Cooperation of Heat Pump and Solar System in the Common Power Unit

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Abstract: The paper explains new possibilities of heat pumps usage in the common power units. The result of applied research is an examination of heat pump and active solar system cooperation eligibility. The aspects of such a cooperation are examined mainly from the energetic point of view, but the economical parameters of the combined system are pointed as well. The results and conclusions are supported by observing the existing combined system assembled at the Department of Electrical Power Engineering at the Brno University of Technology.

Key-Words: heat pump, solar system, heating factor, combined heating system, heating factor increase, natural energy

1 Introduction

The energetic policy of the European Union member states is focused on the usage of alternative power sources. Increasing interest in the alternative power sources such as heat pumps, solar energy and wind energy has appeared recently.

Many utilizable energy resources have insufficient thermal potential for its direct usage. The aim of this paper is to specify application area of heat pumps within combined heat systems. The main invention is the optimization of designed combined system of a heat pump and an active solar system.

2 Current circumstances

It is generally known that both heat pump and solar system can work separately as equivalent heat sources. The effectivity (or more precisely heating factor) of both systems depends on the preliminary parameters. And mainly the possibility of influencing the heat pumps preliminary parameters leads to the idea of heat pump and solar system cooperation.

The invention is that the solar system is used as bivalent source that in the case of decreasing heat pump input parameters (temperature) increases these parameters on required level which can guarantee sufficient heat factor of heat pump. The hypothesis is that such assembled combined system provides very favourable energy balance of whole system.

It is obvious that the cooperation of these two systems can not be judged only from the energetic point of view as the economy is very important as well. The fundamental question is if it is reasonable to invest into purchase of both systems.

The main goals of this paper are summarized in few articles [1]:

- Heat pumps usage determination
- Combined system of heat pump and solar system - its assemblage
- Design of combined system for industry application
- Energetic and economic evaluation of combined system operation

2.1 Solar radiation – the source for heat pump

Solar radiation transformed by the solar system into thermal energy can serve as an energy source for a heat pump. For the purpose of heating the solar energy can be obtained and utilized in two ways: *active* and *passive*. The idea of common power unit with the maximum usage of each element is based on the cooperation of an active solar system and a heat pump.

Such cooperation is based on following presumptions [3]:

- The effectivity of a collector and the amount of heat obtained from the solar panels depends on the temperature of heated medium
- The effectivity and the amount of heat is the bigger the lower is this temperature
- If the obtained heat is used as low-potential heat for a heat pump, its temperature can be tens of °C lower than for the direct heating or preparation of hot service water.

In the case of former realized combined system, it was technically solved as it is mentioned below.

Both systems work separately within the integration. It means that the systems have common storage reservoir and the solar system „only“ increases temperature of heat medium in the storage tank which levels up the effectivity of whole system and the heat pump heat factor as well. It is essential to design the proper area of solar panels and the medium flowage through collectors do its influence on the heating medium is obvious. It is necessary to determine the optimal cooperation of these two systems.

Disadvantage of such power unit is that the solar system has to work with medium temperature acceptable for heating (heating system input temperature), which fundamentally decreases the effectivity of solar system itself during winter time. Another disadvantage of such assembled unit is its price. The whole system has to be over-dimensioned which enhances costs. The result of over-dimensioning is mainly a very long payback period caused by not using the solar panels all over the year. Possible flow sheet of such connection is shown in the figure 1.

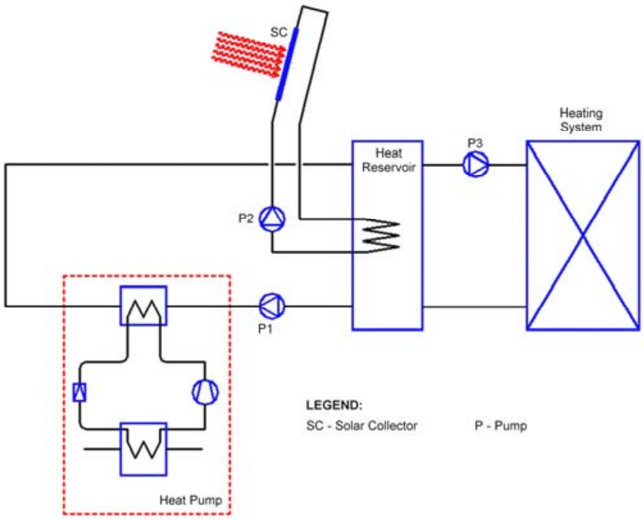

Fig. 1 Heat pump in cooperation with active solar system [1], [4]

