DESIGN, INSTALLATION AND OPTIMIZATION OF TWO SMALL SCALE SOLAR HEATING AND COOLING SYSTEMS

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Abstract

Cooling demand is rapidly increasing worldwide [1]; the combination of solar thermal energy with thermally driven chillers has the potential to replace conventional electric driven compression chillers. Large scale Solar Heating and Cooling (SHC) systems have been successfully demonstrated; smaller systems have not yet entered the market due to various technical and economic reasons. Automated and autonomous package-solutions could facilitate their market entry. The main aim of the FP7 project ALONE is to conceive and manufacture prototypes of market-ready autonomous SHC systems for residential or light commercial applications (small size systems, 5-13 kW of cooling capacity). After manufacturing two prototypes, they were installed at test sites in Bolzano and Firenze (Italy).

A relevant problem in estimating the benefit of the SHC systems is the evaluation of the seasonal performance [2]. For this reason an important role during the system design phase is played by the verification and validation of the numerical models used in system simulation [3]. Models of the two SHC applications were created in TRNSYS [4][5] and simulations were carried out for evaluating yearly operation. Simulation results were compared with monitored data in order to validate numerical models. Performance figures, like Primary Energy Savings, Solar Fraction for cooling (SF cooling) and heating (SF heating) were calculated in order to describe the energy behavior of the cases study.

1 Introduction

Nowadays, high front-end investment costs and designers and installers' lack of experience pose significant barriers to market diffusion of solar heating and cooling systems [6].

In response to this, the ALONE project proposes the development of standard system configurations for reducing design costs for single application and offering the basis for mass manufacturing of packaged solutions. Launched in October 2008, ALONE is a four-year research project, co-funded by the European Union within the Seventh Framework Program. Its main purpose is to provide market-ready autonomous solar assisted systems for heating, cooling and domestic hot water preparation in residential or light commercial applications. Project partners include CREAR (Coordinator), EURAC Research, DLR, CLIMATEWELL and RIELLO.

The project is specifically focused on the design and manufacturing of a standardized control units, named 'Energy Box' (EB), in which valves, pumps and control hardware are centralized.

An EB is designed to allow the installation of a plug&play and reliable hardware and control strategy; in this way the EB promotes the interaction and optimization of all system's components to increase the solar energy harvest and reduce system's fossil fuels consumption.

Seasonal performance evaluation is faced up through monitoring the system and using data collected to validate the numerical models in system simulation. Thanks to the validation procedure used, it is possible (1) to perform an accurate prediction of system's behavior under different boundary conditions, (2) to quantify the confidence and build credibility in numerical models outputs and (3) to solve potential operation conflicts before installation.

2 Case Studies

Energy Box prototypes were installed in two testing sites in Italy, one in Bronzolo and the other in Florence [7]-[8].

2.1 Bronzolo Test Site

This building is located in a new residential area in Bronzolo, a town 10 km to the south of Bolzano. The house was built in 2006 by IPES (Istituto Per l'Edilizia Sociale), an institute for social housing in the Province of Bolzano. The building is divided into eight apartments on three levels. The existing energy plant is comprised of a central ventilation system, a subsoil heat exchanger for preheating and precooling the supply air and a 15kW pellet boiler that drives heating coils (one for each apartment) and provides Domestic Hot Water (DHW).

Figure 1 – Collectors' field and EB in Bronzolo

Integrated into the existing plant, the new system is designed to decrease the use of the pellet boiler and to increase internal comfort during summer. A 40 m^2 solar field was installed on the roof. The solar collectors (CSV 25 models by RIELLO) supply energy to a 3000 l stratified storage tank used to cover the building's DHW demand. When the storage tank has reached its set temperature, additional solar energy is used to partly cover heating or cooling demand.
During the winter months, the air inside the building can be directly heated by the solar field; whereas in summertime, solar energy feeds a 10 kW sorption chiller from Climatewell.
Three different techniques are used to reject heat. First of all, waste air from the building is used; secondly, geothermal probes are used to exchange heat with the ground; finally, a dry cooler takes over when the other two are not affective anymore.

2.2 Misericordia Test Site

Misericordia is a health facility located in eastern Florence [8]. The site has a main building that is used for out-patient services, and a 'secondary' building used for all administrative activities. The two buildings are cooled by an air-conditioning system based on electrically-driven heat pump.
A 108 m^2 solar field comprised of Parabolic Trough Collectors (SOLITEM's PTC1800) is installed on the west side of the building. The solar field is designed to provide direct steam; a Direct Steam Generation (DSG) module supplies saturated steam to an ammonia-water chiller.

