Solar heating/cooling and domestic hot–water systems

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Abstract: Increasing awareness of global warming forces policy makers and industries to face two challenges: reducing greenhouse gas emissions and securing stable energy supply against ever–increasing world energy consumption, which is projected to increase by 71% from 2003 to 2030. In addressing these two issues simultaneously, renewable energies prove themselve attractive, as they are independent from the fossil fuel supply and do not contribute to greenhouse gas emissions. Therefore, providing heating and cooling by utilizing renewable energy such as solar energy is a key solution to the energy and environmental issues. This paper makes references to the solar generation of thermal energy and its use for buildings and domestic water heating, describing both different types of solar equipment and system, and developing a mathematical model for energetical analysis of the solar heating systems. Also, this paper provides a review of the available cooling technologies assisted by solar energy and their recent advances.

Key-Words: Renewable energy sources, Solar energy collection, Solar thermal systems, Buildings heating, Domestic hot–water, Solar cooling technologies, Energetical analysis.

1 Introduction

Global warming occurs when carbon dioxide, released mostly from the burning of fossil fuels (oil, natural gas, and coal) and other gases, such as methane, nitrous oxide, ozone, CFCs, HCFCs and water vapor, accumulate in the lower atmosphere. As results of the rapid growth in world population and the economy, especially in developing countries, total world energy consumption has increased and is projected to increase by 71% from 2003 to 2030. Fossil fuels continue to supply much of the energy used worlwide, and oil remains the primary energy source. Therefore, fossil fuels are the major contributor to global warming.

The awareness of global warming has been intensified in recent times and has reinvigorated the search for energy sources that are independent of fossil fuels and contribute less to global warming. Among the energy sources alternative to fossil fuels, renewable energy sources such as solar and wind garner the public's attention, as they are available and have fewer adverse effects on the environment than do fossil fuels. Four energy sources represent renewable energy: hydro–energy, geothermal energy, solar energy, and wind energy. The prime source of renewable energy is solar energy.

Thermal energy obtained from the sun with a solar thermal system can be used for domestic water heating, and heating or even cooling of buildings. Solar domestic hot–water systems prevail because the hot–water requirement can be well covered by the solar energy offer. Air–conditioning systems are the dominating energy consumers in buildings in many countries, and their operation causes high electricity peak loads during the summer. The solar cooling technology can reduce the environmental impact and the energy consumption issues raised by conventional air–conditioning systems. Therefore, the current paper makes references to the solar generation of thermal energy and its use for building heating and domestic hot–water (DHW), describing both different types of solar equipment and system, and performing an energetical analysis of the solar heating systems. Also, this paper provides a review of the available cooling technologies assisted by solar energy and their recent advances.

2 Solar energy collection by thermal collectors

Solar energy can be converted to chemical, electrical, and thermal processes. Photosynthesis is a chemical process that produces food and converts CO_2 to O_2. Photovoltaic cells convert solar energy to electricity. The thermal conversion process provides thermal energy for space heating and cooling, domestic water heating, power generation, distillation, and process heating. Solar thermal collector collectes the solar energy transforms it into thermal energy and transports heat towards a fluid (water, water plus an antifreeze additive, or air).

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A flat–plate collector generally consists of the following components (Fig. 1): glazing; tubes, fins, or passages; absorber plates; headers or manifolds; insulation; container or casing.

Temperatures far above those attainable by flat–plate collectors can be reached if a large amount of solar radiation is concentrated on a relatively small collection area.

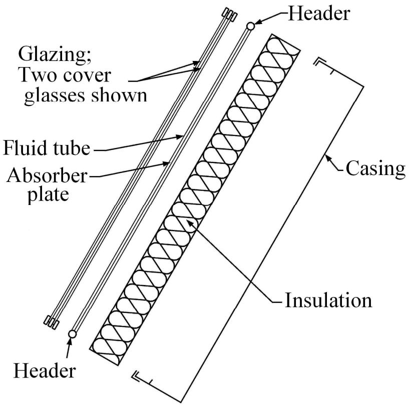

Fig. 1 Exploded cross section through double–glazed solar water heater

A solar collector is characterized by the absorption (α_c), transmission (τ_c) and emission (ε_c) factors. The collector efficiency η_c is defined by relation:

$$\eta_c = \frac{\alpha_c \tau_c I_s - k_c \Delta t}{I_s} = \eta_0 - \frac{k_c \Delta t}{I_s} \qquad (1)$$

in which: I_s is the intensity of solar radiation; η_0 – conversion (optic) factor of collector; k_c – heat transfer coefficient of collector, with values of 2.5…3.8 W/(m^2·K); Δt – temperature difference between the fluid and environment.