3 Common power unit – update conception

As it is mentioned above, the new conception of active solar system and heat pump cooperation reposes upon an simple principal – when the temperature in the suggested combined system falls under the temperature of bivalence, the solar collector activates and the thermal energy obtained from the solar system is used for increasing temperature at the heat pump input. Increasing the temperature at the heat pump input leads to increasing the heating factor of whole unit. The main contribution of such assembled combined system is high effectivity of solar system that works with lower temperature than is the temperature of heating system.. The flow sheet of combined system is shown in the figure 2.

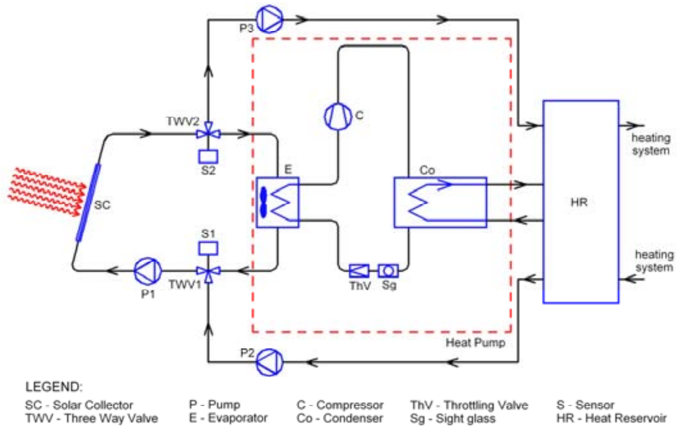

Fig. 2 Technological scheme of new design of combined system [1], [4]

The advantage of the latest conception is applied solar system. The air-heating combined solar collector that allows both air-heating and service water heating is used in this case. This fact appears as a great advantage. During the heating period the solar system is used for heating air that is used for increasing the temperature at the heat pump input. Beyond heating season the solar system is used for heating domestic water.

To confirm the hypothesis stated above, I assembled, thanks to national grant commission of the Czech Republic, a functional model of heat pump using system air-air. The model is assembled at the Department of Electrical Power Engineering at the Brno University of Technology. The solar system was added to the model subsequently so the original hypothesis of applicable cooperation of these systems can be verified.

3.1 Combined system – measured data verification

The main task is to determine how the addition of solar system influences the heating factor of heat pump according to the figure 2. The aim is to use the solar system for pre-heating the input medium – in this case air (heat pump using system air-to-air) – in the heat pump and thereby to increase heating factor and general annual utilization of the system with heat pump.

Invention is to increase the temperature of input medium during heating season (September – April) within the range of $_{\Delta}T = 5 – 10°C$ and to appoint the influence on heating factor subsequently for such temperature drop $_{\Delta}T$. The design of assigned solar system area is provided based on the realized measurement for defined temperature drop $_{\Delta}T$. All results of this research are subjacent by the analysis of measured data on the combined system (all monitored magnitudes and values are closely presented in [4]). During the experiment the three-year long continuous monitoring of solar radiation amount and the air temperature in the chosen area (Brno, Czech Republic) was in progress. This monitoring together with measuring the operational parameters of heat pump (load, coolant temperature, output temperatures, pressure conditions, temperature gradient, heating factor etc.) provided necessary data for designing the real combined system.

Table 1 shows the heat factor growth (COP) monitored on the assembled model of heat pump for particular parameter changes at the heat pump input. There are statistically interpreted changes of COP depending on temperature changes of input medium namely within the range of $_{\Delta}T$ = 5, 8, 10°C. The percentage value of heat factor increase ($_{\Delta}$COP) which is presented in the table 2 is significant for particular area of collector field S = 6, 10, 14 m^2 with the medium flowage speed 830 $m^3.h^{-1}$ that correspond to the rate of air flow of heat pump evaporator.

Table 3 shows the total quantity of thermal energy that is possible to be provided by solar system considering the collector mean efficiency given for required rise of temperature of input medium.. Resulting values of possibly supplied amount of energy by solar collectors are valid for the angle of insolated area slope α = 30°. As it is mentioned above, the resulting values correspond with measured values at the model assembled at the Department of Electrical Power Engineering at the Brno University of Technology (see [4]).

