives in a decision making problem (San, 2012).

The Technique for Order Preference by Similarity to Ideal Solutions (Topsis)

The basic concept of this method is that the selected alternative should have the shortest distance from the negative ideal solution in geometrical sense. The method assumes that each attribute has a monotonically increasing or decreasing utility. This makes it easy to locate the ideal and negative ideal solutions. Thus, the preference order of alternatives is yielded through comparing the Euclidean distances. A decision matrix of M alternatives and N criteria is formulated firstly (Xu, 2011). The normalized decision matrix and construction of the weighted decision matrix is carried out. This is followed by the ideal and negative-ideal solutions. For benefit criteria the decision maker wants to have maximum value among the alternatives and for cost criteria he wants minimum values amongst alternatives. This is followed by separation measure and calculating relative closeness to the ideal solution. The best alternative is one which has the shortest distance to the ideal solution and longest distance to negative ideal solution (Boran et al., 2009).

Compromise Programming (cp)

Compromise programming defines the best solution as the one in the set of efficient solutions whose point is the least distance from an ideal point (Marler and Jasbir, 2004). The aim is to obtain a solution that is as close as possible to ideal. The distance measure used in CP is the family of Lp-metrics and is given as:

$$L_p(a)=\frac{\sum_{j=1}^{j} w_j^p \left|f_j^* - f(a)\right|}{\left|M_j - m_j\right|} \quad (29)$$

Where Lp (a) is the Lp metric for alternative a, f (a) is the value of criterion j for alternative a, Mj is the maximum (ideal) value of criterion j in set A, mj is the minimum (anti ideal) value of criterion j in set A, is the ideal value of criterion j, wj is the weight of the criterion j, p is the parameter reflecting the attitude of the decision maker with respect to compensation between deviations. For p=1, all deviations from f_j^* are taken into account in direct proportion to their magnitudes meaning that there is full (weighted) compensation between deviations (Pohekar and Ramachandran, 2004).

Multi-attribute Utility Theory (maut)

Multi-attribute Utility Theory takes into consideration the decision maker's preferences in the form of the utility function which is defined over a set of attributes The utility value can be determined by determination of single attribute utility functions followed by verification of preferential and utility independent conditions and derivation of multi-attribute utility functions. The utility functions can be either additively separable or multiplicatively separable with respect to single attribute utility. The multiplicative form of equation for then utility value is defined as follows:

$$1+ku\left(x_1,x_2,\ldots x_n\right)=\prod_{j=1}^{n}(1+k\,k_j u_j\left(x_j\right)) \quad (30)$$

Here j is the index of attribute, k is overall scaling constant (greater than or equal to _1), kj is the scaling constant for attribute j, u(.) is the overall utility function operator, uj(.) is the utility function operator for each attribute j (Linkov et al., 2007).