377: Development of a support tool for building design optimization and renewable energy integration

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Abstract

This paper describes a decision-support tool, SERAD, which was created with the aim to be used as an instrument to predict the heating/electrical demand of residential houses and to optimize the design parameters to improve the energy performance. Another aim of this tool is to analyze different renewable energy systems (photovoltaic/thermal solar systems, geothermal heat pumps or wood boiler heating system) and to design them in order to match the energy demands. Different aspects, like economic analysis, environmental impact and energy reduction potential are studied and used as criterions in the last stage of the tool which concerns the selection of the technology. At this point, it is possible to have multiple solutions formed by an arrangement of different systems on the same construction site, their advantages being added. Using a complex multi-criteria decision-support method, SERAD will automatically outrank the alternatives for the specific project by taking into account the weight of each criterion given by the decision maker. SERAD could be used to obtain quick parametric studies and to optimize/observe the impact of different design parameters of the building or renewable energy technologies on the energy demand/supply.

Keywords: building energy demands, renewable energy systems, multi-criteria method

1. Introduction

In France, the building industry contributes to 25% of greenhouse emission gases and 43% of total energy consumption, making it the biggest consumer of energy across all of the economy sectors [1].The energy spent to heat the occupied spaces in the residential sector represents more than 40% from the total energy demand that includes electricity, hot-water and air-conditioning. In this area a major energy reduction can be achieved if a building is correctly designed by engineers and architects, and even more if renewable energy systems are integrated to the construction. Installing multiple renewable sources on the same site is even more appealing when substantial energy savings could be made if the advantages of each source are associated. Knowing the influence of certain design parameters on the energy consumption, it's mandatory to find out what is their correlated impact on the building. Moreover, the energy demands of the building will influence the design of the renewable systems, so it's very important to first optimize the building energy performance and then to analyze the different renewable sources that could be added. The way in which a building and its services operates in practice is extremely complex and modeling it to obtain an accurate estimation of the energy consumption is very difficult. In most of the cases hourly dynamic simulations are mandatory but they demand however a considerable amount of detailed input data and time from even an experienced user and in some cases powerful informatic equipment. To find a compromise between simple and complex methods of evaluating the heating demand is to use energy prediction models that can approximate with accuracy the results from the model to the data obtained from simulations. Simple energy equations could be the primary tools for the designers/architects in the first stage of design, which could help them to quickly find efficient energetic solutions for their future projects. Using a large database of simulations results we have developed energy equations that could predict with good accuracy the monthly heating demand of residential houses in temperate climate. These equations have been implemented in a support-tool called SERAD (Systèmes à Energie Renouvelable et Aide à la Décision) and along with different modules of renewable energy systems have the purpose to be used in a decision support method that will give the best solution for the analyzed building accordingly to financial, environmental and energy reduction criteria.

2. Support-tool structure

SERAD was created as a necessary tool for the decision when having numerous solutions with several criteria. Its development was mandatory in order to proceed with the desired research study, being impossible to analyze such amount