Figure 3 and 4 show behavior of heating factor (ε and COP) depending on the heat pump input temperatures measured on the assembled model of heat pump using system air-to-air. The parameter in these characteristics is the heat pump output temperature (t_{out}). Heating factor (ε) is determined on the basis of Carnot's cycle according to equation (1). Heating factor COP (*Coefficient of Performance*) results from real energy flows measured on the heat pump model (equation (2)).

month	**T_{ave}**	**I_{ave}**	**COP (T_{ave})**	**$COP_{(6)}$ (T_{ave}+5°C)**	**$COP_{(10)}$ (T_{ave}+8°C)**	**$COP_{(14)}$ (T_{ave}+10°C)**
	°C	**$W.m^{-2}$**	**-**	**-**	**-**	**-**
January	0,6	286	0,97	1,24	1,43	1,57
February	5,2	337	1,23	1,54	1,78	1,95
March	6,6	397	1,33	1,65	1,90	2,09
April	11,6	413	1,72	2,09	2,40	2,64
May	13,2	463	1,87	2,25	2,59	2,85
June	19,2	495	2,56	2,99	3,44	3,79
July	20,6	487	2,76	3,19	3,68	4,04
August	21,5	454	2,89	3,33	3,84	4,22
September	17,8	419	2,38	2,80	3,22	3,54
October	8,0	346	1,43	1,76	2,03	2,23
November	7,4	284	1,38	1,71	1,97	2,16
December	3,4	251	1,12	1,42	1,63	1,79

Table 1 [2]

month	**T_{ave}**	**I_{ave}**	**$_{\Delta}$COP (S = 6m^2)**	**$_{\Delta}$COP (S = 10m^2)**	**$_{\Delta}$COP (S = 14m^2)**
	°C	**$W.m^{-2}$**	**%**	**%**	**%**
January	0,6	286	28,0	47,5	62,1
February	5,2	337	25,0	44,1	58,4
March	6,6	397	24,2	43,1	57,3
April	11,6	413	21,1	39,6	53,4
May	13,2	463	20,1	38,4	52,2
June	19,2	495	16,6	34,3	47,7
July	20,6	487	15,8	33,4	46,6
August	21,5	454	15,2	32,8	46,0
September	17,8	419	17,4	35,3	48,7
October	8,0	346	23,3	42,1	56,2
November	7,4	284	23,7	42,5	56,7
December	3,4	251	26,2	45,4	59,8
$_{\Delta}$COP (average) (%)			**21,4**	**39,9**	**53,8**

Table 2 [2]

month	I_{ave}	T_{ave}	$\tau_{day\ ave}$	η_{ave1} ($_\Delta$T=5°C)	η_{ave2} ($_\Delta$T=8°C)	η_{ave3} ($_\Delta$T=10°C)	$Q_{TQm\ theo}$	$Q_{TQm\ real\ 1}$	$Q_{TQm\ real\ 2}$	$Q_{TQm\ real\ 3}$
	W.m^{-2}	°C	h	%	%	%	kW.h.m^{-2}	kW.h.m^{-2}	kW.h.m^{-2}	kW.h.m^{-2}
January	286	0,6	8,26	75	68	64	73,23	54,57	49,96	46,88
February	337	5,2	10,12	76	71	67	95,49	72,67	67,57	64,17
March	397	6,6	12,00	77	73	70	147,68	114,37	107,68	103,21
April	413	11,6	13,90	78	73	70	172,22	133,88	126,37	121,37
May	463	13,2	15,70	79	75	72	225,34	176,94	168,18	162,34
June	495	19,2	16,34	79	75	73	242,65	191,55	182,72	176,84
July	487	20,6	15,70	79	75	73	237,02	186,87	178,11	172,27
August	454	21,5	13,90	78	74	72	195,63	153,36	145,60	140,43
September	419	17,8	12,00	78	74	71	150,84	117,41	110,93	106,61
October	346	8,0	10,12	76	71	68	108,55	82,85	77,21	73,44
November	284	7,4	8,26	74	68	64	70,38	52,38	47,92	44,95
December	251	3,4	7,85	73	65	61	61,08	44,62	40,24	37,32
total $Q_{TQyear} = \sum Q_{TQm}$ (kW.h.m^{-2})							**1780,1**	**1381,5**	**1302,5**	**1249,8**
								for η_{ave1}	for η_{ave2}	for η_{ave3}