The DSG is characterized by a 200-litre steam drum and a condensate collector that re-circulates condensate to the solar field.

Figure 2 – Misericordia building (Florence)

The solar field supplies energy to a 17 kW ammonia-water chiller (ROBUR Technology) modified for direct steam driving, as well as a 23 kW Lithium Bromide Chiller (BROAD Technology) driven by pressurized water. The connection between the SHC plant and the existing system is assured by pre-treating the mechanically ventilated air with a fluid-to-air heat exchanger. Heat is rejected from the chiller to the HVAC system, to a 30 kW emergency dry-cooler, as well as to a nearby swimming pool.

The EB at the Misericordia is characterized by a unique container that incorporates the hydraulic and the electrical systems.

Three operating modes regulate the functioning of the different circuits:

- Summer-Steam Mode: the solar field supplies the ammonia water chiller with saturated steam for the production of cooling for the building air-conditioning;
- Summer–Water Mode: the solar field supplies the ammonia water chiller with pressurized water for the production of cooling for the air-conditioning of the building;
- Winter Mode: The heat produced by the solar field is conveyed to the HVAC equipment for space heating distribution.

3 Simulation

In order to simulate the plant, TRNSYS decks of the two systems were developed. All the system's components (solar collectors, sorption chiller, hot storage tank, heat exchangers, centralized air handling unit and dry cooler) were modeled and the integrated control strategy implemented. Hereafter, the work elaborated with respect to the system setup in Bronzolo will be addressed.

The solar collectors were simulated by means of the type71. The stratified storage tank was modeled with the Type340. In TRNSYS, for the sorption chiller, two types developed by Climatewell are used, one type (Type 826) is the control unit of the chiller and another one (Type 825) is the barrel. A macro containing one type 826 and two types 825 was built. The 1250 m^3/h AHU was also modeled through a macro containing fans, coils and heat recovery unit. With respect to the 6 geothermal probes (5 cm diameter and 80 m length) lay under the building foundation, the Type 952 from the TESS Library was used.

The dry cooler consists of a finned tube heat exchanger bundle arranged below a fan plenum chamber. Forced draft fans draw air across the finned tubes. A type developed by EURAC is

used. It is designed as a counter flow heat exchanger, with both fluids unmixed, where the air flow rate moved from the fans of dry cooler is evaluated with an iterative procedure, to cope with the set water output temperature. The set point can be fixed or variable with the ambient temperature.
For modeling the building and its consumption a macro is used. The macro contains the type 56 for modeling the building and external files for implementing the monitored hourly DHW consumption.
Figure 3, shows the P&I of the system simulated. The dashed line entails the components actually installed into the EB.