A system for converting solar energy into thermal energy is generally provided with the following equipments (Fig. 2): solar collectors, heat storage devices, circulating pumps, heat transport and distribution network, automatization, control and safety devices.

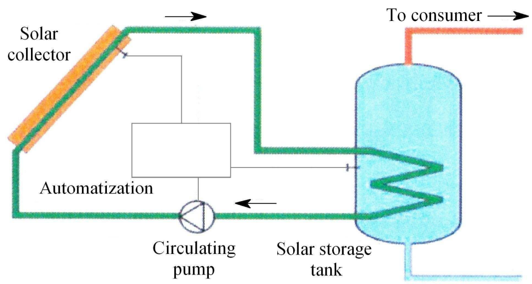

Fig. 2 Solar energy conversion in thermal energy

3 Solar water heating systems

A solar water heater includes a solar collector that absorbs solar radiation and converts it to heat, which is then absorbed by a heat transfer fluid (water, a nonfreezing liquid, or air) that passes through the collector. The heat transfer fluid’s heat is stored or used directly.

Portions of the solar energy system are exposed to the weather, so they must be protected from freezing. The system must also be protected from overheating caused by high insolation levels during periods of low energy demand.

In solar water heating, water is heated directly in the collector or indirectly by a heat transfer fluid that is heated in the collector, passes through a heat exchanger, and transfers its heat to the domestic or service water. The heat transfer fluid is transported by either natural or forced circulation. Natural circulation occurs by natural convection (thermosiphoning), whereas forced circulation uses pumps or fans.

Technique development in field of solar energy in the last 20-25 years has generated the emergence of a diversified range of domestic hot–water solar systems. As an example, are presented three constructive variants used in practice for closed circuit and with heat–exchanger solar systems:

– the standard variant is the simplest and cheapest system with forced circulation, thus being the most common installation. The circulating pump transportes the fluid between solar collector and heat exchanger in the storage tank (coil), when the fluid temperature in solar collector is higher than the domestic hot–water temperature in storage tank;

– for medium and large installations are used two lower–volume storage tanks instead of a large–volume one, and to control the water heating in the two storage tanks is used a three–way valve, driven depending on fluid and tank water temperature (Fig. 3). The storage tanks can be both for domestic hot–water or one for domestic hot–water and another one for heating (pre–heating) of thermal agent in heating system;

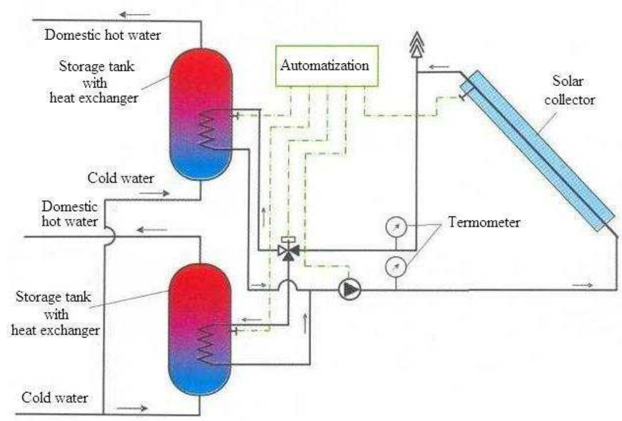

Fig. 3 Closed circuit with two storage tanks system

– another constructive variant is represented by solar collector use for heating of domestic water as well as for heating of swimming pool water by means of a heat exchanger (Fig. 4). For each m^2 of swimming pool with normal depth are necessary 0.5…0.7 m^2 of solar collector.

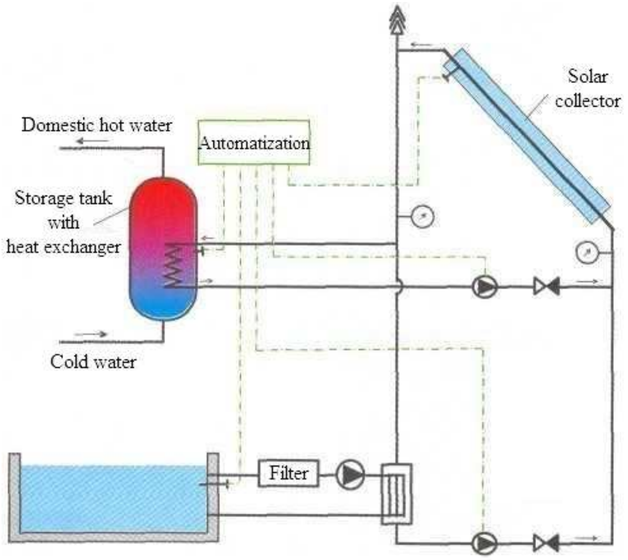

Fig. 4 Solar system for domestic hot–water and swimming pool water heating

4 Solar heating systems

The solar heating systems fall into two principal categories: passive and active.