Table 3 [1]

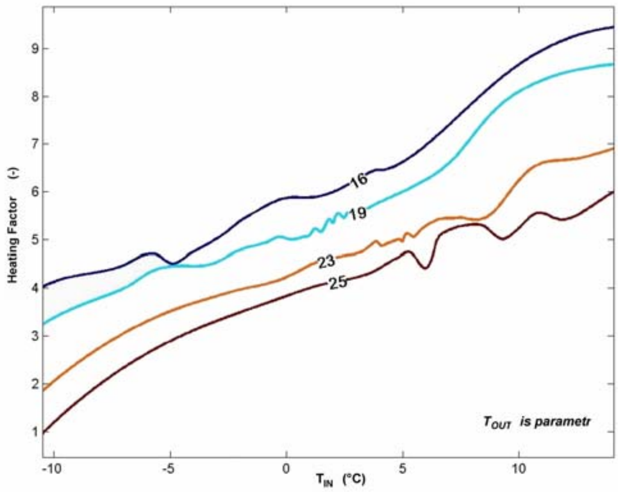

Fig. 3 Behaviour of heating factor on the heat pump model $\varepsilon = f(t_{in}, t_{out})$ [4]

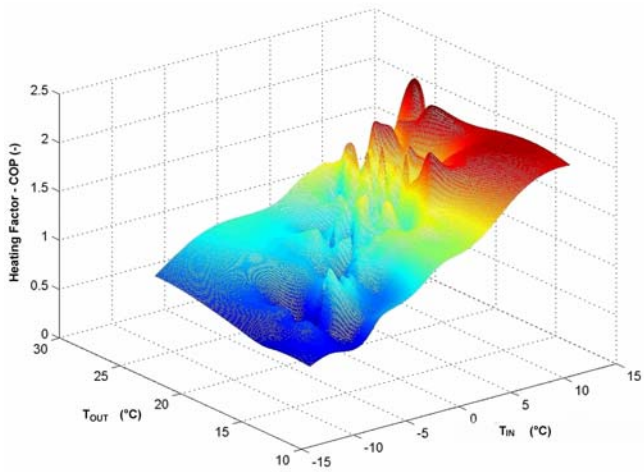

Fig. 4 Behaviour of COP on the heat pump model $COP = f(t_{in}, t_{out})$ [4]

$$\varepsilon = 0,4 \cdot \frac{(T_K + 273,15)}{(T_K - T_0)} \quad (-) \qquad (1)$$

$$COP = \frac{_\Delta T \cdot Q_m \cdot C_p}{P_p} \quad (-) \qquad (2)$$

4 Energy evaluation

Energy evaluation in term of combined system (heat pump and solar system) operation is the fundamental operational indicator. The measured variables derived from the assembled combined system defined above are fundamental for the energy evaluation.

It is essential to mention the fact, that the energy evaluation of combined system operation is not sufficient indicator of its suitable utilization. Integral part of such evaluation has to be an economic evaluation as well.

The result of energy-economic evaluation is the determination of optimal area of solar system for the possibility of increasing the medium temperature at the heat pump input considering the required temperature gradient $_\Delta$T = 5 – 10°C. [1], [2]

To compare heating with the heat pump and other possible power sources, the existing family house project in Brno is used. Initial parameters of described building that are essential for calculation are pointed in the table 4.

territory	t_e	t_{em}	d	t_{es}	Q_{TL}	t_{is}
	°C	°C	day	°C	kW	°C
Brno Czech republic	-12	13	224	4,4	8,4	19

Table 4

The low-energy prefabricated family house is considered. It is a two-storey wood-based building with built-up area of 79 m^2.

Heat demand for heating the building mentioned above is calculated in accordance with standard ČSN EN 832 „Heat Behavior of Buildings – Calculation of Heat Demand – Residential Buildings“ and public notice of the Department of Industry and Commerce no. 291/2001 Digest: „Determination of Energy Usage Circumstances for Power Consumption in Buildings“.

