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Computer programs for analysis of solar domestic hot water systems: RETScreen case study

太阳能生活热水系统分析之计算机程序：RETScreen 案例研究

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Abstract - **The simulation programs are important tools for analyzing different energetic options, including the use of energy efficiency measures and renewable energies. The objective of this study was to analyze comparatively the different computer tools available for modeling of solar domestic hot water systems in buildings. Among the main simulation software in use for this purpose, there are RETScreen International, EnergyPlus, TRNSYS, SolDesigner, SolarPro, e T*SOL. Among the tools mentioned, only EnergyPlus and RETScreen International are free, but they allow obtaining interesting results. In the presented case study can be seen the versatility of the RETScreen program, which allows for analysis of energy production, economic viability and carbon dioxide emissions. Within the range of computer solar water heaters simulators currently available, it is necessary that the user knows the tool specifications, such as programming language and capabilities so one may choose the program that is most suitable to produce the expected results for one's knowledge and modeling skills.**

Keywords - **software, solar energy, water heating, buildings.**

I. INTRODUCTION

In recent years have seen a sharp increase in energy demand of buildings, due to population growth, increased time spent indoors and improvements in the conditions of comfort to users. The contribution of the buildings in relation to energy consumption has reaching values between 20% and 40% in developed countries [1]. In developing countries, energy consumption by buildings is also increasing due to improving people's quality of life. In Brazil, buildings account for 13.7% of final energy consumption and 48.5% of electricity consumption [2].

Over the past 50 years, a wide variety of energetic simulation programs of buildings have been developed, enhanced and are presently in use throughout the energy professionals [3]. From the 1970s, we observed a greater creation of energetic simulation programs increased, result of increased computer availability, the first oil crisis and the growing environmental awareness [4]. The United States Department of Energy lists on its website more than 400 computational tools for evaluating energy efficiency, renewable energy, and sustainability in buildings. A brief description of each program is provided, as well as target audience, programming language and strengths and weaknesses of the tools [5].

Through simulation can evaluate the thermal and energy performance of buildings for different options, such as architectural design, construction components, lighting systems and air conditioning systems. With the computer simulation, we can estimate the amount of energy, the cost of energy use and the environmental impact of different options, even before the construction of the building [6].

An interesting option to reduce the energy demand of buildings, especially residential, is the use of solar water heaters. Studies in different countries have proven the

technical-economic feasibility of this technology compared to conventional sources, such as electricity and natural gas [7-9].

In addition, several studies have shown the potential to reduce carbon dioxide emissions on cooking of the buildings by solar thermal systems, particularly in countries with high dependence on fossil fuel [10-12].

In this context, the objective of this article was to conduct a comparative assessment of different computational tools available, focusing on their abilities and their target audience. In addition, an economic and environmental analysis of solar water heater based on RETScreen International is presented.

II. COMPARATIVE ANALYSIS OF COMPUTER TOOLS

The US government, based on popular features of two programs previously created, BLAST and DOE-2, developed the EnergyPlus. The software have innovative capabilities, including thermal and energy simulation in different zones, time steps smaller than an hour, and input and output data structures adapted to facilitate the development of the interface by third parties. Newer versions allow to calculate the energy and water consumption and the simulation of renewable energy systems, including thermal solar energy. The program is available for platforms Windows, Mac OS e Linux and uses Fortran 2003 as programming language. According to the program developers, high level of computer literacy not required, however engineering background helpful for analysis portions [5, 13].

RETScreen was developed by the Government of Canada and is currently available in 25 languages. It is estimated that there are more than 130,000 users of the program in 222 different countries. The software allows evaluating energy production, financial costs, economic viability and greenhouse gases emissions of systems based on renewable energy sources, including thermal and photovoltaic solar, wind, biomass and geothermal and energy efficiency measures, such as cogeneration. The software also includes databases of products, hydrology, climate and case studies for different types of projects. The program operates in Windows, Linux, and opera with Excel, Visual Basic and C++. As the software uses programming languages more known to the public, the user can easily learn how to use the program through the training material [5, 14].

