OPTIMIZATION OF SOLAR COLLECTORS AREA AND ANGLE BY USING MATLAB ENVIRONMENT

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Abstract

Using of the solar energy is one of the possibilities for decreasing of our dependence on imported energy. Nowadays it becomes quite usual to install solar collectors in family-houses. As concern block of flats, applications with solar systems are not so common. This paper deals with a system of solar collectors used for heating and preparation of hot service water in a particular four-storey block of flats located in Prague.

1 Introduction

The main task of this article is to show the way how to find an optimal area of collectors for different collector's slopes. Economical and ecological criteria are taking into account. The time needed for saving of the same energy amount as was used for the production of all system components is calculated in the ecological part of the project. Similarly the time for saving of CO_2 production is calculated. In the economical part there is calculated repayment time for the three cases. In the first case it is counted with a stable level of energy costs, in the second with a 5 % growth of energy costs per year and the third case is calculated with a state grant from National Fund of the Environment. All the calculations are made for different types of collectors.

2 Description of selected object

The selected object for this case is a low energy four-story building with a basement. Thermal solar collectors will be installed on the flat roof with a southern orientation. The calculations are made for different types of collectors. For the first flat collectors with one selective coat and one cover glass are taking into account. For the second it is calculated with vacuum tubes collectors. Main differences between them are in their prices and efficiency. The maximal area of collectors is limited by the disposition of the roof to the 130 m^2 of absorber.

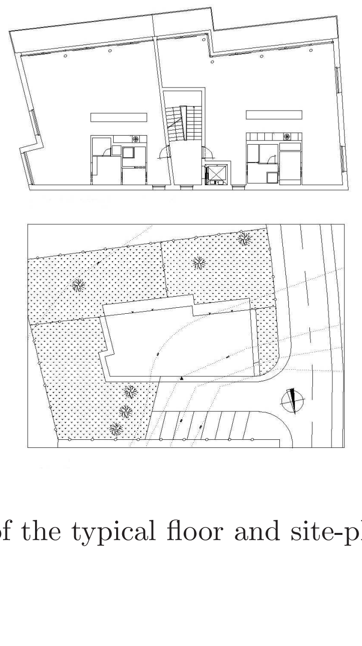

Figure 1: Layout of the typical floor and site-plan of the building.

Scheme of the heating system for this building is shown in Fig.2. Energy from solar collectors is accumulated in a storage tank which is situated at the basement. Energy between the tank and other parts of the system is distributed by external heat exchangers. Hot service water is prepared by a through-flow way. There is a secondary heat source (gas boiler) in case of low energy supply from solar collectors.

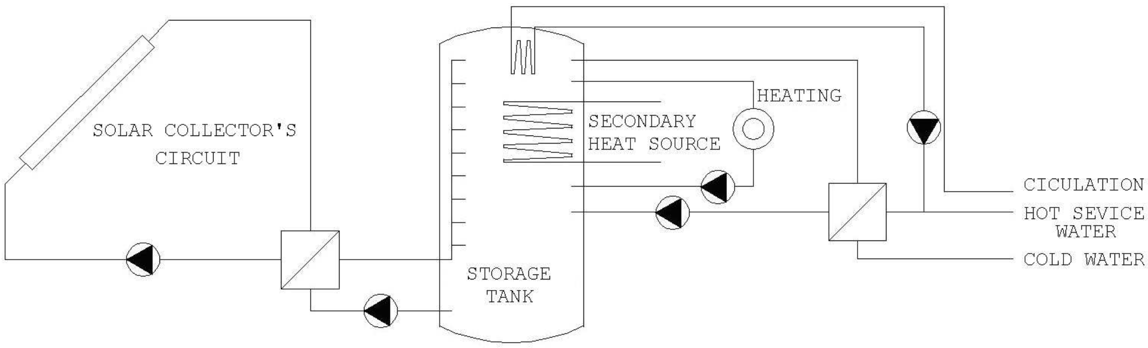

Figure 2: Scheme of the heating system.

