Analysis of Applicability of PLPE Method for the Test of a Solar Cooling System.

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Abstract

Dynamic whole system testing methods are applied to evaluate the performance of heating system driven by renewable energy. The application of dynamic methods is needed to perform a reliable performance evaluation since these systems work under dynamic conditions. However, some procedures described in literature are defined for a specific application.

The PLPE procedure has been developed with the aims of simplification of its application and of having a general applicability. Nevertheless, the PLPE was validated only for a solar assisted heat pump system. The present paper wants to investigate the applicability of the PLPE procedure for the test of a solar cooling system.

The paper shows the representability of the emulations and the accuracy of estimating the seasonal performance for different climates in the case of solar cooling systems. The PLPE can estimate the thermal SPF with an accuracy of the 10%.

Keywords: solar cooling; whole system testing; PLPE method.

1. Introduction

To evaluate the performance of a heating systems, different whole system testing methods (Haller et al. 2013) have been developed and are currently applied by different research institutes. The main motivation to apply a whole system testing method is that the system is studied under realistic working conditions since it is installed as a whole. In this way, it is possible to identify the different effects affecting the performance. Those testing methods allow system optimization, faults detection and resolution before the commercialization of the system or its installation in the final user site.

The procedures presented in literature are applied to some specific typology of heating system such as solar assisted heat pumps systems, solar and biomass system or hot water systems (Albaric et al., 2008, Bales, 2004, Haberl et al., 2009, Lazrak et al., 2015, Menegon et al., 2017b, Schicktanz et al., 2014).

The PLPE (Menegon et al., 2017b) has been developed with the aim of being applicable for different heating and cooling systems. However, this test method has been validated only for a solar assisted heat pumps system.

The present paper would verify the applicability of the PLPE method for the test of a solar cooling system. In the development of the PLPE, the authors have defined the sequence considering a generic heating and cooling system and therefore the boundary conditions are not depending from the system layout.

From the whole system testing method point of view, a solar cooling system is quite different from a solar heating system: when a short sequence is used for the test of a solar system, one of the causes of the deviation on the performance extrapolation is the error on the assessment of the solar contribution. Typically, in a solar heating system, a short sequence can overestimate the solar fraction since it can neglect the summer stagnation since there is a mismatching between load and availability of the source. On the other side, in a solar cooling system, during

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the summer, the solar energy corresponds to its use for the cooling production. It is not obvious that a procedure valid for the characterization of a solar heating system could be valid also for the characterization of a solar cooling system due to these different correspondences between the availability of the source and the requirement of load.

The paper presents the evaluation performed on a solar cooling system during the cooling season and with the use of numerical simulation. The study considers the climates of Bolzano and Palermo, different collector areas (8 m^2, 12 m^2 and 16 m^2) and different sequence lengths (six-day, eight-day and ten-day).

The solar cooling system presented in this paper has been configured in the laboratory and the controls schemes were defined and improved with numerical simulations. The aim of this study it was not to develop a new system concept but to verify the applicability of the PLPE method for the test of solar cooling.

2. Case study

The systems presented in figure 1 has been used to verify the applicability of the PLPE. The system adopts an adsorption chiller of 8kW (SorTech AG, 2009) fed with solar energy. The gas boiler is used as back-up for the domestic hot water preparation.

The numerical model has been developed in TRNSYS 17 (Klein and et al., 2012). The components' models have been validated with experimental data and monitoring data.