Passive solar systems require little, if any, nonrenewable energy to make them function [10]. Every building is passive in the sense that the sun tends to warm it by day, and it loses heat at night. Passive systems incorporate solar collection, storage and distribution into the architectural design of the building and make minimal or no use of fans to deliver the collected energy to the structure. Passive solar heating, cooling and lighting design must consider the building envelope and its orientation, the thermal storage mass, and window configuration and design.

Active solar systems use either liquid or air as the collector fluid. Active systems must have a continous availability of nonrenewable energy, generally in the form of electricity, to operate pumps and fans. A complete system includes solar collectors, energy storage devices, and pumps or fans for transferring energy to storage or to the load. The load can be space cooling, heating, or hot water. Although it is technically possible to construct a solar heating and and cooling system to supply 100% of the design load, such a system would be uneconomical and oversized. The size of the solar system, and thus its ability to meet the load, is determined by life–cycle cost analysis that weighs the cost of energy saved against the amortized solar cost.

Figure 5 shows one of the many systems for domestic hot–water and space heating. In this case, a large, atmospheric pressure storage tank is used, from which water is pumped to the collectors by pump P_1 in response to the differential thermostat T_1. Drainback is used to prevent freezing, because the amount of antifreeze required would be prohibitively expoensive. Domestic hot–water is obtained by placing a heat exchanger coil in the tank near the top, where, even if stratification occurs, the hottest water will be found.

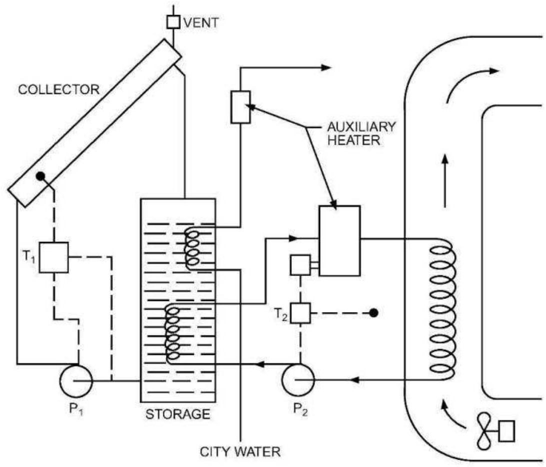

Fig. 5 Solar system for domestic hot–water and space heating

An auxiliary water heater boosts the temperature of the sun–heated water when required. Thermostat T_2 senses the indoor temperature and starts pump P_2 when heat is needed. If the water in the storage tank becomes too cool to provide enough heat, the second contact on the thermostat calls for heat from the auxiliary heater.

Active solar energy systems have been combined with heat pumps for water and/or space heating. The most economical arrangement in residential heating is a solar system in parallel with a heat pump, which supplies auxiliary energy when the solar source is not available. Freeman et al. [2] present information on performance and estimated energy savings for solar–heat pumps.

5 Cooling by solar energy

Solar cooling technology can be classified into three categories: solar electrical cooling, solar thermal cooling, and solar combined power and cooling.

Thermal energy produced from the solar energy can be transformed to useful cooling and heating through the thermochemical or thermophysical processes by using thermally activated energy conversion systems. Thermally activated energy conversion systems are further classified into three categories: open sorption cycles, closed sorption cycles, and thermo–mechanical systems. Solid and liquid desiccant cycles represent the open cycle [4]. The liquid desiccant cycle have a higher thermal COP than the solid desiccant cycle. The ejector cycle represents

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the thermo–mechanical cycle and has a higher COP [4], but needs a higher heat source temperature than other cycles.

Closed sorption cycles are classified in two categories based on the sorption material: liquid sorption and solid sorption. The liquid sorption cycle refers to the absorption cycle, and the solid sorption cycle refers the adsorption cycle, which needs a lower heat source temperature than the absorption cycle.