3 Energy captured by absorber per day

The energy captured by the absorber per day is calculated by the following formula:

$$Q_{A,day} = \eta_A(\tau Q_{S,day,teor} + (1-\tau)Q_{D,day}) \ , \tag{1}$$

where

- $Q_{S,day,teor}$ $[\frac{kWh}{m^2}]$ Theoretical amount of a solar energy on a square meter per day in particular months.
- $Q_{D,day}$ Energy of a diffused radiation in particular months.
- τ [h/day] Proportional time period of sunshine in particular months.
- η_A [-] Collector efficiency, which can be calculated by

$$\eta_A = (1-r) - \left[\frac{(U_1+U_2)(t_A - t_v)}{I_{mean}}\right] , \tag{2}$$

  where

  - $r = 0.2$ [-] Proportional reflection ability of the collector's glass (depends on a glass pollution - the value for Prague).
  - $U_1 + U_2$ [W/m^{2}K] Heat-transmission coefficient for the front and for the back side of absorber. The value for a flat collector with one selective coat and one cover glass is equal to 4.5 W/m^{2}K. The value for a vacuum tubes collector is equal to 2 W/m^{2}K.
  - $t_A = 55$ [°C] Mean temperature of the absorber constant during all year.
  - t_V [°C] Temperature of a surrounding air.
  - I_{mean} $[\frac{W}{m^2}]$ Mean intensity of a solar radiation in particular months.

- t_V, I_{mean}, τ, $Q_{S,day,teor}$, $Q_{D,day}$
  Tabled values for Prague are taking into account. These values vary along the months.

Graph of the energy captured by the absorber is shown in Fig. 3.

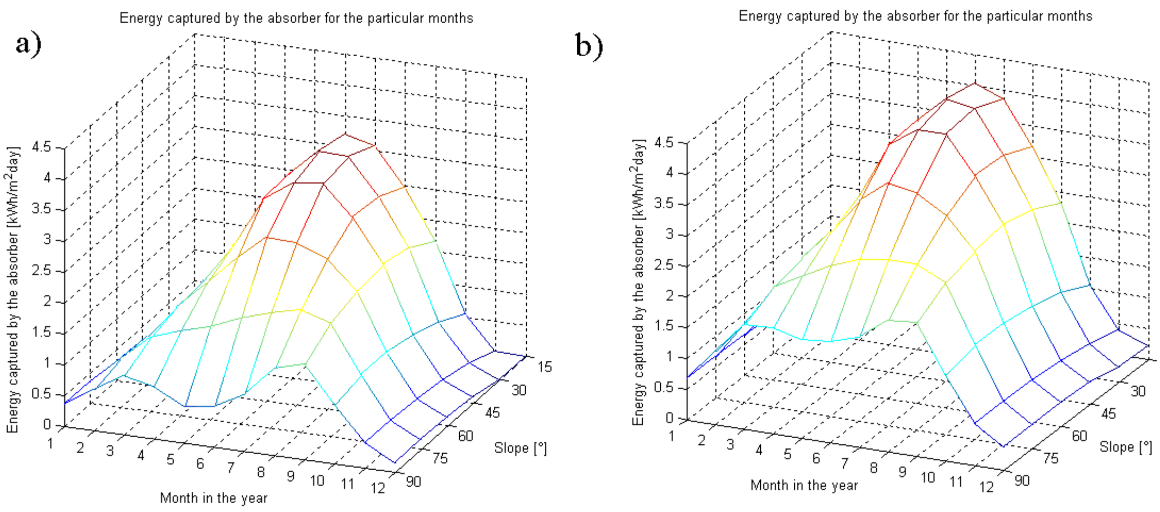

Figure 3: Comparison of the energy captured by the absorber as a function of collector's slope and month in the year. Graph a) shows captured energy for a flat collector while graph b) shows results for a vacuum collector.

4 Total amount of energy which can be substituted by solar collector's energy

For an optimization of a solar system we need to establish energy demands of the building. The most important are demands of hot service water and heating.

- Daily need for hot service water is 50 l per person and day and there are 32 persons in this building.
- Total volume of hot service water is:
  V = 32 x 50 = 1.6 m^3/day.
- Absorbed energy for hot water is:
  E_t = V x c x Δ t = 1.6 x 1.163 x (55-10) = 83.736 kWh
- Total energy amount including 20% losses is:
  $Q_{HSW,day}$ = 1.2 x E_t = 1.2 x 83.736 = 100.483 kWh
- Storage tank is designed for hot water demand 1.5 - 2 days. Therefore the volume of the tank is:
  2 x 1.6 m^3 = 3.2 m^3 $\Rightarrow$ 3000 l
- The total heat loss of the object is:
  Q_c = 20.1 kW.
- Heating demand during the year is derived from the Q_C proportionally to the mean month temperature values t_e.:

$$Q_{HEAT,day} = 24 \cdot Q_C \cdot \frac{t_i - t_e}{t_i - (-12)} = 24 \cdot 20,1 \cdot \frac{t_i - t_e}{32} \tag{3}$$

