An open access tool for building energy audits harmonizing European standards

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Abstract

SEAS (Simplified Energy Auditing Software) is an open access tool for energy audits of residential and office buildings, developed by the University of Pisa (Department of Energy, Systems, Territory, and Construction Engineering), in collaboration with ENEA (Italian National Agency for New Technologies, Energy, and Sustainable Economic Development), funded by the Italian Ministry of Economic Development. The analyzed services are: winter heating by hydronic systems, production of domestic hot water, and lighting and other electrical uses. Production of heat and electricity by renewable energy sources (solar thermal, photovoltaic, biomass heat generators, and heat pumps) is also calculated. The application assesses the different energy flows contributing to the energy balance of the building system on a monthly basis. The calculation methods are based on Italian and European technical standards, properly modified to take into account daily schedules of building usage. The tool has been developed with the intention of spreading energy auditing activities, thanks to the definition of a unified and inexpensive procedure, comprising the economic evaluation of retrofit actions by means of common investment metrics. All the worksheets are freely accessible to energy auditors, together with technical and user manuals (in Italian). Local Governments are expected to promote the use of SEAS, as part of their energy efficiency strategies. As for the reliability of energy calculations, they have been double-validated by both dynamic simulation results (tests have been run on TRNSYS 17) and comparison with actual energy billings. Two test cases are presented: a unit of a duplex house and a historical educational building, with classrooms and offices.

1. Introduction

As recognized by Directive 2010/31/EU, buildings account for 40% of total energy consumption in the European Union and the sector is expanding. Building energy audits are a necessary step towards the application of effective energy reduction measures in the Union.

As pointed out by Thumann and Younger, 2008, a single definition of “energy audit” is not available; its scope, the complexity of the calculations and of the employed energy models, and the level of detail of cost-benefit evaluations to be performed are all issues that each individual auditor can handle differently and that should be defined prior to starting any activity.

In any case, the goal of every building energy auditing process is to identify where energy is generated and exchanged between the zone under exam and its surroundings, considering the actual activities of the users in the building and how the energy systems are run. Besides, an integral part of each audit is to identify opportunities and provide recommendations of actions to be implemented for improving the overall energy performance of the building.

In order to avoid expensive on-site measurement and monitoring periods, the energy models on which the predictions of yearly thermal and electrical energy needs are based should be accurate and reliable, possibly validated by a documented history of energy vectors consumption.

In the present paper, a novel open access tool of building energy simulation specifically tailored to energy audits is presented, together with two applications to existing buildings.

2. Description of the simulation tool and how to use it for an energy audit

SEAS (Simplified Energy Auditing Software) has been developed by DESTEC (Department of Energy, Systems, Territory, and Construction Engineering) of the University of Pisa, in collaboration with UTEE (Energy Efficiency Technical Unit) of ENEA (Italian National Agency for New Technologies, Energy, and Sustainable Economic Development). It analyzes hydronic heating, DHW (Domestic Hot Water) production, and electrical energy demands in residential and office buildings.

The energy simulation model is quasi-stationary, meaning that bihourly and weekly profiles in terms of presence and activities of the users (i.e., manual openings of the windows, use of the shutters) have to be added to obtain weighted averages for energy balances on a monthly basis. Attenuation of the internal set-point temperature as well as intermittent heating are also taken into account.

The architecture of the software – developed in a Microsoft Excel 2010 environment, making extensive use of Visual Basic macros – consists of a long series of worksheets included in a single file. Every worksheet has input fields and related intermediate results. For each input, the source and the level of uncertainty of the added value must be specified in order to filter the reliable fields and focus on the uncertain data for the subsequent tuning process, which will be described afterwards.