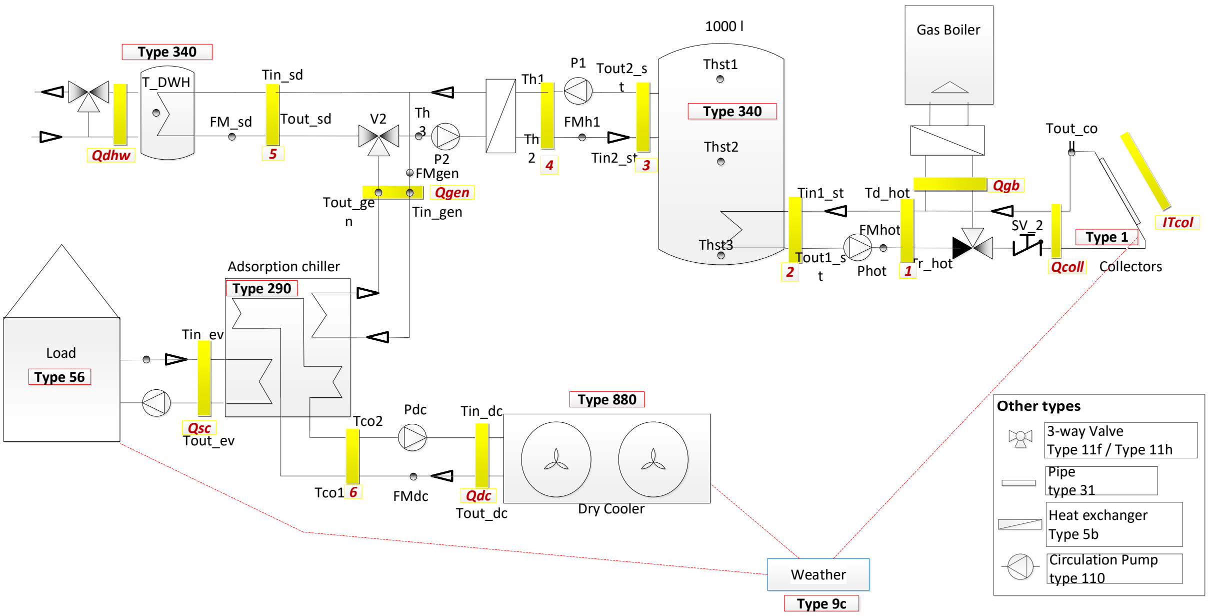

Fig. 1: Layout of the solar cooling system.

The system model uses the following types:

- Storage: Type 340 (Drück and Pauschinger, 2006); the geometry of the storage is defined for the model present in the laboratory. The validation has been performed with monitoring data.
- Adsorption chiller: the type 290 has been developed directly by the manufacturer (SorTech AG, 2009); the model is based on a performance map rated by the manufacturer. Since the DLL cannot be modified, a post-correction has been applied to validate the model according to the dynamic performance of the chiller rated in the laboratory (Menegon et al., 2014);
- Dry cooler: type 880 (Besana, 2009). The model is based on the ε/NTU method and capacitance effects are considered. The validation of the model has been performed with monitoring data.
- Gas boiler: the performance of the gas boiler has been defined in laboratory under stationary condition. Since it was possible to define the heat as a linear regression of the inlet temperature, a calculator has been

set up to calculate the output temperature from the performance map. This kind of calculation well fits with the laboratory test of this unit.

- Other components: standard TRNSYS types. The parameters of each component correspond to the commercial component composing the system (e.g. the electrical consumption has been measured in laboratory and so on).

From the simulation results, the load and source energy have been counted and used to calculate different performance factors. These are the electrical seasonal performance factor, the thermal seasonal performance factor, the solar fraction and the primary energy ratio.

The total electrical SPF (SPF_{el}) is calculated as the ratio of total load to the total electric consumption. The total load is the sum of domestic hot water demand (Q_{dhw}) and the space cooling demand (Q_{sc}). For the electrical consumption (W_{tot}), it is accounted the contribution of all the auxiliaries (chiller, pumps and the fans of the dry cooler).

$$SPF_{el} = \frac{Q_{dhw}+Q_{sc}}{W_{tot}} \qquad \text{(eq. 1)}$$

The total thermal SPF (SPF_{th}) is calculated as the ratio of the total load with the total thermal energy in input. The thermal energy in input is the sum of the collector yield (Q_{coll}) with the gas boiler energy (Q_{gb}).

$$SPF_{th} = \frac{Q_{dhw}+Q_{sc}}{Q_{coll}+Q_{gb}} \qquad \text{(eq. 2)}$$

In this study, the thermal and electrical SPF are considered as sum of total loads. There is not the distinction of cooling SPF and hot water SPF.

The solar fraction is defined as the ratio between the collector yield with the total input thermal energy.

$$SF_{tot} = \frac{Q_{coll}}{Q_{coll}+Q_{gb}} \qquad \text{(eq. 3)}$$

As last performance factor, the primary energy ratio is defined as the ratio between the useful energy to the primary energy input. To define the primary energy a conversion factor of 0.41 for the electrical grid and 0.95 for the gas boiler.

$$PER = (Q_{dhw} + Q_{sc}) / \left(\frac{W_{el}}{\eta_{el}} + \frac{Q_{gb}}{\eta_{gb}} + Q_{coll}\right) \qquad \text{(eq. 4)}$$

3. Method

The flow chart of figure 2 shows the steps adopted to perform the analysis of applicability of the PLPE for the test of solar cooling systems. The first step is the selection of the weather conditions that are boundaries of the test sequence. Then, a short sequence is defined with a clustering classification (Menegon et al., 2017a). The main advantage is that different climates can be easily selected to define the test sequence. In this way, if the manufacturer need a specific climate, it can be set-up. Please note that the PLPE method at now is validated only for European climates.