For the chosen area and construction the heat demand is determined as well as amount of heat required for hot service water heating with the aid of equations (3) – (7).

$$D = d \cdot (t_{is} - t_{es}) \quad \text{(K.day)} \qquad (3)$$

$$Q_{Heat,year} = \frac{e}{\eta_0 \cdot \eta_r} \cdot \frac{24 \cdot Q_{TL} \cdot D}{(t_{is} - t_e)} \quad \text{(Wh.year}^{-1}\text{)} \qquad (4)$$

$$Q_{HW,day} = (1 + z) \cdot \frac{\rho \cdot c \cdot V_{2p} \cdot (t_2 - t_1)}{3600} \quad \text{(Wh)} \qquad (5)$$

$$Q_{HW,year} = Q_{HW,day} \cdot d + 0{,}8 \cdot Q_{HW,day} \frac{t_2 - t_{svl}}{t_2 - t_{svz}} \cdot (N - d) \qquad (6)$$

$$Q_{aneed} = Q_{Heat,year} + Q_{HW,year} \quad \text{(Wh.year}^{-1}\text{)} \qquad (7)$$

Total energy demands of reviewed building are pointed in table 5. Overall heat loss of the family house is Q_{TL} = 8.4 kW.

$Q_{Heat, year}$		$Q_{HW,year}$		Q_{aneed}
MWh.year^{-1}	GJ.year^{-1}	MWh.year^{-1}	GJ.year^{-1}	GJ.year^{-1}
17,0	61,2	5,4	19,6	80,8

Table 5

Following energy and economic analysis is proceeded for two different connections of heat pump within the heating system.

4.1 Heat pump in bivalent connection – version „A“

The air-to-air heat pump with the 7,7 kW rated thermal output is chosen in the first case. It is designed for the underfloor heating in the bivalent connection. Heating performance of the heat pump at the prime source temperature 2°C and output temperature 35°C is P_t = 8,3 kW and heating factor ε = 3,5. Such power source can cover the heat demand of the building up to approximately 98%. The air-conditioning unit (air-air heat pump with 2,5 kW available heating performance) is added to the system to cover the entire heat demand of the building.

Cooperation of these two power sources ensures complete heat loss coverage. Low-temperature underfloor heating is implemented in the considered building due to the prospective usage of the heat pump. This fact leads to improved parameters of the heating system. [1], [4]

Table 6 shows the level of costs for the version „A“.

version „A“	
HP	7.320,-EUR
air condition	3.215,-EUR
installation	1070,-EUR
heat reservoir	630,-EUR
total	**12.235,-EUR**

Table 6

4.1 Heat pump in connection with solar system – version „B“

The air-to-air heat pump with the 5,3 kW rated thermal output is chosen in the second case. Having the prime source temperature 2°C and the output temperature 35°C, the heating performance is than P_t = 5,8 kW and heating factor is ε = 3,6. The type of heat pump is designed so the ratio of heat pump performance and heat loss of the reviewed building is 63% which correspond to 90% of supplied energy for heating [3].

The rest of thermal energy needed for the heating and hot service water heating is provided by the cooperation of heat pump and solar system.

Air-heating combined solar collector is chosen for the cooperation with heat pump. It is intended for air-heating and hot service water heating.

The solar system is during a faction of a year used as a bivalent power source supplementing heat pump while increasing heat pump input temperature. Air is an operating substance in this case. Solar collector is used for hot service water heating in the case when it is not necessary to increase heat pump performance – in such case water is an operating substance.

Based on performed measuring on the model it is possible to derive the direct influence of assigned solar system on heating factor. Percentage increase of heating factor due to the various areas of solar system can be seen in table 7.

Comparison of annual heating costs for particular version appears to be quite interesting. The advantage of combined system is shown in figure 5.

$_{\Delta}$T (°C)	4,5	6	8	10
S (m^2)	10	14	20	24
	$_{\Delta}$COP (%)	$_{\Delta}$COP (%)	$_{\Delta}$COP (%)	$_{\Delta}$COP (%)
	20,9	28,0	47,5	62,1
	18,1	25,0	44,1	58,4
	17,3	24,2	43,1	57,3
	14,4	21,1	39,6	53,4
	13,5	20,1	38,4	52,2
	10,1	16,6	34,3	47,7
	9,4	15,8	33,4	46,6
	8,9	15,2	32,8	46,0
	10,9	17,4	35,3	48,7
	16,5	23,3	42,1	56,2
	16,9	23,7	42,5	56,7
	19,2	26,2	45,4	59,8
$_{\Delta}$COP$_{ave}$ (%)	14,7	21,4	39,9	53,8