The main sections are listed below, in the same order they appear on SEAS:

- climatic data and internal set-points;
- occupancy and activities profiles;
- DHW uses;
- household and office electrical appliances;
- artificial lighting use;
- other non-electric internal loads;
- opaque envelope walls;
- windows;
- natural ventilation;
- ground-exchanging envelope elements;
- thermal bridges;
- building thermal capacity;
- building envelope monthly energy balance;
- scheme of the heating, DHW, and electrical systems;
- heat emission subsystem;
- heating system control;
- heat distribution subsystem;
- DHW distribution subsystem;
- storage subsystems;
- heat recoveries;
- solar thermal generation;
- heating and DHW generators (traditional boilers, biomass heat generators, electrical and absorption heat pumps, heat exchangers from district heating networks);
- photovoltaic system;
- estimated monthly uses of each energy vector for heating and DHW production;
- records of electrical and thermal energy and domestic water billings;
- comparison between energy billings and primary energy calculations.

The heat generators should be added in their order of priority, so that back-up generators are activated only when the power of the previous ones is not enough to fulfill the monthly thermal loads.

The building envelope monthly energy balance is the result of the following contributions:

- heat transmission through opaque elements towards external air, sky, unheated spaces, adjacent buildings, and ground;
- heat transmission through windows and external doors;
- heat transmission through thermal bridges;
- energy losses due to ventilation openings and infiltration cracks;
- internal gains from the electrical and lighting system, from occupants, and from other sources (e.g., cooking activities, stoves, fireplace);

- solar gains through opaque elements;
- solar gains through windows.

The dynamic response of the building is taken into account only by means of a monthly utilization factor for heat gains. In the case of intermittent or attenuated heating, an energy reduction factor is also employed. Both factors are calculated in accordance with ISO 13790:2008.

The entire calculation procedure, which attempts to harmonize a large number of Italian and European technical standards dealing with the topics covered by SEAS, is fully described in Conti et al., 2011.

Once the first energy calculation iteration is completed, deviations from actual energy billings can be reduced by reasonably adjusting the input data labeled with the highest uncertainty level. This tuning process ends when the discrepancies become acceptable. This phase is critical for the overall success of the auditing activity, as reliable subsequent cost-benefit analyses greatly depend on accurate estimates of energy consumptions.

The next SEAS-supported stage of the energy audit is the simulation of retrofit actions on the building envelope and on the heating, DHW production, and electrical systems, including possible use of renewable sources. The auditor identifies possible solutions and SEAS updates the energy consumptions. Besides, costs of the investments and other economic parameters are added (e.g., current and forecasted prices of energy vectors, discount rate, incentives for energy efficiency). Each measure is evaluated in terms of simple and discounted payback periods, NPV (Net Present Value), and PI (Profitability Index). Hence, the auditor completes its tasks, by recommending the most effective actions to the client, in terms of energy savings and economic investment.

3. Validation of seas: presentation of two test cases

3.1 Test Case 1: Historical Educational Building

Two SEAS-supported energy audits have been performed for validation purposes. The first analyzed case is a historical educational building, property of the University of Pisa, having both classrooms and office spaces. This four-story building (gross volume: 4,370 m^3) is located in the historical centre of Pisa and is bordered on the south by another university building and north with private buildings, while to the west and east there are two central streets of the city.

Natural gas and electricity billings are available for the past 4 years of the building's usage. The billing of electricity is shared with the adjacent building, where similar activities take place in classrooms and offices. It has been decided to divide the total electrical energy consumption proportionally to the buildings' gross volumes; this represents a critical assumption of the analysis.

The most uncertain input provided to the simulation tool is the presence profile of students in classrooms, also related to windows' opening and to the use of artificial lighting and other electrical equipment. Thus, the tuning process described in the previous section has been performed on these parameters.

Table 1 shows the comparison between average yearly consumption of electricity and natural gas – documented by the available billings – and SEAS estimates for the same energy vectors.