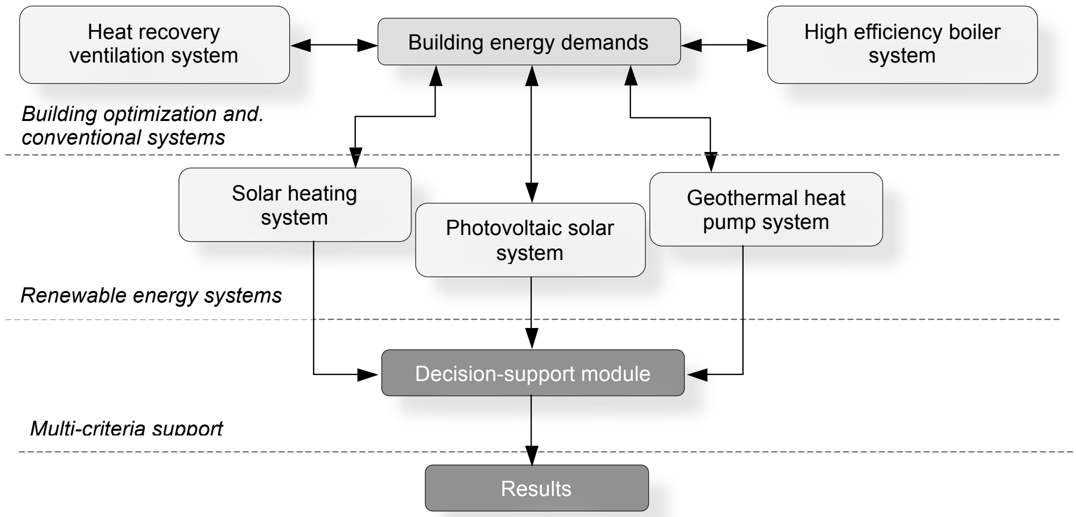

Fig 1. Modular structure of SERAD

of information without the support of a computer tool. This tool is based on a modular structure with different inputs/outputs that are connected between them. In Fig.1 illustrates the modularity of the support-tool and the respective connections between the modules. The first part of the support tool concentrates on the building flux energy and building optimization. In the second part different renewable energy systems are designed based on the data obtained in the previous stage. The last part deals with the investigation of possible solutions and the decision taken based on several criterions. The SERAD tool could be used for new and old buildings due to the large limits on the inputs used for the regression equations, especially on the building thermal insulation.

2.1 Building energy demands

The building energy demands considered in the support tool are the monthly heating and electrical demands. Based on a complete database of electrical equipment it's possible to create different scenarios which can be called later on in the program. Major challenge in this first part was to predict the monthly heating demands. The prediction models had their support structure on the dynamic simulations with an hourly time-step realized using the TRNSYS [2] building simulation software. The TRNSYS building model, known as «Type56», is compliant with general requirements of European Directive [3] on the energy performance of buildings and was a reliably solution in our case. If the outputs were known (monthly heating demands), the challenge was to found in the ,,black-box,,, the inputs and most important the function that would give precise predictions. Finally, we found that the necessary inputs were:

- Building shape factor (B_s) which is defined as the ratio between the heated volume of the building (V) and the sum of all heat loss surfaces that are in contact with the exterior, ground or adjacent non-heated spaces (ΣA_i).
- Building envelope U-value defined in the French Thermal Standard [4] as the building envelope heat loss coefficient which is the average heat loss of thermal transmittance through building envelope including thermal bridges.
- Building time constant (τ) is the third input for the models and is defined as the ratio of the effective thermal capacitance C to the steady-state heat loss coefficient U_h, of the building, which includes the transmission heat loss coefficient of the building envelope and the ventilation heat loss coefficient.
- Window to floor area ratio (WFR) translated by a percentage of heated floor area of the total glazing area.
- Climate coefficient represented by the difference between heating set-point temperature and monthly average sol-air temperature of the considered city. The $T_{sol\text{-}air}$ [5] has been calculated using the monthly outdoor dry-bulb temperature, the monthly average global radiation on horizontal and a default exterior convection coefficient (h_e) [4] with a value of 23 W/m²K for all the analyzed weather files. The regression models are limited on the climate coefficient; they were calculated for the French climate which varies from moderate to warm in the Mediterranean areas. The outdoor temperature limits are e.g. for the month of January from 0.56°C to 8.67°C. However the limitation on the climate, the tool is suitable to calculate the potential of combined renewable energies for any climate. In the case where the climate coefficient could be calculated, the designer/architect has to enter the monthly heating demands calculated by a different method. With a support of a large database of 18.144 simulations, multiple regressions were possible and complex polynomial models were obtained. Good correlation between models and simulations were found, with maximum errors of 5% for the climate of Nice (warm and humid). The models are limited to residential houses were B_s takes values in the range 0.7-1.25 m^3/m^2. To

energetically optimize a building several solutions are possible. Building morphology has a major impact on energy reduction, so higher B_s imply a reduction in the heating demand due to the fact that for a higher heated volume, the heat loss area is lower. Depecker et al. [6] have investigated the relation between the form of the building and its energy consumption. Fig.2 shows the impact of the ratio V/ ΣA_i on the heating demand of a single-family residential house of 100 m² situated in Paris city, with good building envelope insulation (U_{value}=0.7 W/m²K) and with low thermal inertia (τ=10 hours). The heating season is considered from October to April and the heating set-point is 19°C, value that represents the best the French houses heating regime.