Table 7 [4]

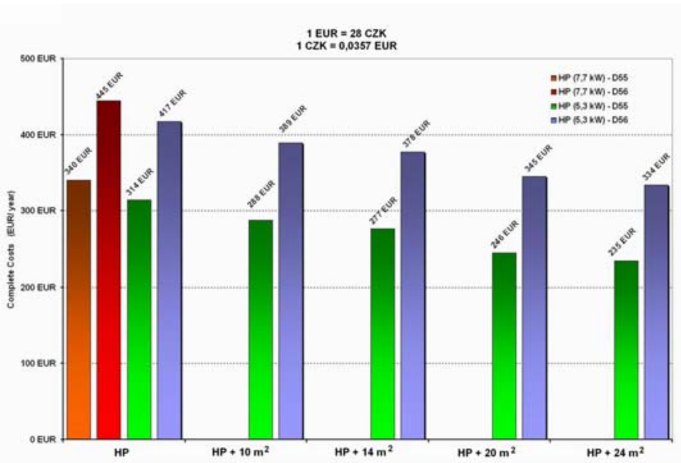

Fig. 5 Cost of Heating [4]

system version „B“ (HP + solar coll.)	price without capital grant EUR	price with capital grant[1] EUR
HP + 2m^2	9.125,-	6.170,-
HP + 4m^2	9.850,-	6.530,-
HP + 6m^2	10.595,-	6.905,-
HP + 8m^2	11.305,-	7.260,-
HP + 10m^2	12.045,-	7.630,-
HP + 12m^2	12.925,-	8.070,-
HP + 14m^2	13.645,-	8.735,-
HP + 16m^2	14.370,-	9.460,-
HP + 18m^2	15.100,-	10.190,-
HP + 20m^2	15.845,-	10.935,-
HP + 22m^2	16.605,-	11.700,-
HP + 24m^2	17.300,-	12.390,-

Table 8 [1], [4]

Total cost of investments of combined system (version „B“) is 8.035,- EUR subsequently increased with costs for providing appropriate area of solar system. Level of investment costs of combined system is for different solar system areas pointed in table 8.

Area of the collector field is very important regarding the new conception of heat pump and solar system cooperation – mainly from the energetic point of view so the energy demands of the building are covered completely. Designed heat pump with the 5,3 kW heating performance covers heating demands up to 90%. The remaining 10% and the energy for hot service water heating have to be supplied by solar system.

As it is obvious in table 5 heat demand is for the reviewed building 17,0 MWh.year^{-1} and total energy for hot service water heating is 5,4 MWh.year^{-1}. Heat pump covers the heat demands up to 90% which correspond to 15,3 MWh.year^{-1}. To ensure the entire heating demand and hot service water heating demand it is necessary to supply remaining 7,1 MWh.year^{-1} of thermal energy by the aid of solar system.

4 Energy-economic analysis

Energy-economic analysis is based on energy demands of the building and on economic parameters such as net present value NPV and internal rate of return IRR. The results of the analysis can be seen in figure 6 and 7 and it clearly define the possibilities and sphere of energy and economic utilization of solar system in connection with heat pump for the considered building with total heat loss Q_{TL} = 8,4 kW which is determined based on the average month values of solar emission rate measured in the laboratories at the Department of Electrical Power Engineering at the Brno University of Technology. Graphs provide answers about applicability of heat pump and solar system cooperation and about selection of optimal area of solar system working in such connection. It is essential to mention that the analysis is proceeded for a certain type example but it is supported with many applied measurements on the model of heat pump and solar system assembled at the Department of Electrical Power Engineering at the Brno University of Technology.

Required amount of thermal energy for the building is in the graphs marked with red line. The amount of necessary energy is Q_{aneed} = 22,4 MW.year^{-1} including energy required for hot service water heating. Graphs explain that from the area S = 11,4 m^2 of collector field, the heat pump and collector field combined system is able to cover the energy demands of the building (this fact is marked with yellow area in the graph). This area is from above delimited by a curve which conform to the amount of energy supplied by the combined system providing that the solar system is used during the period

September – April (heating period) and it is used for increasing the air input temperature within heat pump keeping temperature gradient $_{\Delta}T = (5 \div 10°C)$ which has positive effect on the heating factor level of heat pump that thanks to this fact ensures required energy supply. Amount of energy supplied by the solar system is derived upon required minimum air flowage supplied by solar collectors to the heat pump input and upon required input medium temperature gradient $_{\Delta}T$.