ENERGY VECTOR	BILLINGS	SEAS ESTIMATES	DEVI-ATION
Electricity	103.8 MWh/yr	95.5 MWh/yr	-8.0%
Natural gas	55.9 MWh/yr	56.8 MWh/yr	1.5%

Table 1 – Yearly consumption of energy vectors: billings vs. SEAS evaluations for Test Case 1

A DHW production and distribution system is not present, so natural gas is employed only for heating classrooms and offices. Thermal energy calculations are in satisfactory agreement with the billings. On the other hand, electrical energy consumption is underestimated, probably due to the above-mentioned splitting operation on electricity billings, which can be quite inaccurate, especially considering the presence of food and beverage vending machines only in the other building.

Table 2 reports the heating season energy balance of the building envelope. The main terms are heat losses through opaque walls and windows. A very large contribution is also given by internal gains, due to the intense use of the building during working hours.

ENERGY CONTRIBUTION	ESTIMATED VALUE
Heat losses through opaque walls (except for ground-facing elements) : Q_{tr_o}	-40.15 MWh
Heat losses through windows: Q_{tr_w}	-13.88 MWh
Heat losses via thermal bridges: Q_{tr_tb}	-1.03 MWh
Heat losses through ground-facing elements: Q_{tr_g}	-7.58 MWh
Air infiltration losses: Q_{inf}	-1.40 MWh
Natural ventilation losses: Q_{ve}	-3.28 MWh
Electrical internal gains: Q_{int_el}	7.87 MWh
Other internal gains: Q_{int_ot}	11.92 MWh
Solar gains from opaque walls: Q_{sol_o}	3.28 MWh
Solar gains from windows: Q_{sol_w}	5.93 MWh
Heating demand (from energy balance) : Q_{H_nd}	-38.32 MWh

Table 2 – Energy balance according to SEAS (heating season) for Test Case 1

As for the retrofit actions, it has to be remarked that the external envelope, as well as other building elements, cannot be modified due to the historical and artistic value of the construction. This notwithstanding, three recommendations have been given:

- thermal insulation of the garret (220 m^2), with reduction of horizontal wall thermal transmittance from 1.60 to 0.32 W/(m^{2}K); natural gas savings of 5.7% can be achieved and the calculated discounted payback period is 22 years (discount rate: 2%, lifespan of the structural solution: 50 years, NPV=7530 €, PI=1.8);
- installation of thermostatic valves on radiators and addition of a climatic control module on the heat generator; the efficiency of the heating control system increases from 93% to 97% and natural gas savings of 2.7% can be obtained (discounted payback period: 11 years, lifespan of the control actuators: 15 years, NPV=550 €, PI=1.5);
- substitution of the existing traditional boiler with a biomass generator of reduced power (from 128 kW to 80 kW, lifespan: 15 years) and installation of an inertial storage tank; in spite of an 8.4% increase of heating energy consumption due to the lower efficiency of the biomass boiler, the discounted payback period is only 4 years, owing to the very low cost of biomasses, compared to natural gas (0.03 against 0.08 €/kWh), NPV=31200 €, PI=4.9.

The performed analysis shows that the latter recommendation leads to the best economic investment.

3.2 Test Case 2: Residential Unit of a Duplex House

The second energy audit was performed on a two-story residential unit (95.6 m^2) of a duplex house built in the eighties and located in the town of Camaiore, Province of Lucca. The longer side of the building lies on the northeast-southwest direction. The zone under analysis is bordered on the northwest side with another house of similar size and thermo-structural characteristics, mostly unoccupied in winter and kept at a set-point temperature of 15°C. Another building, located in the northeast, screens the wall on that side to direct and diffuse solar gains and to long-wave radiation towards the sky. All the other external walls are unscreened.

The heating and DHW production systems have been recently retrofitted (in 2007), with the installation of a condensing boiler, thermostatic valves on all the radiators, two solar thermal collectors (dedicated to DHW production), and an inertial storage tank. The energy vector for producing thermal energy is LPG (Liquefied Petroleum Gas), due to lack of connection to the natural gas urban distribution network.