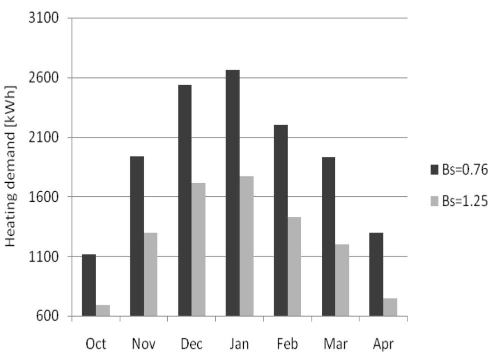

Fig 2. Impact of building shape factor on the heating demand

The WFR is assumed to be 20% and the glazing distribution is 40% South, 20% North, East and West. The prediction models were created for different glazing orientation distribution accordingly with the reference cases used in the latest French standards, but also for different ones. The building thermal inertia could be also a good element in the optimization process. The most noticeable effect of inertia on the building is seen especially in mid-season and in summer periods when the cooling demand is highly reduced when using a heavyweight building by comparison to a light one. The benefits of a high building thermal mass are not only related to energy reduction but also with the indoor thermal comfort of inhabitants.

Table 1. Impact of building time constant on the heating demand

Building time constant [hours]	**4**	**20**	**50**	**70**	**100**
January	1785	1770	1743	1725	1697
April	771	743	703	684	668

Table 1 illustrates how an increase in building time constant from 4 to 100 hours affects the annual heating demand of the same residential house presented previous, but with the hypothesis that B_s is equal to 1.25. For January month a slight reduction of 5% between the minimum and maximum time constants presented before is observed, while for April month when the solar energy is higher this reduction goes up to 14%. Moreover, the glazing area could modify an increase/decrease on the heating/cooling demand of a house. Persson et al. [7] showed that by using energy-efficient windows it would be even better than having a highly insulated wall without windows. This is because the window can collect and use the solar energy to heat the house during periods when the sun is shining and the outdoor temperature is lower than the indoor temperature. The most appropriate size of a window for energy smart design depends on building orientation and the amount of thermal mass in the internal building materials. The French standard is proposing a reference case of 16.5% of WFR but this value could go up to 22%, higher values increasing the risk of overheating during the summer period unless the shading protections are used. The glazing area should always be analyzed in the same time with the thermal inertia, because higher glazing area and higher building time constant could have major impact on heating demand reduction. The proposed prediction models are promising features to be easy and efficient forecast tools for comparing heating demand of residential buildings. Furthermore, they allow quick parametric studies during early design stage of a project, instead of using more complicated and time consuming simulation software.

2.2 Renewable energy systems

The results from the first level of the SERAD tool are used for the second stage which represents the design of renewable energy systems. Several physical models were implemented and validated.

2.2.1 Solar thermal energy

The solar energy use is ideal for the production of domestic hot water or to heat a house with a floor radiant system. To recover the solar energy and then to transport it to a storage tank, solar panels are being used. Currently, many producers are manufacturing solar panels with different thermal characteristics. One of the most important parameters of system design is the panel's efficiency and surface. Eq.1 shows the calculation of this efficiency based on several parameters:

$$n = n_0 - \frac{U_1(T_{mf} - T_e)}{H^*} - \frac{U_2(T_{mf} - T_e)^2}{H^*} \quad (1)$$

where n_0 is the optical efficiency of the solar panel, U_1/U_2 are the heat loss coefficients by conduction and convection, T_{mf} is the medium hot water temperature , T_e is the exterior temperature and H* is the global solar radiation. The SERAD results were compared and validated with another tool called SOLO 2000. A simple financial calculation is made, using parameters like the system investment, system life-time, replaced energy cost, payback time or tax reduction. Concerning the environmental impact a comparison is made with other common energies (gas, electrical, carbon), the results being expressed in tones of CO_2 avoided by year. Using the same building hypothesis we analyzed six solutions where the solar panels are only used to in the domestic hot water (DHW) process. The yearly energy demand to produce the DHW was found to be 2893.6 kWh for 4 persons in Paris. Table 2 shows how the solar panels' surface and efficiency affect the energy reduction and payback time. The first three solutions consider to an increase in the surface (3,4 and 5 m^2, n=0.67) and the last cases correspond to the same increase in panels' area but with a lower optical efficiency and higher heat losses (n=0.47).