Swartman et al. [8] emphasize various absorption systems. Typical refrigerant/absorbent pairs used in the absorption system are water/lithium bromide (H_2O/LiBr) and ammonia/water (NH_3/H_2O). Jordan and Liu [5] discusses commercially available H_2O/LiBr absorption refrigeration systems. Grossman [3] provided typical performances of the single– and multi–effect absorption cycles, as shown in Table 1.

Table 1. Typical performance of absorption cycles

Type	COP	Heat source temp. [°C]	Type of solar collectors
Single effect	0.7	85	Flat plate
Double effect	1.2	130	Flat plate/compound parabolic concentrator
Triple effect	1.7	220	Evacuated tube/concentrating

Solar absorption systems utilize the thermal energy from a solar collector to separate a refrigerant from the refrigerant/absorbent mixture. As shown in Table 1, the flat–plate solare collectors can be used for the single–effect cycle. However, the multi–effect absorption cycles require high temperatures above 85 °C, which can be delivered by the evacuated tube or concentating type collectors. Since the multi–effcet absorption cycles require considerably higher desorber temperatures, the single–effect absorption cycle is mostly used for the typical low–cost absorption cycle solar cooling.

The typical absorption cycle solar cooling system consists of an absorption chiller, a solar collector, a hot–water storage tank, and an auxiliary heater, as illustrated in Figure 6.

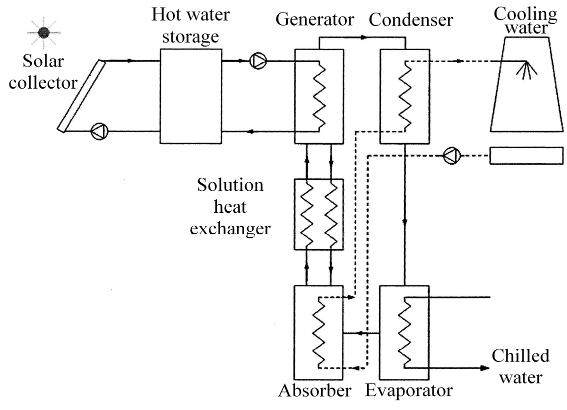

Fig. 6 Schematic of absorption cycle solar cooling system

Syed et al [7] developed a single–effect H_2O/LiBr absorption chiller of 35 kW nominal cooling capacity, assisted by a 49.9 m^2 array of flat–plate solar collectors. In their system, thermal energy produced by the solar collector was stored in a 2 m^3 hot–water storage tank.

Trombe and Foex [9] suggested using an intermittent single–stage NH_3/H_2O absorption system assisted by the solar energy for ice production, several researchers explored the feasibility of such systems.

To improve the unsteady nature of the solar heat from the solar collector to the absorption system, Chen and Hiraha [1] proposed a new type of absorption cycle that was co–driven both by solar energy and electricity. In the conventional absorption cycle solar cooling system, the cooling capacity is determined by the heat energy delivered to the generator by the solar collector and the COP of the absorption cycle. However, in their proposed system, total energy delivered to the generator could be controlled by adjusting the mass flow rate through the compressor. For the new cycle COP value is of 0.8, higher than conventional cycle.

6 Energetical analysis of solar heating systems

Based on the equation (3) the operation regime of the solar collector can be analyzed:

– if $I_s > k_c\Delta t/\eta_0$, the circulating pump is in operation and thermal agent temperature in solar collector will increase;

– if $I_s = k_c\Delta t/\eta_0$, the circulating pump switches off;

– if $I_s < k_c\Delta t/\eta_0$, the thermal agent does not circulating in solar system.

The solar energy collected on collector surface can be written as:

$$I_s = I_D + I_d \qquad (2)$$

in which: I_s is the total irradiation; I_D – direct irradiation; I_d – diffuse irradiation.

The possible recovered energy is given by:

$$E = \int_n I_D(\tau)\mathrm{d}\tau + \int_n I_d(\tau)\mathrm{d}\tau + \int_{N-n} I_d(\tau)\mathrm{d}\tau \qquad (3)$$

in which: n is the effective hours with solar radiation; N – maximum possible hours with solar radiation.

