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Calculation of performance indicators for solar cooling, heating and domestic hot water systems

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Abstract

In the framework of the French R&D project MeGaPICS (Method towards Guarantee of Performances for Solar Cooling and Heating applications – funded by Agence Nationale de la Recherche), a selected number of indicators are defined. The final goal is to find the right indicators to guarantee the performance of solar cooling, heating and Domestic Hot Water (DHW) systems. The selection process consists in several steps, which are presented in this article. First part sets up the best practice of configuration schemes for both packaged small size installation and large-scale units. Second part deals with annual and seasonal performance indicators. Then they are applied to different existing installations (French and European units), using monitoring data. Finally, some boundaries are defined for those indicators.

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Keywords: Solar cooling; guarantee; performance; indicators; monitoring data

1. Context

Most of the solar cooling systems use absorption or adsorption chillers, worldwide [1] as well as in France [2]. Many different hydraulic schemes are designed which make the installations not comparable between each other [3], [4]. Moreover, how to say that a solar cooling, heating and Domestic Hot Water system is operating well, and that their thermal performances are fully satisfactory?

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The MeGaPICS project aims is to find a method to guarantee the performance of these systems. For this purpose, it focuses on a better knowledge of solar cooling and heating systems, developing tools to compare theoretical performances and real ones, and setting up best practice cases and guidelines.

In this paper, two defined generic hydraulic schemes have been selected and various performance indicators have been defined. Then, these indicators are calculated for several systems and the results are compared to possible theoretical boundaries in order to quantify the level of quality of the systems. Finally, target values are proposed for each indicator.

Nomenclature

Q_{sol}	Global irradiation on collector area	kWh
Q_1 at Q_{10}	Thermal energy defined according to Fig. 1 and Fig. 2	kWh
E_1 at E_{14}	Auxiliary electrical consumptions defined according to Fig. 1 and Fig. 2	kWh
V_1	Water consumption of the heat rejection system	m^3
E_{aux} & $E_{aux\ sol}$	Parasitic electricity demand of the whole system and of the solar part	kWh
$Q_{loss\ HS}$ & $Q_{loss\ CS}$	Thermal losses of the hot and cold storages	kWh
$Q_{loss\ HB}$ & $Q_{loss\ CB}$	Thermal losses of the storages due to the hot and cold backup system	kWh
ESU	Useful solar energy	kWh
R_{gHB} & R_{gCB}	Generation efficiency of the hot and cold backup system	-
$Cons_{HB}$ & $Cons_{CB}$	Hot and cold backup system energy consumption	kWh
η_{HS} & η_{CS}	Hot and cold storage efficiency	-
COP _{th}	Thermal coefficient of performance of the sorption chiller	-
PER	Primary Energy Ratio	-
ε_x	Primary energy conversion factors of the energy X	-
ϵ_x	Cost per kWh of the energy X	€/kWh
R_{coll} & R_{sol}	Collector thermal yield and solar thermal efficiency of the system	-
PSU	Useful solar thermal productivity	kWh/m ²
COP _{elec sol}	Electrical coefficient of performance for solar energy	-
WC_{spe}	Specific water consumption of the system	l/kWh
kWhcost	Operation cost of the system	€/kWh
I_{conf} , I_{data} & I_{fct}	Comfort, monitoring data lost and functioning indicators	%
T_{hot} , T_{cold}	Reference hot and cold storage temperatures	°C
T_{amb} , T_{av} , T_{ext}	Reference ambient, collector average and external temperatures	°C
N_{month} , N_{cool}	Number of months in functioning and cooling mode	-
ENS	Average annual daily value of the irradiation on the collector	kWh
I_{min} , I_{max} , I , $I\%$	Minimum, maximum, value and percentage value of the considered indicator	-

2. Configuration schemes

Based on the knowledge and experience of the partners, two generic configuration schemes are defined for specific applications and can be used to identify main components and energy flows of the system:

- Application n°1: small scale system for family houses, small multi-dwellings, using a small size packaged ab/adsorption solar system (Fig. 1.). This configuration is an adaptation of the solar combi-system including the cooling function, also called SSC+ or Solar Combi + [6].
- Application n°2: large scale system for multi-dwellings, offices and commercial applications, using customized systems (Fig. 2.). This scheme represents the current configuration of the market.