Table 2. Impact of solar panels surface and efficiency on the supply/demand match and payback time

Sol.	Supply energy [kWh]	Supply/demand match [%]	Payback Time [years]
1	1561	53.94	8.25
2	1790	61.81	9.59
3	1931	66.73	11.12
4	1172	40.52	10.98
5	1511	52.24	11.36
6	1680	58.01	12.77

It can be observed from Table 1 that a low panel's efficiency has a major impact on the energy reduction but also on the payback time an increase from 8 years to 11 years being noticed. The hypothesis is that in all solutions the price of panel's area is the same, but the users have the possibility to change all the data. One of the advantages of SERAD is that is an open source tool, the users being allowed to modified all the parameters. The environmental impact of the proposed solution is analyzed and compared to equivalent gas energy and the results showed that a 316 $kgCO_2$/year reduction is possible with solution 1, while for the solution 3 this reduction could arrive to 392 $kgCO_2$/year. If for example, the six solutions are combined with a wood boiler heating system, the CO_2 emission avoided will be 2.3 tones/year. Moreover, compared to an equivalent electrical energy the total cost per year is reduced from 1236 € to 672 € in the case of a wood boiler. The values are approximately, but the users can modified all the input data, like the price of electricity/gas, monthly electrical/gas subscription, wood price, type of wood, boiler efficiency, boiler maintenance costs, etc. The hypothesis used for the previous calculations are that the burning efficiency is 80%, and dry wood is used for better burning performance. The number of connections between the systems is increasing very fast and to find an optimum based on our criteria could be a difficult even impossible task. That's why, support tools like SERAD are so necessary for this kind of research.

2.2.2 Photovoltaic solar energy

Photovoltaic energy is an interesting solution to convert the sunlight to electricity using photovoltaic or solar cells. SERAD second module makes it possible to evaluate the energy production and the economic viability of various types of photovoltaic projects. The photovoltaic systems have relatively few components, but the behavior of these components is not linear and their interactions are complex. In SERAD, simplified algorithms are used in order to minimize the need for data input and to accelerate calculations, while maintaining an acceptable level of precision. In most of the cases the system is connected to the town electric network so in the case where there is no storage cells, this energy could be sell to the local supplier (see Figure 3).

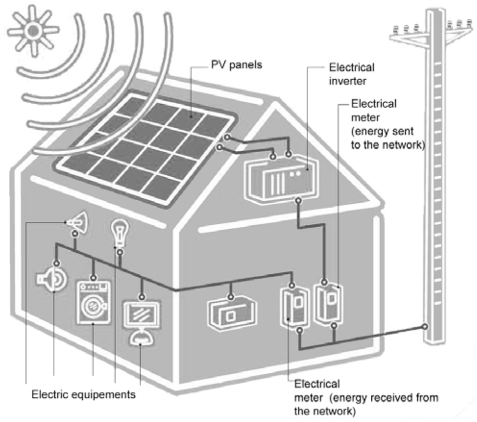

Fig 3. Photovoltaic solar system integrated into a residential house

In the first part of calculations we estimate the quantity of solar energy collected during one year by the PV panels, according to their slope, their orientation and according to the monthly values of the incidental solar radiation on a horizontal surface. In the second part the power supply is obtained based on different design parameters, like the PV panel's losses, control-system, type of panels or surface. Figure 4 illustrates in which way the PV area influents the supply/demand match. The hypothesis considered for this example case are that the electric consumption is 10 kWh/day, the slope is 45° oriented South and the surface area is 10, 15 and 20m^2. The Paris weather data are used for these calculations.

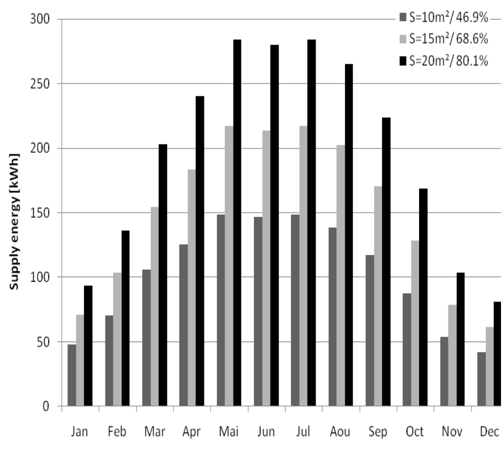

Fig 4. Impact of PV area on the monthly supply energy and the supply/demand match

Using the photovoltaic solar energy 1.12 tones CO_2/10 years could be avoided for the first solution, 1.64 tones CO_2/10 years for the second solution and 2.14 tones CO_2/10 years for the last one. Like for the solar heat system a financial calculation is realized based on several factors like the electricity selling/buying price, yearly maintenance costs, initial investment, tax reduction etc. The photovoltaic solar system could be installed on the same building where the solar heat panels where previously set up, their advantages in energy reduction being added.