The evaluation has been performed comparing a numerical simulation of the sequence with the annual simulation. The numerical model has been defined in the previous section. The system has been simulated considering six-day sequences defined for the climates of Bolzano and Palermo. A parametric simulation was done to investigate different collector areas (8 m^2, 12 m^2 and 16 m^2). In addition, the climate of Bolzano has been simulated to investigate different sequence lengths of six days, eight days and ten days.

In this study, the system is studied under the summer conditions. The seasonal energies indicated in the tables are referred from June to September. The test sequences were defined considering the annual file and then only the days between June and September have been simulated.

The short sequence is also the boundary condition of the laboratory test. However, the results of the laboratory test are not present in this study.

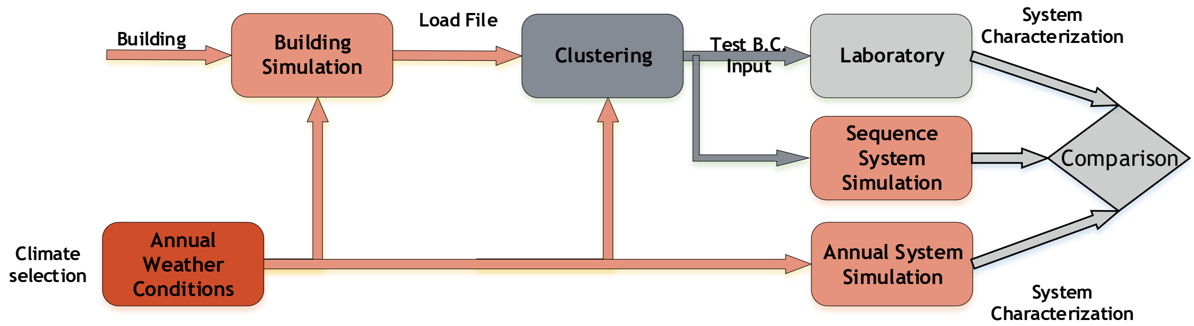

Fig. 2: Method for the evaluation of applicability of the PLPE for the test on a solar cooling system.

The seasonal performance is calculated from the short sequence according to the PLPE method. Specifically, the PLPE methods calculates the annual energies from the short sequence with the direct extrapolation indicated with (eq. 5). The daily energies of the sequence are weighted with the cluster size of each day (N_i).

$$Q_a = \sum_{i=1}^{Nc} Q_i \cdot N_i \qquad \text{(eq. 5)}$$

In the (eq. 1), Q represents the energies of load (space heating, DHW, total), the energy of sources (e.g. solar collector) and the consumptions (e.g. electric, gas). The subscript "a" indicates the annual value (in this study referred as cooling season), "seq" the sequence, "i" the number of the day and Nc the number of clusters.

The deviation with the annual simulation of the values calculated with the eq. 1 is calculated as follows:

$$\delta = \frac{Q_{a,seq} - Q_a}{Q_a} \qquad \text{(eq. 6)}$$

Where the deviation δ is calculated for the different parameters calculated in this study: space-cooling load, DHW, total load, the collector yield, the electric consumption, the gas consumption, the electric and thermal SPF, the solar fraction and the primary energy ratio.

4. Results

This section presents the results of the parametric simulation performed for the solar cooling system during the summer season. The parametric simulations have considered different collector areas and different sequence lengths. The simulations were performed for the climates of Bolzano and Palermo.

4.1. Evaluation for different sequence length

Figure 4, figure 5 and table 1 present the simulation of the solar cooling system with 8 m^2 of collector area. These results are referred to the simulation of the cooling season, the six-day sequence, the eight-day sequence and the ten-day sequence. As indicated in the section 3, the short sequences are defined for the entire year and only the days between June and September were simulated.