The SolDesigner is a German program specialized in analysis of hydraulic design and control of solar thermal systems. It is useful for finding solutions for hot water projects and water solar heating in buildings and pools. SolDesigner produces a highly qualified design of the solar system and estimates for costs and energy production. The program is available for Windows platform and as well as RETScreen, uses Excel. According to the program developers, is not necessary programming knowledge to handle the SolDesigner [5].

The SolarPro was developed in United States and allows simulate the operation of solar hot water heating systems, hour by hour, for one year, such as EnergyPlus. Dozens of customizable variables can be incorporated into the simulation. The program operates in Windows computer platform and uses programming language of the type Visual Basic. To manage the program is recommended that the user have general knowledge of solar thermal processes [5].

TRNSYS, the Transient Systems Simulation Program, that has been commercially available since 1975, continues to develop by the international collaboration of the United States, France, and Germany. The program is primarily an equation solver program based on numerical techniques that allows the user to change the simulation complexity through of the inclusion of mathematics modules. As the EnergyPlus, it simulates buildings and their energetic systems in multi-zone, including solar thermal systems. TRNSYS operates Windows platform and uses as main programming language FORTRAN, although some components can also be written in C++. To operate this computer program, it is recommended that the user has some knowledge of FORTRAN, especially if he/she wants to modify the default calculation module [5, 15].

T*SOL is a German simulation program for the planning and professional design of solar thermal systems. The standard module contains a large number of configurations of hot water system, space heating systems and swimming pools. As the main capacity is the project design, the presents an extensive database with solar heating products, which facilitates its implementation. The program works in Windows operating system and uses Delphi programming language. Just as most of the programs mentioned above, it is not necessary programming knowledge to operate the T*Sol, just some prior information about operation of solar water heaters [5].

The EnergyPlus, RETScreen International, SolDesigner, SolarPro, TRNSYS and T*Sol tools have distinct capabilities and consequently are intended for different users. Some are simple, with the main function of design, while others make a more detailed analysis of the system. In Table 1 is shown a comparison among different computer programs for analysis of domestic solar water heaters, indicated by the Department of Energy of the United States. It is noted that only the RESTcreen and EnergyPlus are free, however it is possible to meet a wide audience with these programs, including students, civil construction professionals, energetic planners and researchers.

SolarPro, SolDesigner and T*Sol has been used more by construction professionals, while TRNSYS, EnergyPlus, and RETScreen International are more widely used in scientific research, especially due to its detailed analysis modules and be validated by several tests. Some scientific studies conducted with the aid of such software tools are presented below.

TABLE 1. CHARACTERISTICS OF COMPUTATIONAL PROGRAMS FOR ANALYSIS OF SOLAR DOMESTIC HOT WATER SYSTEMS

Program	Application	Audience	Strengths	Weaknesses	Access
EnergyPlus	Building performance, energy simulation, heat and mass balance, load calculation	Engineers, architecture consulting firms, utilities, federal agencies, researchers	Detailed and accurate simulation Allows to import geometry from CAD programs	Text input may make it more difficult to use than graphical interfaces	Free
RETScreen International	Energy, economic and environmental analysis of projects based on renewable energy and efficiency energetic	Engineers, architects, technologists, planners, facility managers, educators, researchers	Friendly platform and tool for easy application	n/a	Free
SolDesigner	Design of solar water heaters and circuits of hot water	Officials, tech-design engineers, house-owners, builders, plumbers	Detailed design of the thermal solar system	Does not give simulated energy yields	Not Free
SolarPro	Solar water heating, thermal processes, renewable energy, simulation	Solar design engineers, solar contractors, do-it-yourselfers	Accurate and detailed simulation	Level of user input can be cumbersome	Not Free
TRNSYS	Energy simulation, building performance, load calculation, renewable energy, energy efficiency	Engineers, architects, researchers, consulting firms	Allows modeling at different levels of complexity. Interacts with various other simulation packages	Require detailed information about the building and energy system	Not Free
T*SOL	Solar thermal heating, swimming pool heating, solar planning and design	Solar specialists, planners, engineers, heating technicians, plumbers, energy consultants	Precise calculations possible very user friendly	n/a	Not Free

Source: [5].