Green area in the graphs defines possible area of attached solar system with respect to energy and economic demands without obtaining the state grant:

- energy demands on the system are marked by yellow area in the graph
- from the economic demands point of view the combined system is compared to a system that uses separately operating heat pump. Green curves represent the internal rate of return (IRR) of both compared projects without obtaining possible state grant. On the contrary the blue curves represent the same fact but regarding possible state grant obtaining in the maximum amount. Areas marked as „**A**“ and „**B**“ represent situation in which - regarding the internal rate of return - the combined system is more favourable then the original project with heat pump. It is obvious that areas „**A**“ and „**B**“ differ with regard to a version with or without state grant and also with respect to relevant electricity rate:
- for the electricity rate D55 (see [5]) the situation is as follows:
    - when not counting in possible state grant than IRR level proceeds above 5%[2] for the areas of solar system in between 11,4 – 17 m^2 on condition that designed system solves energy demands of the building. For assigned areas which are larger then the ones mentioned above, the project is an inconvenient investment. The picture shows that the IRR value of combined system having from $14 m^2$ to $20 m^2$ proceeds approximately about 5% level. To determine the maximum possible area of solar system the net present value (NPV) of the project is essential. This indicator is most favourable in the case when combined system has up to $S = 17\ m^2$.
    - when counting in the state grant the IRR value of the project with separate heat pump 8%. In this case the sufficient area of the solar system is in between 11,4 – 20,3 m^2 (see figure 6). This fact means that in case of obtaining state grant for an applied system it is more favourable to assemble combined system.
- for the electricity rate D56 (see [5]) the situation is following:
    - concerning the project with heat pump in bivalent connection the internal rate of return is 4% (see figure 7). IRR value of combined system falls under this 4% value when attaching $S = 14\ m^2$ solar system. Suitable area of solar system is from 11,4 m^2 to 14 m^2.
    - when counting in the state grant the IRR value of the separate heat pump project is 7%. Compared to the situation with electricity rate D55 the determination of solar system area in case of achieving the state grant proceeds in between 11,4 – 20,5 m^2. The curve slope that indicates internal rate of return of the combined system shows more favourable conditions from the economic point of view then the case when the state grant is not confirmed.

Regarding the results pointed in the graphs and figures of this paper it could be summarized that the cooperation of heat pump and solar system – regarding situation when the solar system is during the heating period used for pre-heating the input medium in the heat pump – is favourable both from the energy and the economic point of view. In the surveyed situation with realized combined system the optimal area of attached solar system proceeds from 12 m^2 to 14 m^2. Applied research of alternative sources applications confirms the fact that very important issue for evaluation of the system is not only the energy evaluation but the economic analysis of system operation as well as the sphere of its application.