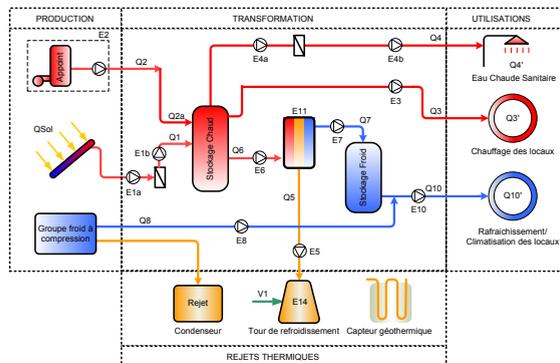


Fig. 1. Generic scheme for application n°1

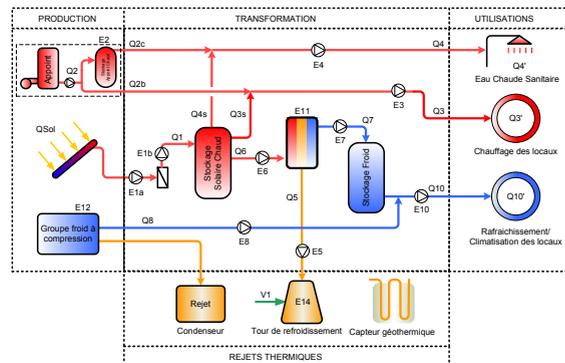


Fig. 2. Generic scheme for application n°2

3. Performance indicator and classification

In order to quantify the performance level of a solar heating and cooling plant, 12 indicators are defined at different levels and in line with the generic scheme of an installation (Fig. 1 and 2). Some of them were already defined by the IEA SHC program Task 38 [3], other correspond to best practice, common or professional use. Some of them can be used at different stages of the project implementation, from the feasibility study to operation. Each indicator and necessary value is precisely defined in the Table 1 as a function of the energy flows and for the two different configurations scheme (Fig. 1 and 2). They can be classified according to the following categories:

3.1. Necessary values for indicator calculation

In order to calculate the different performance indicators, some necessary values are defined : the useful solar energy (ESU), the parasitic electricity demand of the whole system (E_{aux}) and of the solar part ($E_{aux\ sol}$), the thermal losses of the hot and cold storage ($Q_{loss\ HS}$ and $Q_{loss\ CS}$), the thermal losses of the hot storage due to the heating backup system ($Q_{loss\ HB}$), the thermal losses of the cold storage due to the cooling backup system ($Q_{loss\ CB}$), the final energy consumption of the heating backup system ($Cons_{HB}$) and of the cooling backup system ($Cons_{CB}$). Each of these quantities is defined in the Table 1.

3.2. Thermal efficiency indicators

The thermal efficiency indicators describe the main thermal losses of the system through the hot (1) or (2) and cold (3) storage and the thermal coefficient of performance of the chiller (4).

3.3. Global performance indicator

The global performance indicators represent the overall system performances and take into account the solar energy use as well as the heating and cooling backup energy use. The global performance indicator defined is the primary energy ratio (5). Another one, not introduced in this paper, could be the seasonal performance factor.

3.4. Solar performance indicators

The solar performance indicators evaluate the system capacity to use the available solar irradiation. They are defined as the collector thermal yield (6), the solar thermal efficiency (7), the useful solar thermal productivity (8) and the electrical coefficient of performance of the solar thermal system (9).