Canadian researchers studied the optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS, in Montreal. For these weather conditions, it was obtained the optimal system could provide 83-97% and 30-62% of the hot water demands in summer and winter, respectively. It is also determined that this system can provide about 54% of the heating energy needs of water per annual solar energy [16].

In another study, TRNSYS program was used to evaluate the performance evaluation of a net-zero-energy house in Datong, China. The hot water system with electric backup was designed considering the family of three people, with the total daily demand of 150 liters for water heating and 250 liters for radiant floor heating. For the conditions of Datong, was verified by simulation that to meet this hot water demand would be necessary a system with 7.6 m² of solar collector and hot water tank with 400 liters capacity [17].

Italian researchers applied EnergyPlus program to analyze of net-zero-energy households in your country. In total 40 economically and technically feasible energy efficiency measures for a high performing single-family house were evaluated. Through simulation, it was found that to attend the demand of domestic hot water would be needed a solar heater with gas backup with 5.9 m² solar collector, coupled to a thermal reservoir 800 liters, which is also used for other heating purposes in the housing, for an annual solar fraction of 80% [18].

Greek investigators used the RETScreen InternationalI to analyze the technical and economic viability of solar water heaters in Thessaloniki. It was found that a solar system with electric assistance, designed to meet an annual solar fraction of about 60%, in such meteorological conditions, can provide 1,702 kWh $year^{-1}$, with payback of five years, internal rate of return of 21.8% per year internal rate of return and net present value of 2,103 euros [19].

The RETScreen International program was also applied to evaluate the potential to reduce of carbon dioxide by means of solar water heaters in households in the Serbia. For an electricity grid mix of 73% thermal and 27% hydro power plants, the installation of a system to meet a typical house represents the reduction 31 to 34 tCO_2 during the system lifetime, depending on the region of the country considered [12].

According to a Canadian Government survey, in the period of 1998 to 2004, this tool was used in the design of projects had a total installed capacity of 1,000 MW of generation by several renewable sources, avoiding the emission of 630 kt CO_2/year [20]. The following a case study is presented

to demonstrate the applicability of RETScreen International for design and life cycle analysis of a domestic hot water system, in a typical Brazilian dwelling.

III. RETSCREEN CASE ESTUDY

The RETScreen International program was used to analyze a solar water heater, designed to meet a typical Brazilian dwelling. It conducted a study of economic feasibility and reduction of greenhouse gases emissions of the solar system, compared to using electric energy. The electrical water heating system without storage, also known as electrical resistance showerheads, is the water heating system most widely used in Brazil. This appliance is present in 73.5% of Brazilian dwellings, accounting for around 24% of electricity consumption in these conditions [21].

It was considered a typology of dwelling intended for a family of four people, with two bedrooms, a living room, a kitchen and a bathroom, with a total area of 63 m². This model has features representing 58% of Brazilian dwellings [22].

This study considered a solar system consisting of flat solar collectors and horizontal thermal reservoir, with natural circulation of water (thermosyphon effect). The parameters adopted for the design of the solar domestic hot water system are as follows:

- Dwelling with four residents;
- A daily bath per resident;
- Water consumption per bath of 50 liters;
- Bath time of 10 minutes;
- Bath temperature equal 40 °C;
- Flat solar collector with copper pipes and glass cover, optical efficiency factor of 0.779 and global coefficient of loss of 6.795 W/(m².K); and
- Horizontal thermal reservoir with stainless steel coating and polyurethane insulation.