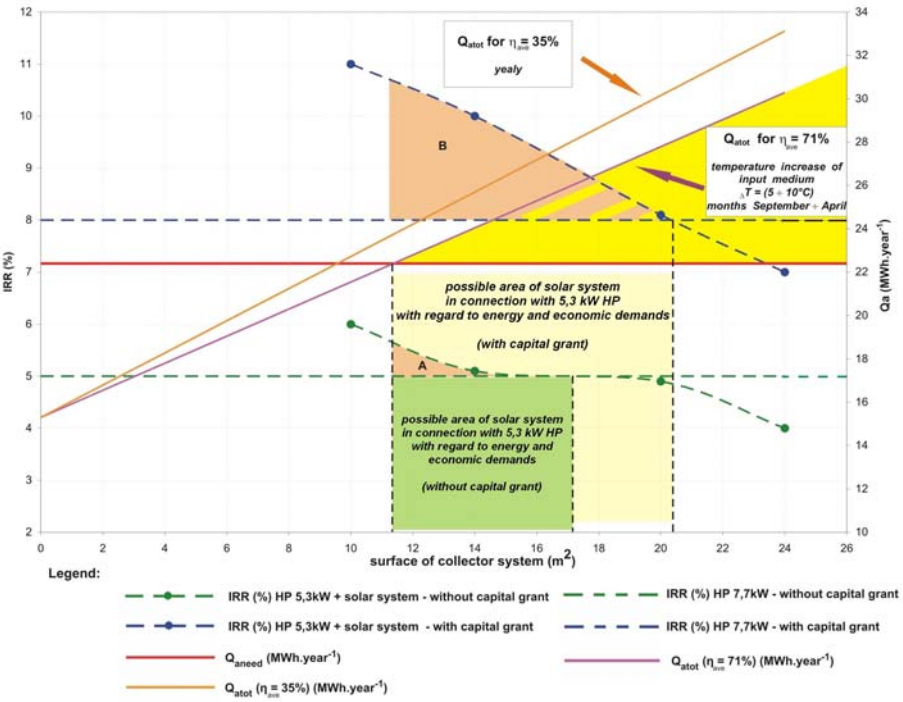

Fig. 6 Determination of collector area cooperation with HP 5.3 kW in tariff D55 [4]

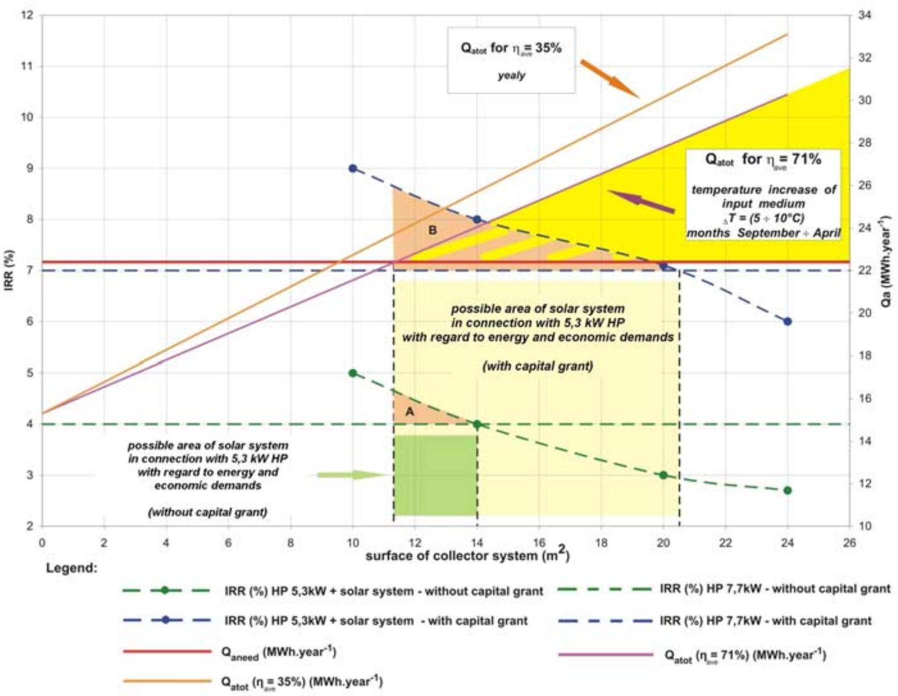

Fig. 7 Determination of collector area cooperation with HP 5.3 kW in tariff D56 [4]

5 Conclusion

Presented study accomplished within the scope of the dissertation thesis themed „Heat Pumps in the Combined Thermal systems“ explains new possibilities of cooperation between alternative power sources. Newly designed combined system of heat pump and active solar system is from the energy and economic point of view more preferable to the original solution which uses energy supplied by solar system only for accumulator therefore the system works with high temperature. The results of this study affirm primary hypothesis about favourable cooperation of heat pump and solar system. The contribution of the study is above all in the original conception of technical solution and in the new sight at the possible cooperation of these systems. The thesis is an important principle for designing the combined systems within technical field and it provides information necessary for energy-economic evaluation of such systems. The conclusions of this work have already been improved within the context of construction of low-energy buildings in the Czech Republic. All the introduced information in the study are supported with long-term measuring on the combined system focused mainly on increasing the operation efficiency of heat pumps in combined thermal systems.

Acknowledgments:
This paper contains the result of research works funded from project No. MSM0021630516 of the Ministry of Education, Youth and Sports of the Czech Republic.

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[1] possible acquired state grant is considered at the maximum amount according to the conditions pointed in records (see [6]) for providing the state grant – scheme 1.A and 4.A

[2] value of internal rate of return (IRR) for the project in which the power sources is heat pump in bivalent connection together with electric boiler and air-conditioning unit