Table 1. Calculation method of the different indicators

Indicators	Application	Calculation method
η_{HS}	1	$\eta_{HS}=1 - Q_{loss\ HS} / (Q1 + Q2a)$, with $Q_{loss\ HS} = Q1 - Q3s - Q4s - Q6$ (1)
	2	$\eta_{HS}=1 - Q_{loss\ HS} / Q1$, with $Q_{loss\ HS} = Q1 +Q2a - Q3 - Q4 - Q6$ (2)
η_{CS}	1 and 2	$\eta_{CS}=1 - Q_{loss\ CS} / Q7$, or $\eta_{CS}=1 - Q_{loss\ CS} / (Q7 + Q8)$, with $Q_{loss\ CS} = Q7 - Q10 + Q8$ (3)
COP_{th}	1 and 2	$COP_{th} = Q7 / Q6$ (4)
PER	1 and 2	$PER = (Q10 + Q3 + Q4) / (E_{aux} \times \epsilon_{elec} + Cons_{CB} \times \epsilon_{CB} + Cons_{HB} \times \epsilon_{HB})$ With $Cons_{HB} = Q2 / R_{g_{HB}}$ and $Cons_{HB} = Q8 / R_{g_{CB}}$ (5)
R_{coll}	1 and 2	$R_{coll} = Q1 / Q_{sol}$ (6)
R_{sol}	1 and 2	$R_{sol} = ESU / Q_{sol}$ (7)
PSU	1 and 2	$PSU = ESU / S_{coll}$ (8)
$COP_{elec\ sol}$	1 and 2	$COP_{elec\ sol} = ESU / E_{aux\ sol}$ (9)
WC_{spe}	1 and 2	$WC_{spe} = V1 / Q7$ (10)
kWh_{cost}	1 and 2	$kWh_{cost} = (E_{aux} \times \epsilon_{elec} + Cons_{CB} \times \epsilon_{CB} + Cons_{HB} \times \epsilon_{HB} + V1 \times \epsilon_{water}) / (Q10 + Q3 + Q4)$ (11)
ESU	1	$ESU = Q3 +Q4 - Q2a + Q_{loss\ HB} + (Q10 - Q8 + Q_{loss\ CB}) / COP_{th}$ With $Q_{loss\ CB} = Q_{loss\ CS} * Q8 / (Q8 + Q7)$ and $Q_{loss\ HB} = Q_{loss\ HS} * Q2a / (Q1 + Q2a)$ (12)
	2	$ESU = Q3 - Q2b +Q4 - Q2c + (Q10 - Q8 + Q_{loss\ CB}) / COP_{th}$ (13)
E_{aux}	1	$E_{aux} = E1a + E1b + E2 + E4a + E5 + E6 + E7 + E8 + E11 + E14$ (14)
	2	$E_{aux} = E1a + E1b + E2 + E5 + E6 + E7 + E8 + E11 + E14$ (15)
$E_{aux\ sol}$	1	$E_{aux\ sol} = E1a + E1b + \Sigma_{cool} (E5 + E6 + E7 + E11 + E14) \times Q1 / (Q1 + Q2a)$ (16)
	2	$E_{aux\ sol} = E1a + E1b + E5 + E6 + E7 + E11 + E14$ (17)

3.5. Ecological impact indicator

The ecological impact of the system is evaluated through the specific water consumption (WC_{spe}) of the heat rejection system (10).

3.6. Economical indicator

The economical indicator is defined as the operation cost of the system (11).

3.7. Quality indicators

The main goal of the quality indicators is to evaluate the reliability of the installation through a functioning time indicator of the system (t_{fct}) and a number of lost monitoring data (I_{data}). Another quality indicator has been defined as the evaluation of the quality of indoor conditions regarding the expected indoor temperature (I_{conf}) which are defined according to the German DIN 1946 standard [7] for the summer period and the French RT 2012 standard [8] for the winter period. These indicators are defined as percentage values reported to the expected functioning time of the system.

4. Indicator calculation applied to monitored solar installations

The indicators are calculated for 11 systems monitored by the project partners (Banyuls [9], Solaclim [10], Rafsol [11], Sonnenkraft [12] and Solera [13]) or by IEA SHC Task 38 [5] participants. These 11 installations and the corresponding 17 years of monitoring data on a monthly basis present a large range of designs as well as various applications. The main characteristics of the 11 systems are presented in Table 2. Due to missing data, all indicators may not be calculated for all the systems; accordingly only relevant indicators are presented.