- Total amount of energy which can be substituted by solar collector's energy is calculated per day. This value differs according to the month:

$$Q_{tot,day} = min(Q_{A,day} \times A; (Q_{HSW,day} + Q_{HEAT,day})), \tag{4}$$

where A [m^2] is the area of the absorber.

	t_e	$t_i - t_e$	$Q_{HEAT,day}$
I	-1.5	21.5	324.1
II	0	20	301.5
III	3.2	16.8	253.3
IX	14.9	5.1	76.88
X	9.4	10.6	159.8
XI	3.2	16.8	253.3
XII	-0.2	20.2	304.5

Table 1: Energy needs for heating in particular months.

- Total energy from solar collectors per year:

$$Q_{tot,year} = \sum Q_{tot,day} \times n_{mon}, \tag{5}$$

where n_{mon} is a number of days in a month.

5 Return of energy used for production and CO_2 emissions

A very important aspect for an evaluation from an ecological view is the return time that is needed for saving the same amount of energy as was used for the production of the solar collectors system. Here is the way how to estimate it.

- The energy level dependent on the year when it is evaluated:

$$Q_{EN}(n) = Q_{tot,year} \times n – E_p \times n – E_{s1} – E_{s2} \times A, \tag{6}$$

where:

n – Number of years.

E$_{s1}$ – Energy used for a production of the solar system's components.

E$_{s2}$ – Energy used for a production of the components which is dependent on the absorber's area.

A [$\mathbf{m^2}$] – Area of the absorber.

E$_p$ - Operation of pumps: E_p = 3 x 500 kWh/year = 1500 kWh/year

As concern CO_2 emissions the calculation of return time is the same except the necessity to add two following terms.

- Amount of CO_2 emissions from using of gas for heating and hot service water in a gas boiler:
  e_{gas} = 219 g/kWh.
- Emissions produced during the electricity production process:
  e_{el} = 603 g/kWh.

Saved CO_2 emissions are calculated by formula:

$$Q_{CO_2}(n) = Q_{tot,year} \times n \times e_{gas} – E_p \times n \times e_{el} – E_{s1} – E_{s2} \times A \tag{7}$$

The input data for this chapter are shown in Tab 1., Tab 2. and Tab 3. The results of these calculations may be seen in Fig. 4. The energy return time for flat collectors is less than 3 years as concern vacuum collectors it is even less than 2 years. The first point which reaches zero line is the 45° slope with 30 m^2 area of the collectors for both cases. Very interesting are also crosspoints between splines where the most profitable is slope 60° and as for the highest areas the slope 75°.

The second part of the ecological view is the estimation of return time for saving of CO_2 emissions which were produced during the production process of solar system's components. Results are shown in Fig. 5. In comparison to the energy the return time is longer: 3 and 4 years.

	Pcs.	MJ	kWh	g_{CO_2}	total kWh	total g_{CO_2}
Storage tank 3000l	1	23412	6503.33	1569678	6503.33	1569678
Tank's insulation	1	534.6	148.5	15444	148.5	15444
Heat exchanger	2	541	150.278	36240	300.556	72480
Pump	3	444	123.333	29770	370	89310
Piping Cu 1m	40	58	16.1111	3200	644.444	128000
Piping insulation 1m	40	3	0.83333	200	33.3333	8000
Expansion tank	1	541	150.278	36240	150.278	36240
Total					**8150.44**	**1919152**

Table 2: Energy used for the production of components independent on the installed area E_s1.

	MJ/m^2	kWh/m^2	CO_2/m^2
Flat collectors	2280	633.3	124000
Holders for collectors	2050	569.4	104905
Total		**1203**	**228905**

Table 3: Energy used for the production per m^2 – flat collectors E_{s2}.

	MJ/m^2	kWh/m^2	CO_2/m^2
Vacuum tubes collectors	670	186.1	57700
Holders for collectors	2050	569.4	104905
Total		**755.6**	**162605**

Table 4: Energy used for the production per m^2 – vacuum tubes collectors E_{s2}.