Building usage profiles obtained from interviews of the occupants, data recovered from design documents and technical sheets, and all the parameters recorded during the building inspection have been inserted in the appropriate input worksheets of SEAS.

The tuning procedure has been performed on the following inputs:

- shutters utilization profiles;
- ventilation openings profiles;
- fireplace usage.

Electricity and LPG billings are available from 2009 to 2011. Table 3 shows the very good agreement between average yearly consumption of electricity and LPG and SEAS results.

ENERGY VECTOR	BILLINGS	SEAS ESTIMATES	DEVI-ATION
Electricity	2490 kWh/yr	2394 kWh/yr	-3.9%
LPG	8076 kWh/yr	7900 kWh/yr	-2.2%

Table 3 – Yearly consumption of energy vectors: billings vs. SEAS evaluations for Test Case 2

ENERGY CONTRIBUTION	ESTIMATED VALUE
Heat losses through opaque walls (except for ground-facing elements): Q_{tr_o}	-7103 kWh
Heat losses through windows: Q_{tr_w}	-1077 kWh
Heat losses via thermal bridges: Q_{tr_tb}	-507 kWh
Heat losses through ground-facing elements: Q_{tr_g}	-739 kWh
Natural ventilation and air infiltration losses: Q_{ve}+Q_{inf}	-797 kWh
Internal gains: Q_{int}	2406 kWh
Solar gains from opaque walls: Q_{sol_o}	1723 kWh
Solar gains from windows: Q_{sol_w}	675 kWh
Heating demand (from energy balance): Q_{H_nd}	-5418 kWh

Table 4 – Energy balance according to SEAS (heating season) for Test Case 2

Table 4 illustrates the heating season energy balance of the building envelope. As in Test Case 1, the main energy flow is heat transmission through opaque walls. Internal and solar gains (especially from opaque walls, owing to their high thermal transmittance) are also important contributions.

As far as DHW production is concerned, Table 5 shows the monthly fraction (*f*) of total load supplied by the solar thermal system (SEAS implements the *f*-chart method described by Duffie and Beckman, 1991) and the residual energy to be generated by the boiler.

MONTH	*F* value	RESIDUAL ENERGY
January	0.30	132.3 kWh
February	0.43	98.4 kWh
March	0.77	38.9 kWh
April	0.91	7.9 kWh
May	1.00	0.00 kWh
June	1.00	0.00 kWh
July	1.00	0.00 kWh
August	0.97	0.00 kWh
September	0.99	0.00 kWh
October	0.74	43.1 kWh
November	0.33	125.3 kWh
December	0.19	142.9 kWh
Whole year	0.71	588.8 kWh

Table 5 – DHW production and solar thermal system: monthly f values and residual thermal energy for the boiler

As in Test Case 1, three retrofit actions are simulated and recommended:

- insulation of the roof (55.8 m^2), with reduction of thermal transmittance from 1.46 to 0.32 W/(m^{2}K); LPG savings of 24.9%, discounted payback period of 32 years (discount rate: 2%, lifespan of the solution: 50 years), NPV=7160 €, PI=1.4 (a grant from the Italian Government covering 55% of investments in energy efficiency is assumed to be obtained);
- installation of a climatic control module on the boiler; LPG savings of 2.7%, discounted payback period of 6 years (lifespan of the control actuator: 15 years), NPV=377 €, PI=2.5;
- installation of a photovoltaic system on the roof (electrical peak power: 2 kW, total area of the modules: 13.2 m^2) and access to dedicated national incentives; yearly electrical energy production of 2410 kWh, discounted payback period of 15 years (lifespan of the photovoltaic modules: 25 years), NPV=5110 €, PI=1.4.

According to SEAS results, in spite of different initial investments and estimated payback periods, all the three proposed measures are profitable.