Table 2. Installation configurations

Names	Solera	Solaclim	Sonnenkraft	Rafsol	A	B	C	D	E	F	Banyuls
Configuration	1	2	2	2	1	1	1	2	1	2	2
Heating	1	1	1	0	1	1	1	1	1	0	0
Cooling	1	1	1	1	1	1	1	1	1	1	1
DHW	0	0	0	0	0	0	0	0	1	0	0
Cold backup	0	0	0	0	0	1	0	0	0	0	0
Hot backup	1	0	1	0	1	1	1	1	1	0	0

Fig. 3 and Fig. 4 present the result of the indicator calculation for the 11 systems. The values for each indicator can vary among the different installations but also between the different years of monitoring.

For the thermal efficiency indicators (Fig. 3.), the hot storage efficiency can be low (0.5 for installation F), but also high (0.94 for installation B). The same disparity can be observed for the cold storage efficiency, between 0.49 (installation B) and 0.97 for Solaclim. The thermal COP gives important information on the functioning conditions of the chiller: for absorption chiller, low value (0.16, installation D) can be observed, but high value for a single effect chiller is also reported (0.72, Solera). The only adsorption chiller monitored (Solaclim) has a COP_{th} value lower than the absorption chillers (0.32).

For the global performance indicator (Fig. 3.), the primary energy ratio is between 0.53 (Solera with a direct electrical heating backup system) and 1.22 (Sonnenkraft with a vapor compression heat pump as hot backup system).

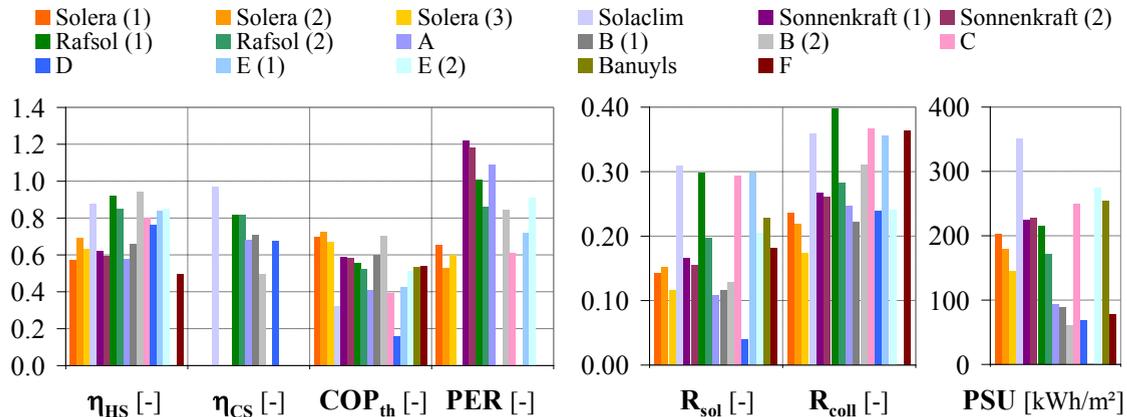


Fig. 3. Overview of the thermal efficiency (η_{HS} , η_{CS} and COP_{th}), global performance (PER) indicators and solar performance indicators (R_{sol} , R_{coll} and PSU)

For solar performance indicators (Fig. 3. and Fig. 4.), the useful solar thermal productivity presents important variations (from 60 kWh/m² for unit B, to 351 kWh/m² for Solaclim) depending on the functioning time of the installation. The collector thermal yield is around 0.2 for the most of the units, with a minimum of 0.17 (Solera) and a maximum of 0.4 (Rafsol). The solar thermal efficiency can be very low (0.04 installation D) but also higher than some value of collector thermal yield (0.31 for Solaclim).