Figure 4 presents the space cooling load, the collector yield, the total radiation on collector surface and the gas boiler consumption. From the figure, it can be seen that the six-day sequence presents the higher deviation with the entire simulation while the deviation is reduced with the eight-day sequence and the ten-day sequence. The six-day sequence evaluates a lower cooling demand and a lower contribution of gas boiler while it overestimates the collector yield. The overestimation of the collector yield is a direct consequence of the higher irradiation on the collector. Since the irradiation is a known boundary condition, this deviation can be corrected by reducing the irradiation of the sequence in order to reach the level of the cooling season. However, in this study there is not any correction of boundary conditions since the procedure is the same presented for the SAHP system. (Menegon et al., 2017b). This consideration will be considered for any future development of the procedure.

The eight-day sequence and the ten-day sequence lead to a similar evaluation of seasonal performance. These two sequences overestimate the collector yield of about 10%, the eight-day sequence presents a similar deviation on the gas boiler consumption while the ten-day sequence is more precise (2.9% of deviation).

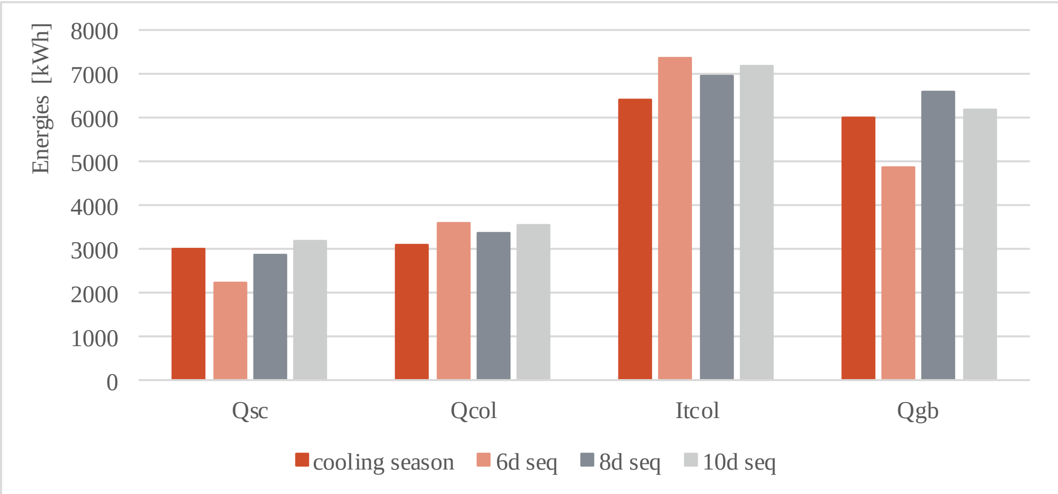

Fig. 4: Solar cooling system simulation. Energies calculated with summer simulation and short sequences. Collector area of 8 m^2.

Figure 5 presents the collector efficiency, the thermal SPF, the electrical SPF and the PER. The first outcome is that all the sequence identify correctly the collector efficiency.

As indicated the previous figure, the six-day sequence presents a higher deviation on the other performance factors. That is a consequence of the not correct assessment of the contribution of the solar collector and the gas boiler. Indeed, the higher collector yield previously presented lead to a higher solar fraction. With the higher solar contribution also the thermal losses increase and this can be noticed by the lower thermal SPF.

Again, the eight-day and ten-day sequence present similar results and these two sequence represent well the cooling season conditions.

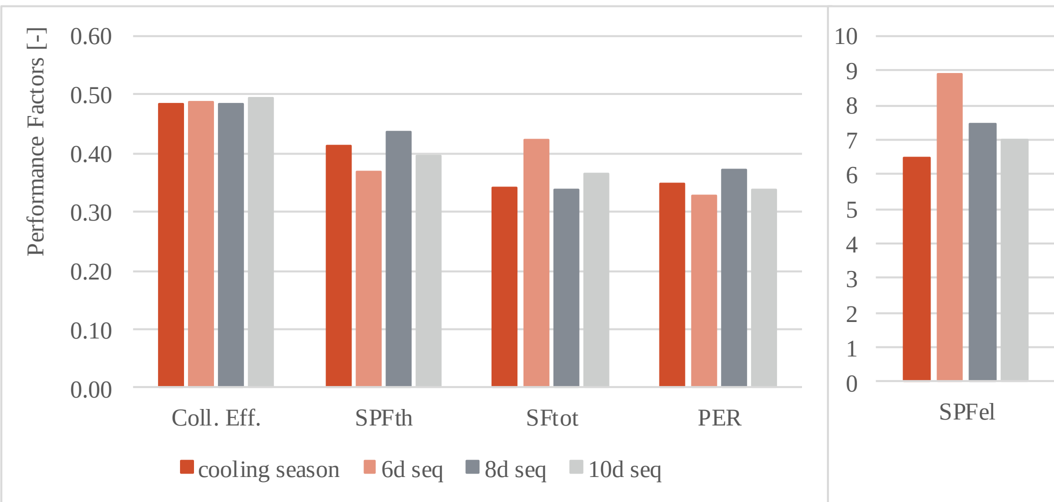

Fig. 5: Solar cooling system simulation. Performance factors calculated with summer simulation and short sequences. Collector area of 8 m^2.