Introducing the ratio $f = n/N$, the relation (3) becomes:

$$E = \int_{fN} [I_D(\tau) + I_d(\tau)]\mathrm{d}\tau + \int_{1+fN} I_d(\tau)\mathrm{d}\tau \qquad (4)$$

The maximum collected energy, function of the collector efficiency, is given by:

$$E_{\max} = \int_N [\eta_0 E(\tau) - k_c\Delta t]\mathrm{d}\tau \qquad (5)$$

The equation (5) has two solutions τ_1 and τ_2 when $E = k_c\Delta t/\eta_0$ (η_c=0). Analyzing the variation of daily maximum solar energy (Fig. 7) results that:

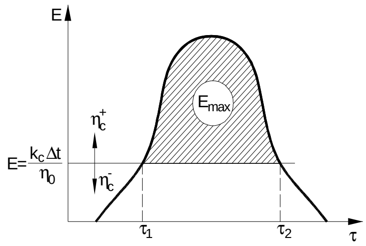

Fig. 7 Daily maximum solar energy

– above the line η_c=0, solar energy can be used to heat up the fluid in collector, and the marked area placed between the $E(\tau)$ curve and the line η_c=0 represents the maximum value of solar energy $E_{\max}$ in a day. Thus, is obtained:

$$E_{\max} = \int_{\tau_1}^{\tau_2} \eta_0 E(\tau)\mathrm{d}\tau - k_c\Delta t(\tau_2 - \tau_1) \qquad (6)$$

– under the line η_c=0, solar energy cannot be used because it is lower than the energy demand for fluid heating.

Because during a day there are periods with and without sun, the effective solar energy E_{ef} is different from the maximum solar energy $E_{\max}$, and it is given by:

$$E_{ef} = \int \{\eta_0[I_D(\tau) + I_d(\tau)] - k_c\Delta t\}\mathrm{d}\tau + \int [\eta_0 I_d(\tau) - k_c\Delta t]\mathrm{d}\tau \qquad (7)$$

Using the notations τ_1 and τ_2 for the solutions of equation:

$$\eta_0[I_D(\tau) + I_d(\tau)] - k_c\Delta t = 0 \qquad (8)$$

and τ'_1, τ'_2 for the solutions of equation:

$$\eta_0 I_D(\tau) - k_c\Delta t = 0\,, \qquad (9)$$

the relation (7) can be written as:

$$E_{ef} = \int_{\xi} \{\eta_0[I_D(\tau) + I_d(\tau)] - k_c\Delta t\}\mathrm{d}\tau + \int_{\xi'} [\eta_0 I_d(\tau) - k_c\Delta t]\mathrm{d}\tau \qquad (10)$$

in which: ξ is the number of hours between τ_1 and τ_2 with sun; ξ' – number of hours between τ'_1 and τ'_2 without sun.

The integral equation (10) can be solved when the meteorological data are known. At the same time one considered the day like a sum of $f\times N$ hours with sun and ($1–f\times N$) hours without sun. Taking into consideration this simpliffy supposition, to calculate the effective solar energy, the following cases should be analyzed (Fig. 8):

– if τ_1 and τ_2 does not exists, that means: $k_c\Delta t/\eta_0 > I_D+I_d$ then $E_{ef} = E_{\max} = 0$, and the solar energy cannot be used;

– if τ'_1 and τ'_2 does not exists, that means: $k_c\Delta t/\eta_0 > I_D$ and $k_c\Delta t/\eta_0 < I_D+I_d$, then the effective solar energy is given by equation:

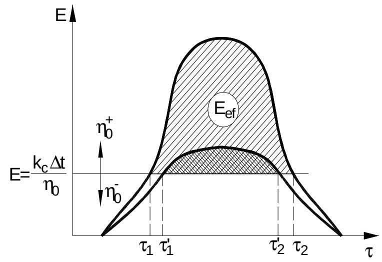

Fig. 8 Daily maximum effective solar energy

$$E_{ef} = f\int_{\tau_1}^{\tau_2} \{\eta_0[I_D(\tau) + I_d(\tau)] - k_c\Delta t\}\mathrm{d}\tau\,, \qquad (11)$$

which is equivalent with:

$$E_{ef} = fE_{\max} \qquad (12)$$

– if $k_c\Delta t/\eta_0 < I_d < I_D+I_d$, then the effective solar energy is given by:

$$E_{ef} = f\int_{\tau_1}^{\tau_2} \{\eta_0[I_D(\tau) + I_d(\tau)] - k_c\Delta t\}\mathrm{d}\tau + (1-f)\int_{\tau_1}^{\tau_2} [\eta_0 I_d(\tau) - k_c\Delta t]\mathrm{d}\tau \qquad (13)$$

or:

$$E_{ef} = fE_{\max} + \eta_0(1-f)\int_{\tau'_1}^{\tau'_2} I_d(\tau)\mathrm{d}\tau - + (1-f)k_c\Delta t(\tau'_2 - \tau'_1) \qquad (14)$$