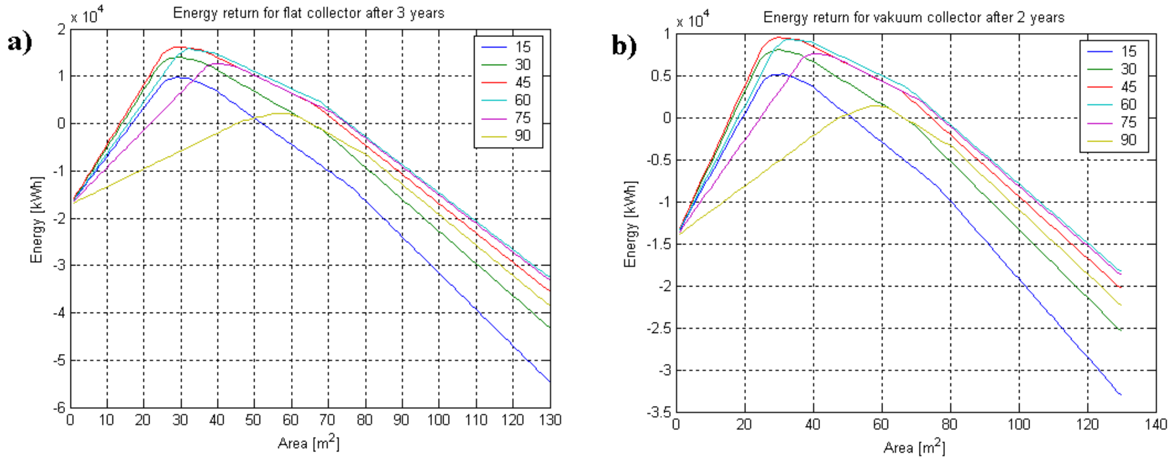

Figure 4: Energy return after 3 years for flat collectors (a) and after 2 years for vacuum tubes (b) collectors.

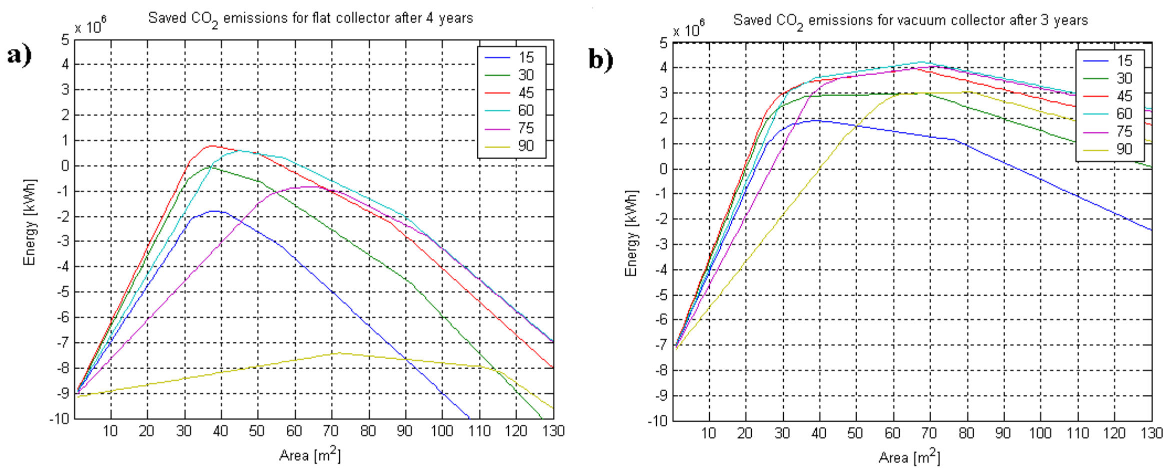

Figure 5: Saved CO_2 emissions after 4 years for flat collectors (a) and after 3 years for vacuum tubes (b) collectors.

6 Economical calculations

The other view to the solar energy is of course economical one. In the calculation there were taken into account additional costs, which wouldn't be paid in the case without solar collectors. Operation costs are also included by the consumption of pumps similarly to the energy calculations. The costs of the system components are divided according to the dependence of the installed area as it is possible to see in Fig. 5, Fig. 6. and Fig. 7.

- The cash-flow of installation is calculated by the following formula:

$$C_0(n) = Q_{tot,year} \times n \times p_{gas} - E_p \times n \times p_{el} - C_{s1} - C_{s2} \times A \tag{8}$$

Where

n - Number of years.

p_{gas} = 2.6 CZK/kWh - The price for 1kWh produced by gas boiler (including losses).

p_{el} = 1.1 CZK/kWh - The price for 1kWh electricity (including losses).

A [m^2] - Area of the absorber.

E_p - Energy for consumption of pumps: $E_p = 3$ x 500 kWh/year = 1500 kWh/year

$Q_{tot,year}$ - The energy from solar collectors per year.