3.3 Test Case 2: Validation by Dynamic Simulations

The accordance between SEAS evaluations of energy vectors demands and actual energy billings on a yearly basis for the two presented test cases is not sufficient to conclude that SEAS is able to accurately predict every term of the energy balance. In order to exclude that positive and negative contributions conveniently cancel each other, a dynamic simulation of Test Case 2 has been executed on the software TRNSYS 17.

Hourly climatic data (temperature, solar irradiation, wind) of all the Italian provinces have been recently made available by CTI (Italian Committee of Thermotechnics). Thus, the typical meteorological year of the Province of Lucca has been used as an input of the building envelope dynamic simulation. The same correlation between external air temperature and sky temperature used in SEAS (and based on ISO 13791:2012) has been implemented in TRNSYS.

Two central winter months (January and February) have been simulated. Energy balances obtained by SEAS and TRNSYS are shown in Table 6. With respect to Table 4, some terms had to be aggregated for comparison purposes, as TRNSYS calculates the net heat flux through an opaque wall, superimposing heat losses to solar gains.

ENERGY CONTRIBUTION	ESTIMATED VALUE according to seas	ESTIMATED VALUE according to TRNSYS
$Q_{tr\_o}+Q_{tr\_w}+Q_{tr\_tb}+Q_{tr\_g}+Q_{sol\_o}$	-3542 kWh	-3961 kWh
$Q_{ve}+Q_{inf}$	-357 kWh	-379 kWh
Q_{int}	913 kWh	861 kWh
Q_{sol_w}	271 kWh	486 kWh
Q_{H_nd}	-2715 kWh	-2992 kWh

Table 6 – SEAS vs. TRNSYS energy balances (January and February)

As expected, deviations of ventilation losses and internal gains estimates are very small (5.8% and 6.0%, respectively), since the same bihourly profiles of occupants conduct have been entered in both codes. Predictions of solar gains from windows disagree (44.2% deviation); specifically, they are overestimated by TRNSYS, in which the extensive usage of shutters during daylight hours and the presence of external obstructions have not been simulated, for the sake of simplifying the building model, as far as resistive envelope components have been concerned. As for net transmission losses, which represent the larger contribution to the building envelope energy balance, the origin of the observed discrepancies (10.6%) can be explained by analyzing the energy fluxes passing through each external component, as reported in Table 7. In particular, it has to be remarked that physical models of heat transfer through opaque walls are very different for the two codes:

- SEAS uses a quasi-stationary balance of the thermal zone, a single node where all the parameters are lumped, including heat capacity;
- TRNSYS calculates, for each wall, the time evolution of the temperature field across its thickness and also takes into account long-wave radiation heat exchanges between the internally-facing elements of the analyzed space; on the other hand, thermal bridges have to be simulated by properly increasing wall thermal transmittances.

Hence, acceptable agreement between SEAS and TRNSYS net transmission losses seasonal estimates represents an important verification of the reliability of the simplified methodology implemented by SEAS.

Figure 1 illustrates the evolution of internal and external air temperatures, sky temperature, and imposed set-point temperature profile (decreased during the night from 17°C to 16°C), according to the TRNSYS dynamic simulation. Apart from short overheating and overcooling phases, the internal air temperature remains within the target values of the control system.

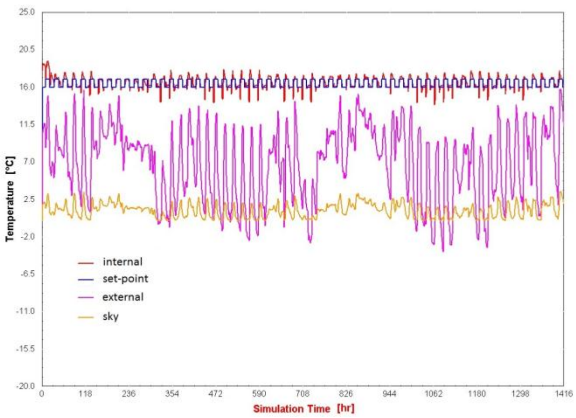

Fig. 1 – Evolution of internal and external air, sky, and set-point temperatures, according to TRNSYS