The solar system was simulated for the weather conditions of the city of Belo Horizonte, Minas Gerais, Brazil (latitude -19°55'15"; longitude -43°56'16"). Belo Horizonte receives annual average daily solar radiation, in the horizontal plane, of 4.34 kWh/m²/day and has an average annual temperature of 22.3°C.

Through the implementation of the RETScreen International program was proposed to size two solar water heaters, one with annual solar fraction of 70% and other with 80%. It is emphasized that 70% is the minimum value of annual solar fraction recommended by the Brazilian standard used as a reference for sizing of solar water heaters, the NBR 15569: Solar Water Heating System in Direct Electric Circuit [23]. The results are shown in Table 2.

TABLE 2. SIZING OPTIONS FOR THE SOLAR DOMESTIC HOT WATER SYSTEM, ON METEOROLOGICAL CONDITIONS OF BELO HORIZONTE, BRAZIL.

Annual solar fraction (%)	Solar collector area (m²)	Thermal reservoir capacity (L)
70	2.0	200.0
80	3.0	200.0

It was presented two sizing options as an example in this work, but it can simulate various other by the program, including changing the type of solar collector and thermal reservoir. The software has a database with hundreds of solar heating products, with their technical characteristics, to assist the program user.

After defining various design options, it can be check, which shows the better economic feasibility by using the RETScreen International software. The parameters considered in this study to analyze the economic feasibility of the solar domestic hot water system, compared to electric shower, are as follows:

- Cost of the solar system with an annual solar fraction of 70%, including the costs of acquisition and installing: US$ 980;
- Cost of the solar system with an annual solar fraction of 80%, including the costs of acquisition and installing: US$ 1,090;
- Electricity tariff for the residential sector in Belo Horizonte including taxes: US$ 0.215/kWh;
- Horizon of the solar system planning: 20 years;
- Discount rate: 8% per year; and
- Annual adjustment of electricity tariff: 2% per year.

The results of the economic feasibility analysis of the solar system, found through the program's application, are presented in Table 3.

TABLE 3. INDICATORS OF ECONOMIC FEASIBILITY OF A SOLAR WATER HEATER ON THE METEOROLOGICAL CONDITIONS OF BELO HORIZONTE, BRAZIL, COMPARED TO ELECTRIC SHOWER USE.

Indicator	Solar fraction 70%	Solar fraction 80%
Internal rate of return	26.8% per year	27.7% per year
Net present value	US$ 1,809	US$ 2,129
Simple payback	4.1 year	3.9 year
Benefit-cost ratio	2.85	2.95

Therefore, it was verified that, between the two proposed design options, the system with annual solar fraction of 80% presented a higher profitability to the owner of the dwelling. However, it is noteworthy that the two design options showed good indicators of economic feasibility, with payback time within the first quarter of the estimated useful life for the solar

heater and a rate of return greater than 25% per year. The rates of return obtained were more than triple the discount rate considered for the project, of 8% per year. In this study was regarded that the owner of the dwelling has the initial capital to invest in the solar water heater, however the program also allows evaluate the economic viability considering financing and subsidies.

Besides being interesting to the owner of the dwelling, the use of solar water heaters is also economically attractive to the National Electric System. As the electric showerheads have high power, around 3 to 8 kW, and is turn on mostly at the beginning of the night, contribute to increase the peak demand of the national load curve, creating costs for demand supply. The installation of each solar domestic hot water system generates a saving US$336 to US$405 for National Electric System, considered the costs of expanding capacity [24].

In case one want to calculate through the RETScreen International software the reduction of greenhouse gas emissions from the clean energy project. For this case study, it was found that the replacement of the electric showerhead by the solar water solar heater with annual solar fraction of 70% e 80% was, respectively, 97 and 112 kgCO_2equivalent/year. For comparison, the Figure 1 is shown the avoided emissions of the system with annual solar fraction of 80% in relation to different sources of energy.