C_{s1}, C_{s2} - The costs of the solar system components

	Pcs.	price/pcs.	Total price
Storage tank 3000l	1	61200	61200
Tank's insulation	1	18600	18600
Heat exchanger	2	32500	65000
Pump	3	4500	13500
Electronic regulation	1	4000	4000
Piping Cu 1m	40	222	8880
Piping insulation 1m	40	124	4960
Expansion tank	1	2500	2500
Transportation, others	1	9080	9080
Total [CZK]			**187720**

Table 5: Fixed costs - C_{s1}.

	Price / m^2
Flat collectors	5036
Holders for collectors	2766
Others (including assembly)	6211
Total [CZK/m^2]	**14013**

Table 6: Costs for m^2 absorber - flat collector C_{s2}.

	Price / m^2
Vacuum tubes collectors	5452
Holders for collectors	3833
Others (including assembly)	6211
Total [CZK/m^2]	**15497**

Table 7: Costs for m^2 absorber - vacuum tubes collector C_{s2}.

The results of economical part are shown in Fig. 6. The return time of an investment is much longer than the return time of energy. 30 years is quite long time because it is estimated life-time of the system. But the prices of energy are increasing every year. The growth rate was even more than 10% last year. Therefore it is calculated also the return time with 5% growth rate every year.

- The previous formula (8) is changed in terms with prices of energy and gas:

$$C_{5\%growth}(n) = Q_{tot,year} \times n \times \sum(p_{gas} \times 1.05^n) - E_p \times n \times \sum(p_{el} \times 1.05^n) - C_{s1} - C_{s2} \times A \quad (9)$$

After 17 years it is possible to get an investment back as it is shown in Fig. 7.

The European Union and the Ministry of Environment support renewable resources of energy, therefore in some cases it is possible to reach state grant for the solar system from the National Fund of Environment. Fig. 8 is showing how the return time is changed to 15 years after getting 50% of costs as a grant. The growth rate is not included in this case.

- Calculation with a state grant:

$$C_{50\%grant}(n) = Q_{tot,year} \times n \times p_{gas} - E_p \times n \times p_{el} - 0.5 \times C_{s1} - 0.5 \times C_{s2} \times A \tag{10}$$

In all of the economical results is possible to see that the first point when is reached an investment recovery is around the 30 m^2 area with the 45° slope.

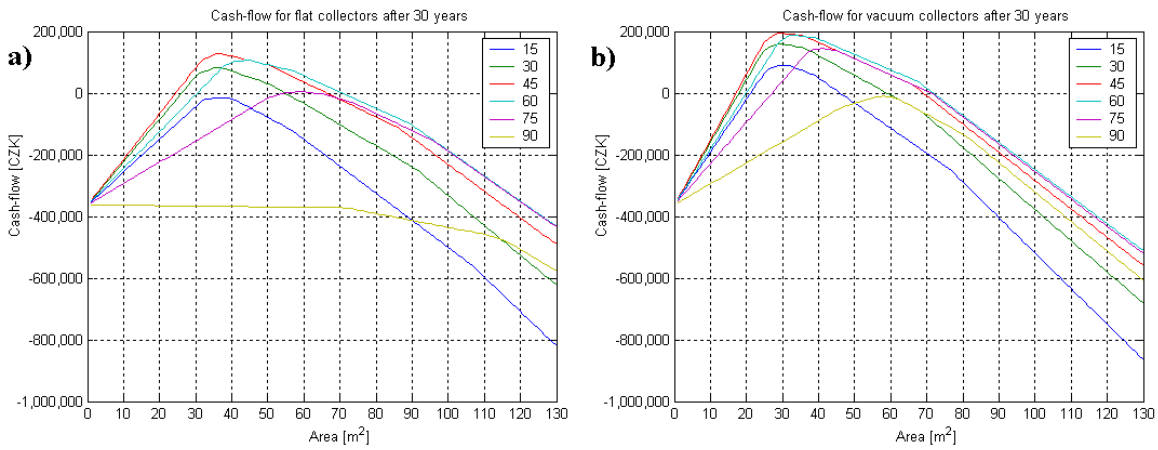

Figure 6: Cash flow after 30 years for flat (a) and vacuum tubes (b) collectors.