Table 1 completes the information of previous figures and presents the deviation calculated between the short sequences and the summer simulation. It can be noticed that the deviations of the six-day sequence are too high while the deviation of the other two sequences are in line with other methods presented in literature.

Tab. 1: Solar cooling system simulation. Performance figures calculated with summer simulation and short sequences. Collector area of 8 m^2.

	Performance figures				Deviation [%]		
	cooling season	six-day	eight-day	ten-day	six-day	eight-day	ten-day
Qsc [kWh]	3007.70	2241.87	2892.22	3182.55	-25.5%	-3.8%	5.8%
Qcol [kWh]	3116.17	3587.50	3375.43	3564.13	15.1%	8.3%	14.4%
ITcol [kWh]	6434.82	7375.50	6969.40	7211.70	14.6%	8.3%	12.1%
Qgb [kWh]	6020.77	4869.64	6612.66	6195.22	-19.1%	9.8%	2.9%
Coll. Eff [-]	0.48	0.49	0.48	0.49	0.4%	0.0%	2.1%
SPFth [-]	0.41	0.37	0.44	0.40	-10.6%	5.6%	-4.3%
SPFel [-]	6.48	8.90	7.40	7.00	37.3%	15.2%	8.0%
SFtot [-]	0.34	0.42	0.34	0.37	24.4%	-0.9%	7.1%
PER [-]	0.35	0.33	0.37	0.34	-5.7%	6.8%	-2.6%

The analysis has been repeated with the collector area of 12 m^2 and 16 m^2. The figure 6 presents the energies calculated for the 12 m^2 of area while the figure 7 presents the energies calculated for the 16 m^2 area. The figure 8 and figure 9 presents the performance factors respectively for the 12 m^2 and 16 m^2 cases.

When the collector area is increased, the contribution of solar collector increases and therefore the consumption of gas boiler decreases. Passing from 8 m^2 to 12 m^2, the collector yield increases about the 37% while the gas boiler consumption decreases about 15%. By adding other 4 m^2 to the collector area (passing from 12 m^2 to 16 m^2) the collector yield increases about 33% and the gas boiler consumption decreases about the 17%. It can be noticed that the thermal losses increase since the sum of collector yield with the gas boiler is increasing from 9136 kWh to 9416 kWh (from 8 to 12m^2) and from 9417 kWh to 10002 kWh (from 12 to 16m^2).

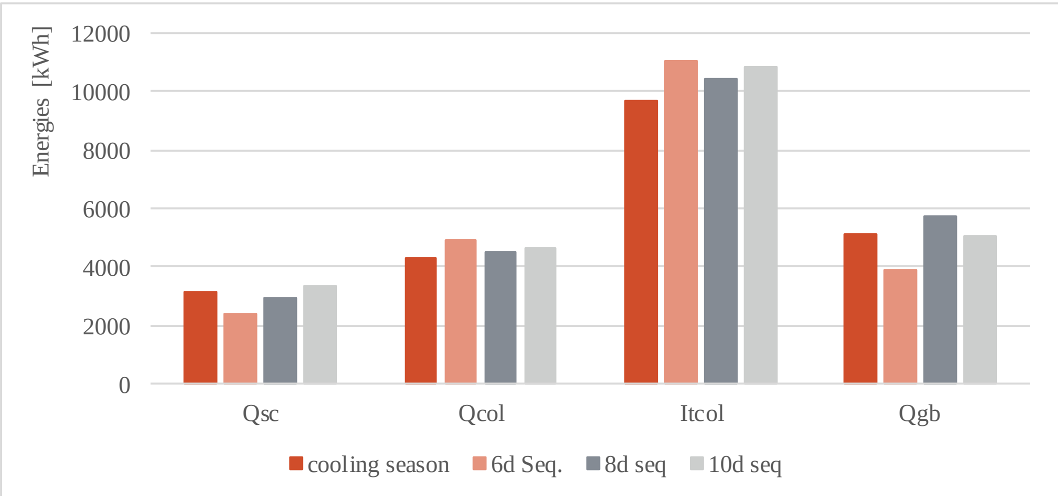

Fig. 6: Solar cooling system simulation. Energies calculated with summer simulation and short sequences. Collector area of 12 m^2.