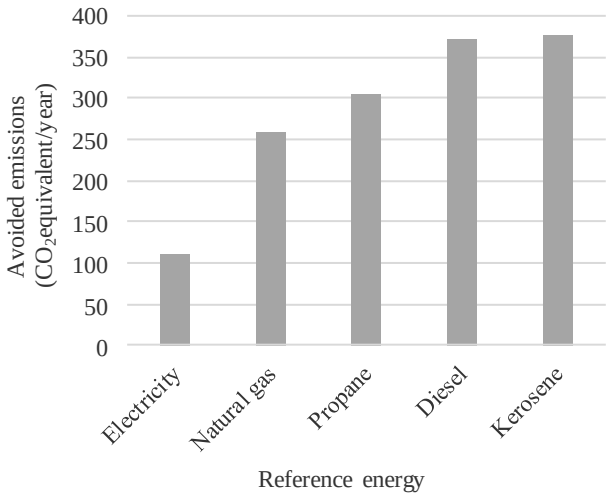

Fig.1, Reduction of greenhouse gas emissions of a solar domestic hot water system with an annual solar fraction of 80%, in Belo Horizonte, Brazil, compared to using of other energy sources.

The mitigation of emissions by the use of solar water heaters in relation to electricity was much lower compared to non-renewable energy sources in the studied case. This occurs because the Brazilian electric energy matrix have large share of renewable sources, around 79.3% [2]. The emission factor of greenhouse gases by the electricity system in Brazil is 0.087 tCO_2equivalente/MWh, while in the United States, China and Australia is respectively 0.522, 0.766 and 0.841 tCO_2equivalente/MWh [24]. It is noteworthy that solar thermal energy has other environmental benefits beyond reducing emissions of greenhouse gases. Large hydroelectric plants, source most used in Brazil for the production of electricity, generate negative impacts on the local and regional environment due to the need to flood large areas.

The program also allows to convert the emissions avoided in several equivalent mitigation measures. Table 4 is presented some measures equivalent to the installation of solar water heaters in 1,000 households with an annual solar fraction of 80% in Belo Horizonte, Brazil.

TABLE 4. EQUIVALENT EMISSIONS MITIGATION OF GREENHOUSE GASES TO THE INSTALLATION OF SOLAR DOMESTIC HOT WATER SYSTEM IN 1,000 DWELLINGS, IN BELO HORIZONTE, BRAZIL.

Mitigation measure	Quantity
Gasoline not used	48,123 liters per year
Oil not consumed	260 barrels per year
Urban solid waste recycling	37 tons per year
Forest absorbs carbon dioxide	10 hectares per year

This feature of the RETScreen International program is interesting to facilitate the user's understanding about the negative environmental impact avoided by the use a renewable energy source, in this case, the solar domestic hot water system.

IV. CONCLUSION

Computational tools for the modeling of solar water heaters have been used, throughout the world, to assist professionals in tasks such as sizing and energy analyses. Nowadays, there is a wide variety of programs for different users. Amongst the most widespread tools, there are RETScreen International, EnergyPlus, TRNSYS, SolDesigner, T*SOL and SolarPro.

Among the tools mentioned, only the EnergyPlus and RETScreen International are free, but allow obtaining interesting results, and they are designed for a diverse audience, including designers, researchers and energy planners. The first program has a module of detailed energy analysis of solar water heaters, while the second one has modules of economic feasibility of the system and greenhouse gas emissions analysis. In the presented case study can be seen the versatility of the RETScreen program, which allows for analysis of energy production, economic viability and carbon dioxide emissions.

Therefore, within the range of computer solar water heaters simulators currently available, it is necessary that the user know the tools specifications, such as programming language and capabilities so one may choose the program that is most suitable to produce the expected results for one's knowledge and modeling skills.

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