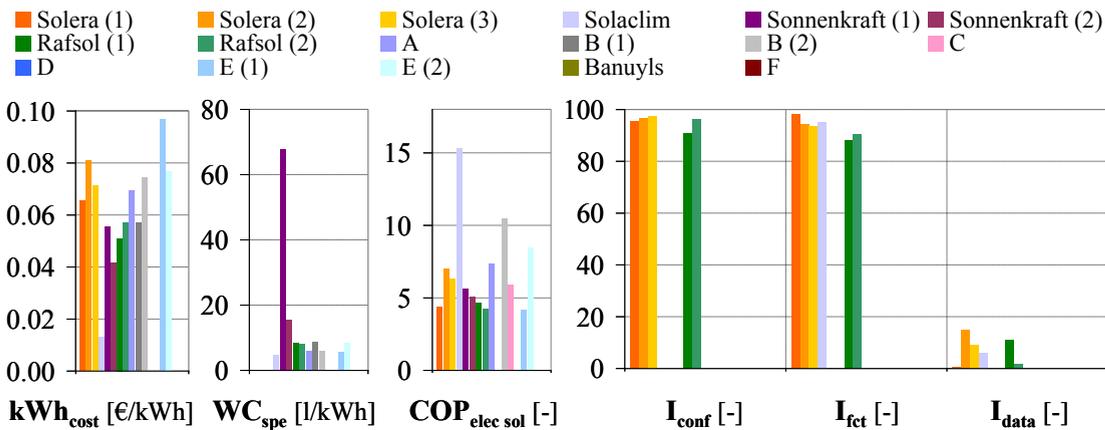


Fig. 4. Overview of the solar performance ($COP_{elec sol}$), ecological impact (WC_{spe}), economical (kWh_{cost}) and quality (I_{conf} , I_{fct} and I_{data}) indicators

For the ecological impact indicator (Fig. 4.), except for Sonnenkraft (67.8 l/kWh during the first year due to a failure) the values are between 0 (for the geothermal probes of Solera) and 8 l/kWh (for the open cooling tower of Rafsol, B and E installations).

For the economical indicator (Fig. 4.), the range of the operation cost is between 0.013 €/kWh for Solaclim (installation without any backup system) to 0.097 €/kWh for installation E.

The different quality indicators (Fig. 4.) show well functioning system with comfort and functioning time indicators higher than 90% and a lost monitoring data indicator lower than 10% (except for the 2nd monitoring year of Solera). The limited available data for this quality indicator calculation is the only limiting point.

5. Target values definition

One major difficulty is that an absolute value of the indicators is not enough to rank the quality and efficiency of a system because most of them are strongly related to external boundary conditions (climate, thermal loads), technology used (adsorption vs absorption, single glazed/double glazed flat plate collector/evacuated tubes, type of backup). To overcome this difficulty, it is thus necessary to introduce target value for each indicator. These target values consist in minimum or maximum limits, and finally a methodology is proposed to assess the overall quality of each installation.

5.1. Target value for the thermal efficiency indicators

The target values for the hot and cold storage efficiency are determined from the theoretical heat losses of the storage as defined in the French RT2005 standard [14]. Because equations (18) and (19) are annual values for the thermal losses of storage, the equations take into account running time of the system ($N_{\text{month}} / 12$). The hot reference temperature (T_{hot}) is considered as a function of the running time in cooling mode (80°C) and in heating mode (60°C).

The proposed target value for the thermal COP of the chiller is function of the nominal thermal COP (from manufacturer data sheet) multiplied by a factor of 0.8 to take into account chiller integration in the system (20). This factor seems to be relevant as it has also been observed for compression vapor system when comparing electrical COP and SPF [15]. A limitation for this method could be that manufacturers do not use the same boundary conditions for the evaluation of the nominal thermal COP: the definition of common test conditions for thermally driven chiller is currently a subject addressed within IEA SHC Task 48 [16].

5.2. Target value for the global performance indicator

The minimum value for the primary energy ratio is defined according to Eicker [17] at 1.

5.3. Target value for the solar performance indicators

The reference collector thermal yield is calculated using the standardized coefficients of the quadratic equation efficiency of the collectors installed on the system (21), the average annual air temperature of the location (T_{ext}) and the average annual daily value of the irradiation (ENS) on the collector area. The average temperature of the collector (T_{av}) is assumed to be 80°C for cooling systems only or 62.5°C for the others.

The reference solar efficiency is defined as a function of the collector thermal yield and the thermal COP of the installation. The running mode is considered through the number of month in cooling mode of the installation (N_{cool}), (22).