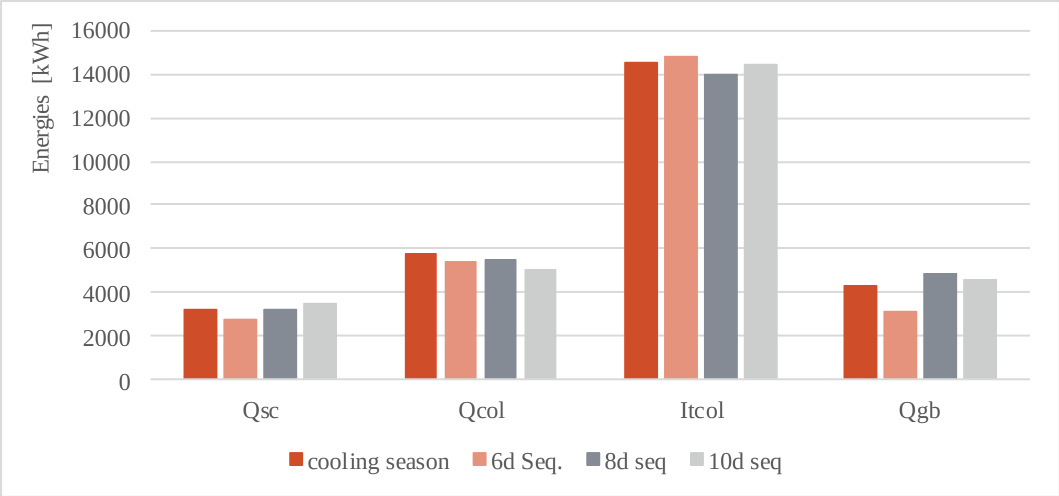

Fig. 7: Solar cooling system simulation. Energies calculated with summer simulation and short sequences. Collector area of 16 m^2.

The electrical SPF and the thermal SPF do not variate with the variation of collector area also if the denominator increase since the load slightly increases. Instead, the solar fraction increases with the collector area passing from 0.34 (8 m^2) to 0.46 (12 m^2) and finally to 0.57 (16 m^2).

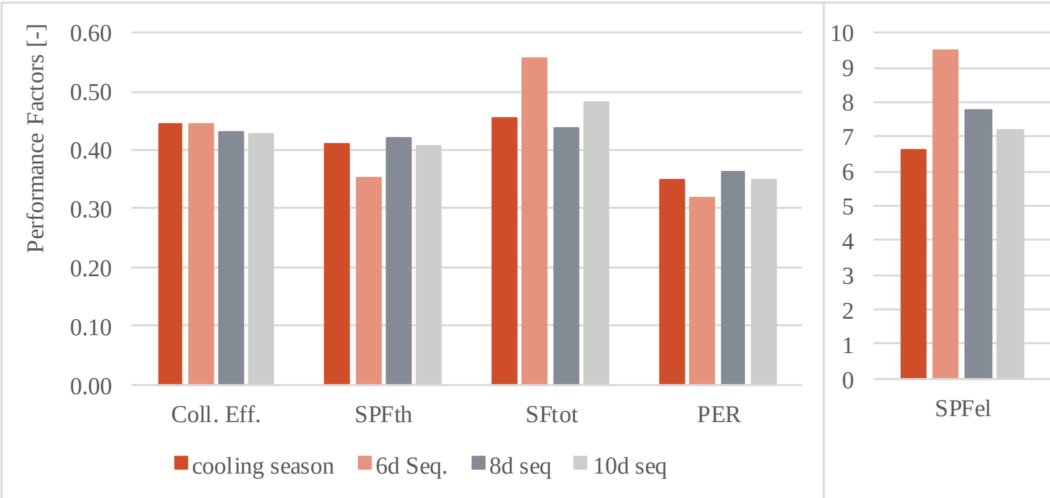

Fig. 8: Solar cooling system simulation. Performance factors calculated with summer simulation and short sequences. Collector area of 12 m^2.