Substituting notation:

$$E_d = \int_{\tau'_1}^{\tau'_2} I_d(\tau)\mathrm{d}\tau - \frac{k_c\Delta t}{\eta_0}(\tau'_2 - \tau'_1), \qquad (15)$$

the equation (14) can be written as:

$$E_{ef} = fE_{\max} + (1-f)\eta_0 E_d \qquad (16)$$

Neglecting the heat losses between collector and storage tank the average temperature of fluid in collector t_{cm} will be approximately equal with the average temperature in storage tank t_{ac} ($t_{cm} = t_{ac}$). The average energy delivered by storage tank is calculated as:

$$E_{ac} = 24k'(t_{ac} - t_i) \qquad (17)$$

where: k' is the conventional heat transfer coefficient between storage and heated space.

The energy conservation law of the radiator is writted as:

$$Gc_p(t_{ac} - t'_{ac}) = k_R(t_{mR} - t_i) \qquad (18)$$

in which: G is the fluid flow rate for heating; c_p – specific heat of fluid; t_{ac}, t'_{ac} – the inlet and outlet temperatures of fluid in the radiator; k_R – heat

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transfer coefficient of radiator; t_{mR} – average temperature of the radiator surface.

Assuming the average temperature of the radiator surface equals to the average temperature of fluid in radiator, the equation (18) becomes:

$$Gc_p\left(t_{ac}-t_{ac}^{'}\right)=k_R\left(\frac{t_{ac}+t_{ac}^{'}}{2}-t_i\right) \tag{19}$$

Using relations (18) and (19) is obtained:

$$t_{mR}=\frac{2Gc_p t_{ac}+k_R t_i}{k_R+2Gc_p} \tag{20}$$

Neglecting the heat losses between storage tank and radiators the heat provided by radiator will be equal to the heat delivered by storage tank:

$$k_R\left(t_{mR}-t_i\right)=k'\left(t_{ac}-t_i\right) \tag{21}$$

Combining equations (18) and (21) gives:

$$k'=\frac{2Gc_p k_R}{k_R+2Gc_p} \tag{22}$$

The daily energy demand for heating is given by:

$$E_{nec}=24q_0V\left(t_i-t_e\right) \tag{23}$$

in which: q_0 is the specific heat loss of the space; V – heated volume; t_i – indoor air temperature; t_e – outdoor air temperature.

Representing the curves $E_{ef} = f(t_{ac})$, $E_{ac} = f(t_{ac})$, $E_{nec} = f(t_{ac})$ the optimal collector surface could be establish (Fig. 9). In Figure 9–a, the intersection point A between E_{ef} şi E_{ac} curves is under the E_{nec} line. In this case the stored energy is lower than the energy demand of the consumer. Thus an auxiliary heat source is necessary. The abscise of the point A represents the average temperature $t_{ac,m}$ in storage.

When the intersection point A' is above the E_{nec} line (Fig. 9–b), the stored energy is higher than the energy demand of consumer. In this case the fluid temperature in solar collector will be higher which can lead to lower collector efficiency.

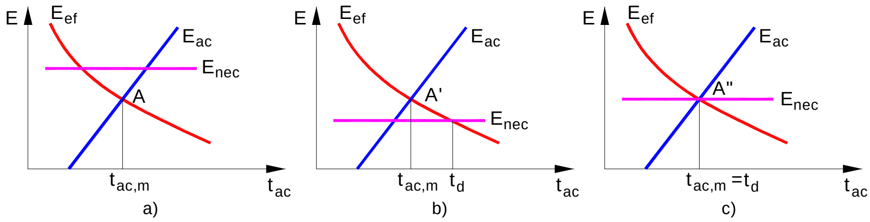

Fig. 9 Daily variation of E_{ef}, E_{ac} and E_{nec} with storage fluid temperature

The optimal surface of solar collector is obtained when the collected and stored energy is equal with the consumer energy demand (Fig. 9–c).

7 Conclusions

Related to the other renewable ecological sources (hydro–energy, wind energy, geothermal energy), solar energy use leads to simple installations with relatively low costs. The efficiency of solar heating and/or domestic hot–water systems with seasonal energy storage can be improved by conceiving mixt systems with heat pumps or other forms of energy.

To obtain high thermal performance of solar heating and cooling systems an optimal calculus shall be done. The collector surface, storage tank volume and storage period are the most important factors which have a decisive influence about the efficiency of these systems.

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