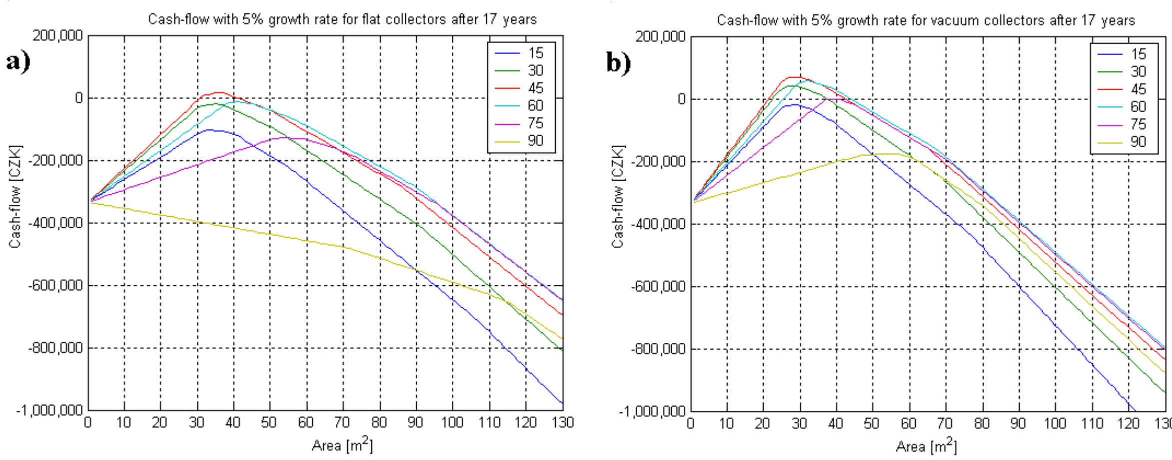

Figure 7: Cash flow with 5% growth rate after 17 years for flat (a) and vacuum tubes (b) collectors.

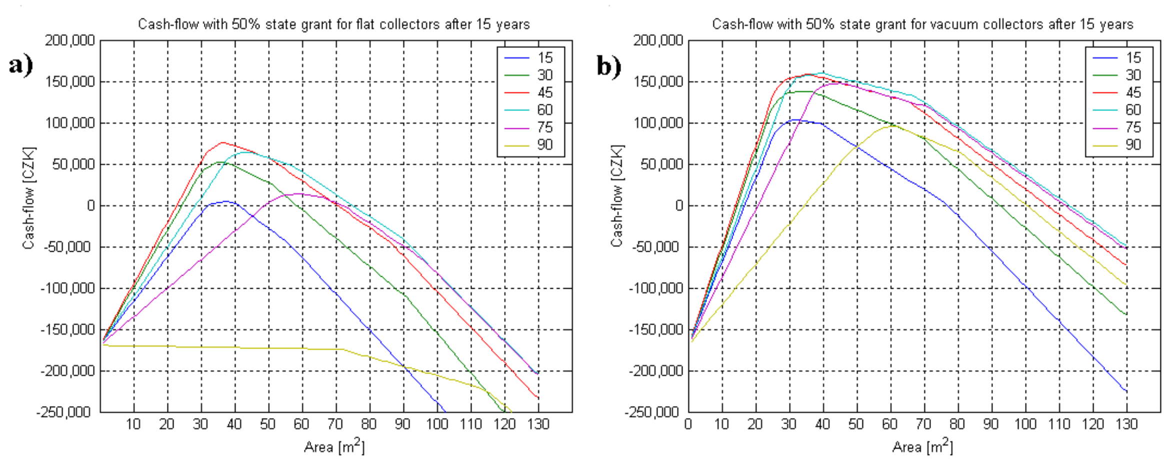

Figure 8: Cash flow with 50% state grant after 15 years for flat (a) and vacuum tubes (b) collectors.

7 Conclusion

It is possible to find an optimal collector's area when the investment and energy return is lowest. In both types of collectors is this point the area of 30 m^2 and slope 45°. The return time is quite low for the energy calculations (2 and 3 years) and CO_2 emissions calculations (3 and 4 years). The investment recovery is much higher: 30 years for simple return, 17 years for the calculations with growth rate and 15 years in case of obtaining grant.

Optimal area and slope differs according to the ecological or economical priorities. Economically it is best to use collectors with 35 m^2 and slope 45°, but for saving the highest amount energy during the working life it is better to install collectors with the maximal area and slope 75°.

Optimal area and slope depends also on the real working life of the collectors. Safely it is possible to take into account 15 years of working life, but probably it could be much more. Quality constructions can easily reach 30 years of working time then the more profitable solution is with the more extensive area and for the slope of 60° or 75°.

Another very important factor which influences economical calculations is the energy price growth. This case was made for 5% growth rate, but likely it is a very conservative estimate so that the return time will be much lower and an optimal area and slope will be higher.

Acknowledgement

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