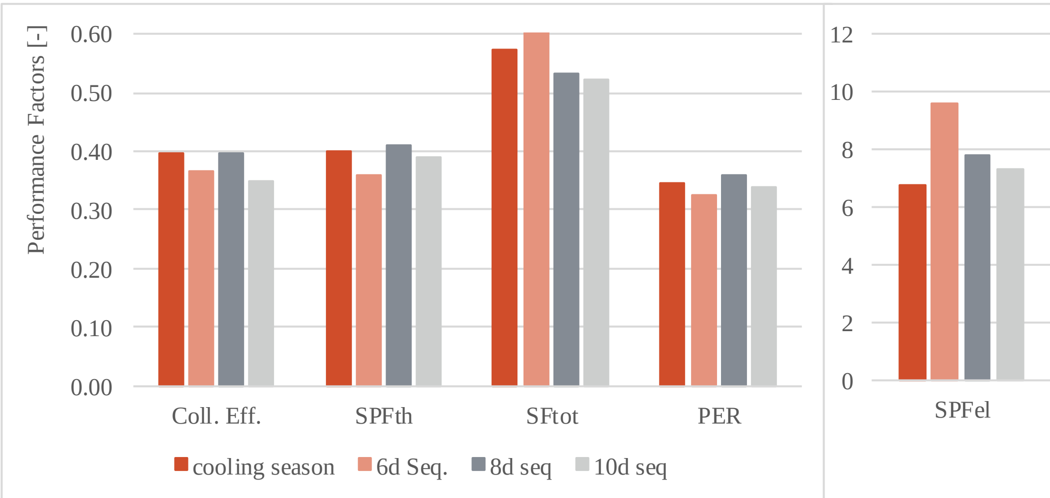

Fig. 9: Solar cooling system simulation. Performance factors calculated with summer simulation and short sequences. Collector area of 16 m^2.

Table 2 and table 3 present the values indicated in the previous figures and the deviation of the sequences with the entire cooling season.

The simulation performed for these two configurations of higher collector area confirm the lower accuracy of the six-day sequence as it was pointed out in the case of 8 m^2 of collector area. Indeed, the deviations of the six-day sequence is included in a range of 8 to 25% (with one outliner that is the SPFel). Instead, the accuracy of the eight-day sequence is closed to the accuracy of the ten-day sequence. Both sequences reach a deviation lower than 12% with the exception of the SPFel.

All the simulations have presented an higher deviation of SPFel. This can be explained in the following way: in the case of solar cooling system, the electric consumption is very low, and therefore a small variation of the absolute value of total consumption lead to a high variation in relative terms.

Tab. 2: Solar cooling system simulation. Performance figures calculated with summer simulation and short sequences. Collector area of 12 m^2.

	Performance figures				Deviation [%]		
	cooling season	**six-day**	**eight-day**	**ten-day**	**six-day**	**eight-day**	**ten-day**
Qsc [kWh]	3098.79	2388.84	2910.30	3325.10	-22.9%	-6.1%	7.3%
Qcol [kWh]	4289.33	4915.62	4500.12	4634.03	14.6%	4.9%	8.0%
ITcol [kWh]	9652.22	11063.30	10454.10	10817.60	14.6%	8.3%	12.1%
Qgb [kWh]	5127.81	3896.13	5753.72	5016.42	-24.0%	12.2%	-2.2%
Coll. Eff [-]	0.44	0.44	0.43	0.43	0.0%	-3.1%	-3.6%
SPFth [-]	0.41	0.35	0.42	0.41	-13.8%	2.7%	-1.3%
SPFel [-]	6.63	9.48	7.75	7.19	43.0%	16.9%	8.4%
SFtot [-]	0.46	0.56	0.44	0.48	22.5%	-3.6%	5.4%
PER [-]	0.35	0.32	0.36	0.35	-8.5%	4.4%	0.2%

Tab. 3: Solar cooling system simulation. Performance figures calculated with summer simulation and short sequences. Collector area of 16 m^2.