2.2.3 Geothermal heat pumps

To maintain a comfortable temperature in a building can require an important quantity of energy. Compared to other energy sources for the heating which must be transferred on long distances, the energy of the ground has the advantage of being available on the spot and in great quantity. A geothermal heat pump (GHP) is used to concentrate or modify the level of temperature of this free heat coming from the ground, before distributing it in the building. Each kW of electricity used by a GHP makes it possible to extract more than 3 kW of heat from renewable energy of the ground. The most important part concerns the calculation of the length of the exchanger which must accumulate the heat of the ground. Based on a modeling of the buried pipes and ground we calculated the length necessary to meet the energy needs obtained previously by the predictive models. The coefficient of performance (COP) is an important design parameter, along with the buried pipes thermal characteristics. Using the same hypothesis for the 100 m^2 residential house we analyzed the impact of a vertical ground heat pump system on the environmental impact and the payback time. It was found that the necessary length is 123 m, a payback time of 3 years (taking also into account the advantage for the summer period when the heat pump produces cold water which is distributed in the radiant floor) and a 15.7 tones of CO_2/10 years avoided compared to an equivalent gas energy.

2.3 Multi-criteria decision support

Knowing the numerous alternatives between the system presented and plus the building energy optimization it was mandatory to use a multi-criteria decision analysis method. In our case we used the ELECTRE III [8] method which is classified as an "outranking method" of decision making. The ELECTRE methodology is based on the concordance and discordance indices. For an ordered pair of alternatives (A_j,A_k), the concordance index c_{jk} is the sum of all the weights for those criteria where the performance score of A_j is least as high as that of A_k, i.e. The second condition is a discordance condition d_{jk} whereby the bad scores are required to be above a specific threshold. The value of this threshold is not absolute and may be adjusted so as to investigate the stability of the ranking. Figure 5 illustrates the general structure of the outranking method. The final goal of the method is to automatically help the user in the decision process.

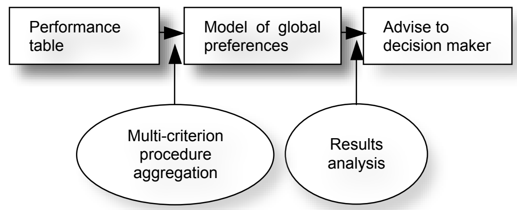

Fig 5. Global structure of the ELECTRE method

In our case the alternatives and criterions are presented in Table 3. The designer will enter for each of the criterions a weight based on what he prefers to be more valuable in his project. Between a list of proposed alternatives, the one which respects the condition on the criterions weights will be chosen. As example, if the designer wants to give more weight to the environmental impact criterion of the solution and based on a scale of weights, he can choose a higher value. The payback time criterion could have in this case less importance, e.g., half of the weight of the environmental criterion.

Table 3. Solutions and criterions used in the multi-criteria method

Alternatives + building optimization		
Solar heat panel surface 1	PV solar panel surface 1	Geothermal heat pump
Solar heat panel surface 2	PV solar panel surface 2	Geothermal heat pump
…	…	…
N solutions	N solutions	N solutions
Criterions		
Energy reduction	Payback time	Environmental impact

3. Conclusions

Based on the large database of values obtained from simulations, multiple regression analysis helped in finding heating demand prediction models. It was found that with five inputs and using complex polynomial equations is possible to predict the monthly heating demand with a 5% relative error. Building morphology and thermal inertia were found to be important design parameters when trying to optimize the building, a reduction of up to 40% being possible. Different renewable energy systems models were implemented in the SERAD support tool and financial and environmental calculations are realized. Knowing the great number of alternatives between the systems and the building, a decision-support method had to be applied. The final decision depends on the weight given to each criterion by the decision maker. Energy efficient measures are taken into account for the tool calculation on different levels starting with the thermal insulation, heating scenario, internal gains scenario and values, ventilation recovery or high efficiency boiler. The SERAD tool development is still in progress and will be available on web at the end of the next year.

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