The French EMERGENCE program [18] has defined a minimum annual value for the useful solar productivity of 350 kWh/m². This value is used here as a target value (23).

Up to now, the minimum solar electrical coefficient of performance is defined according to the EMERGENCE program [18] at 5, but this value seems to be too low.

5.4. Target value for the ecological impact indicator

The maximum value for the specific water consumption of the system is defined according to [19] with a maximum water consumption of 2.7 liters per kWh of evacuated energy (24).

5.5. Target value for the economical indicator

The maximum operation cost of the system is defined by comparison of an equivalent system (25). The equivalent system is only the hot and cold backup systems of the considered system. If the efficiency of the hot or cold backup systems is unknown or non-existent, the reference system considered is a gas heater ($R_{g_{HB}} = 0.75$) for the DHW and heating productions and a vapor compression chiller ($R_{g_{CB}} = 2.46$) for the cooling production. According to [3], the reference parasitic electricity consumption of the system is assumed to be 2% of the distributed energy.

5.6. Target value for the quality indicators

The minimum values assumed for the comfort indicator and for the running time indicator are 90%. For the data lost indicator, the minimum value assumed is 10%.

Table 3. Calculation method of the target of the different indicators for the configurations 1 and 2

Target	Calculation method
$\eta_{HS, min}$	Equation (1) or (2) with: $Q_{loss HS, ref} = [N_{HS} \times 4.2 \times V_{HS}^{0.55} \times (T_{hot} - T_{amb}) \times 365 \times N_{month}] / (12 \times 1000)$ (18)
$\eta_{CS, min}$	Equation (3) with: $Q_{loss CS, ref} = [N_{CS} \times 4.2 \times V_{CS}^{0.55} \times (T_{amb} - T_{cold}) \times 365 \times N_{month}] / (12 \times 1000)$ (19)
$COP_{th, min}$	$COP_{th, ref} = 0.8 \times COP_{th, manufacturer}$ (20)
$R_{coll, min}$	$R_{coll, ref} = a0 - a1 \times (T_{av} - T_{ext}) / ENS - a2 \times (T_{av} - T_{ext})^2 / ENS$ (21)
$R_{sol, min}$	$R_{sol, ref} = R_{coll} \times (N_{cool} \times COP_{th} / N_{month} + 1 - N_{cool} / N_{month})$ (22)
PSU_{min}	$PSU_{ref} = 350 \times N_{month} / 12$ (23)
$WC_{spe, max}$	$WC_{spe, max} = 2.7 \times (1 + COP_{th}) / COP_{th}$ (24)
$kWh_{cost, max}$	$kWh_{cost, max} = [0.02 \times (Q4 + Q3 + Q2) \times \epsilon_{elec} + (Q4 + Q3) / R_{g_{HB}} \times \epsilon_{HB} + Q10 / R_{g_{CB}} \times \epsilon_{CB}] / (Q10 + Q3 + Q4)$ (25)

5.7. Evaluation of the installation using target values

As it is very difficult to identify only one relevant quality indicator for SHC systems, it is proposed to represent a system using a graphic chart showing the difference between the defined indicators and the associated target values. In this way, two calculation methods for the percentage indicator values, depending of the kind of target indicators: minimum (26) or maximum values (27), are defined:

$$I_{\%} = 100 \times [1 + (I - I_{\min}) / I_{\min}] \tag{26}$$

$$I_{\%} = 100 \times [1 + (I_{\max} - I) / I_{\max}] \tag{27}$$

With this calculation method, each indicator is compared to his target value. A good result for an indicator results in a value higher than 100%. In order to obtain a suitable presentation, min and max limits are applied to the indicators: for a value lower than 0%, the value is considered to 0% and for a value higher than 200%, the value is limited at 200%.

For the 4 systems operated by the partners (Solera, Sonnenkraft, Rafsol and Solaclim), the performance graphic chart is presented on Fig. 5.