	Performance figures				Deviation [%]		
	cooling season	**six-day**	**eight-day**	**ten-day**	**six-day**	**eight-day**	**ten-day**
Qsc [kWh]	3247.60	2751.08	3237.54	3473.65	-15.3%	-0.3%	7.0%
Qcol [kWh]	5729.52	5386.93	5530.74	5011.45	-6.0%	-3.5%	-12.5%
ITcol [kWh]	14478.34	14751.00	13938.80	14423.50	1.9%	-3.7%	-0.4%
Qgb [kWh]	4273.12	3161.03	4886.19	4581.28	-26.0%	14.3%	7.2%
Coll. Eff [-]	0.40	0.37	0.40	0.35	-7.7%	0.3%	-12.2%
SPFth [-]	0.40	0.36	0.41	0.39	-10.4%	2.5%	-2.6%
SPFel [-]	6.77	9.59	7.79	7.30	41.6%	15.0%	7.7%
SFtot [-]	0.57	0.63	0.53	0.52	10.0%	-7.3%	-8.8%
PER [-]	0.34	0.33	0.36	0.34	-5.5%	4.0%	-1.3%

3.2. Evaluation for different climate

The last analysis considers the climate of Palermo that has been simulated with a six-day sequence. Again, the system has been evaluated for different collector area of 8 m^2, 12 m^2 and 16 m^2.

In the case of the climate of Palermo, it can be seen that the six-day sequence is more accurate than the six-day sequence defined for the climate of Bolzano.

The results of this simulations confirm the trends noted for the climate of Bolzano with a different magnitude. The increase of collector area from 8 m^2 to 12 m^2 leads to an increase of collector yield of 45% and a decrease of gas boiler consumption of 19%, while the increase from 12 m^2 to 16 m^2 leads to an increase of collector yield of 35% and a decrease of gas boiler consumption of 26%. Again, the increase of the collector area is connected to the increase of the cooling load connected to the thermal losses. Therefore the thermal SPF is close to be constant while the solar fraction increases.

The six-day sequence presents the higher deviation on the gas boiler consumption (about 14% over the three simulations) and on the electrical SPF. This second deviation is due to the very low value of denominator of the electrical SPF and therefore a small variation leads to a higher deviation of the ratio. All the other performance figures are evaluated with a deviation lower than 10%.

Tab. 4: Solar cooling system simulation. Performance figures calculated with summer simulation and short sequences. Climate of Palermo.

	8mq			**12mq**			**16mq**		
	cooling season	**six-day**	**δ [%]**	**cooling season**	**six-day**	**δ [%]**	**cooling season**	**six-day**	**δ [%]**
Qsc [kWh]	4247.1	4556.4	6.8%	4437.9	4654.6	4.7%	4519.0	4593.0	1.6%
Qcol [kWh]	4088.9	4064.5	-0.6%	5937.0	5743.2	-3.4%	8034.1	7741.2	-3.8%
ITcol [kWh]	7823.0	7877.6	0.7%	11734.5	11816.4	0.7%	17601.7	17724.6	0.7%
Qgb [kWh]	7526.0	8813.9	14.6%	6107.5	6825.5	10.5%	4544.6	5505.6	17.5%
Coll. Eff [-]	0.523	0.516	-1.3%	0.506	0.486	-4.1%	0.456	0.437	-4.5%
SPFth [-]	0.432	0.435	0.7%	0.432	0.454	4.7%	0.420	0.426	1.3%
SPFel [-]	6.248	8.241	24.2%	6.312	8.336	24.3%	6.735	8.871	24.1%
SFtot [-]	0.352	0.316	-11.5%	0.493	0.457	-7.9%	0.639	0.584	-9.3%
PER [-]	0.360	0.376	4.3%	0.363	0.394	7.9%	0.360	0.378	4.8%

5. Conclusions

The PLPE method has been developed with the aim of being applicable for different typologies of heating and cooling systems. Since the method has been developed considering a reference system that is a solar assisted heat pump system, the aim of this paper was to further investigate on the applicability of the PLPE method. The case study presented in this paper is a solar cooling system that can provide also domestic hot water. The solar cooling system has been configured in laboratory with the aim to verify the test method and not to present a new concept of solar cooling.

The results have shown that the six-day sequence defined for the climate of Bolzano is not representing well the performance of the cooling season while the eight-day sequence and the ten-day sequence represent well the seasonal performance. The evaluation has been performed also variating the collector area of the system and the obtained deviation has investigated. The PLPE is not affected by the variation of the collector area and it is able to reach an accuracy of about 10%.

The simulation has been performed also for the climate of Palermo where the system has been evaluated with only the six-day sequence. In this case, differently from the climate of Bolzano, the reached accuracy is good. The trends evaluated for the variation of collector area are confirmed.

In conclusion, with a proper sequence length, the PLPE method applied to a solar cooling system is able to reach an accuracy of about 10%.

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