EXTERNAL WALL	seas ESTIMATE	TRNSYS ESTIMATE
Roof (55.8 m²)	-1024 kWh	-1576 kWh
Floor (51.1 m²)	-379 kWh	-303 kWh
North-East opaque wall (18.8 m²)	-524 kWh	-501 kWh
South-East opaque wall (32.5 m²)	-502 kWh	-610 kWh
South-West opaque wall (14.0 m²)	-185 kWh	-193 kWh
North-West opaque wall (7.0 m²)	-95 kWh	-160 kWh
Wall separating the two units of the duplex house (39.3 m²)	-107 kWh	-135 kWh
South-East windows (6.8 m²)	-355 kWh	-350 kWh
South-West windows (2.6 m²)	-136 kWh	-133 kWh
Thermal bridges	-235 kWh	n/a
Total energy flux through external walls	-3542 kWh	-3961 kWh

Table 7 – SEAS vs. TRNSYS energy fluxes through each external component (January and February)

The element giving the largest deviation between SEAS and TRNSYS results is the roof. This is coherent with the more accurate TRNSYS building physical model. In fact, in winter, the roof is particularly cold, even on the internal side, not only because of its low conductance, but also due to low solar gains and high long-wave thermal radiation towards the sky. All the other opaque elements of the room – which are warmer – transfer heat to the roof, causing increased transmission losses. Therefore, SEAS, using a simplified model that does not take into account heat exchange between internal surfaces, tends to underestimate these losses.

On the other hand, the floor is warmer than the other external walls, due to the higher temperature of the ground, with respect to external air. Thus, for the same reasons explained above for the roof and taking care of changing the sign of heat fluxes, SEAS tends to overestimate transmission losses towards the ground.

Figure 2 reports the temperature evolution of the external face of the roof obtained by TRNSYS dynamic simulation, showing values always higher than the sky temperature, but generally lower than the external air temperature.

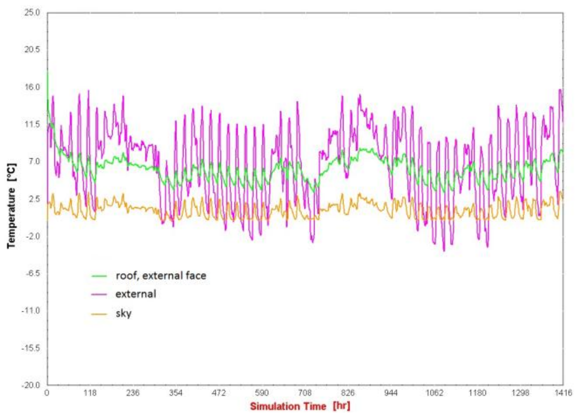

Fig. 2 – Evolution of roof (external face), external air, and sky temperatures according to TRNSYS

In spite of the observed differences between SEAS and TRNSYS estimates of energy flows through single external envelope elements, a satisfactory agreement of the total transmitted energy – as well as of the other terms involved in the building energy balance – is reached, indicating that SEAS predictions are consistent not only with energy billings, but also with overall dynamic simulation results.

4. Conclusion

The presented energy auditing software, intended to be open, flexible, and user-friendly, has proven to be suitable for accurately assessing the electrical and thermal energy flows in residential and office buildings and in hydronic heating systems. Consequently, SEAS can evaluate energy and economic savings introduced by possible retrofit actions.

The calculation procedure makes use of the most recent technical standards, performing small integrations and modifications intended to optimally simulate real usage of the building envelope and systems. Besides, the energy auditor can modify climatic data and other standard input parameters, in order to increase the accuracy of energy consumption predictions.

Like every new tool, SEAS will have to be monitored and periodically updated. Further validation of energy estimates is in sight, to be performed on other test cases and exploring different types of buildings and systems.

5. Acknowledgement

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