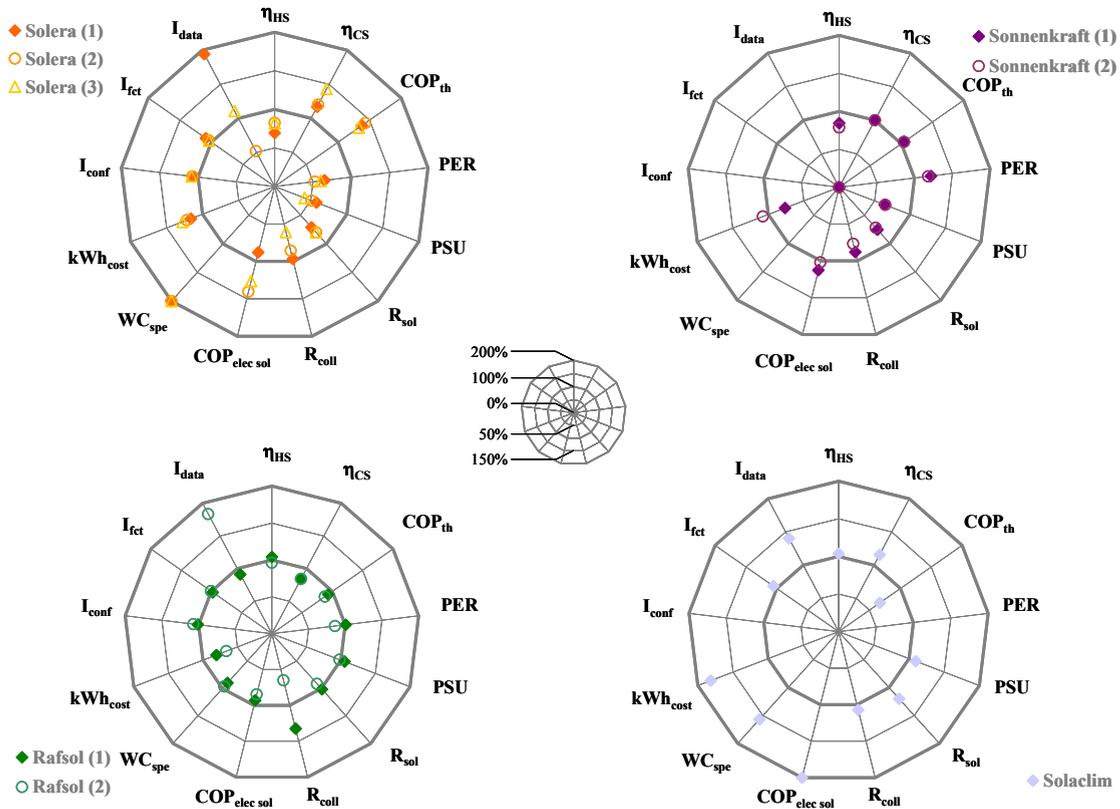


Fig. 5. Overview of quality of the installations: SOLERA, SONNEKRAFT, SOLACLIM and RAFSOL

Based on the 4 installations overview performances presented on Fig. 5, the proposed methodology shows very balanced installation (Rafsol), good installation despite a low thermal COP (Solaclim). For Solera and Solaclim, the results are more mitigated with good and bad values for the indicators. For Solera, the low PER is due on one hand to the direct electric boiler used as heating backup system and, on the other hands, to the decrease of the cooling needs of the building which result in a lower solar performance. For Sonnenkraft, except the high water consumption, the solar performances are not optimal but the PER value of the installation is high. Anyway, the performance cartography methodology allows a quick and an overall installation performances and points the necessary improvements.

6. Conclusion and perspective

The comparison of performance indicators and definition of target values show that SHC systems need a common procedure to measure the system performance.

Whereas international and well known indicators like PER (or SPF) seems appropriate to compare different systems, alone they are not easy to manipulate for solar cooling and heating system, due to a large number of hypothesis that should be taken into account. It appears necessary to include other indicators (solar, thermal, ecological and quality) in order to provide a good overview of the performances of a SHC installation. In this way, the methodology presented in this paper can be used in order to present the global performances of this kind of system.

However, the MeGaPICS project partners still work on a selection process to choose which is or are the write indicator(s) to use, in order to guarantee SHC performances.

Acknowledgements

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