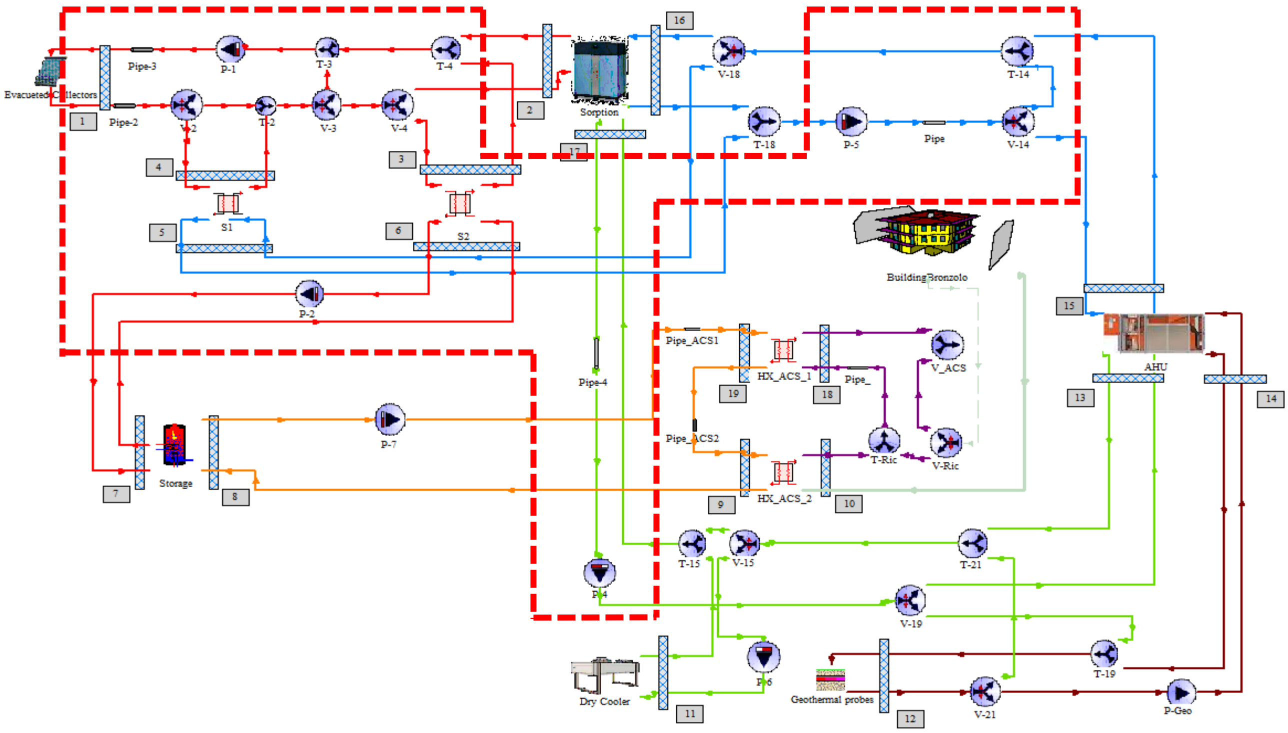

Figure 3 - Bronzolo's system layout

Energy fluxes through the system were computed at significant stations (see numbered marks from 1 to 19) to evaluate both the correctness of the simulations and the performance figures for the evaluation of the system's efficiency.

4 Mathematical model Validation

Monitoring data recorded from July 2011 were used for numerical models validation and additional control strategy optimization. An iterative procedure was used for validating the components' mathematical models [9]. In a first step, manufacturers' datasheets are used for setting up the mathematical model. The results of the component's operation in the simulation environment are compared with the monitored data. In particular, the agreement between the numerical model and the real element is checked by comparing a characteristic performance figures for the inspected component (e.g. solar collector's efficiency curve). In case of a good agreement, the procedure is stopped, otherwise the model definition is further detailed.
Here the validation of the collectors' field is reported as an example. in the Figure 4, the rated efficiency curve for the single collector is compared with the performance of the entire field, which has been obtained by the monitored data.

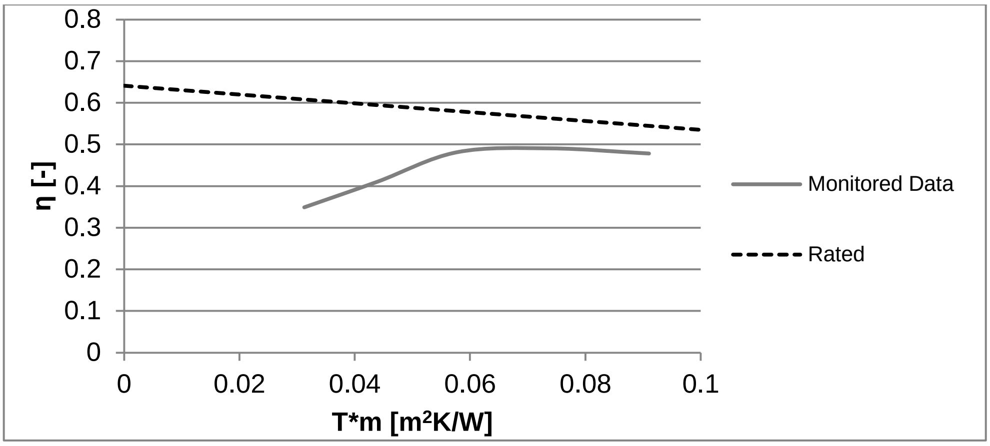

Figure 4 - Rated efficiency curve for the single collector compared with the monitored performance of the entire field

The difference between the two curves is significant: around 10% for T*m value higher than 0,06 and even higher for T*m lower than 0,06. Therefore a parameter identification procedure was performed to recognize the best fitting model parameters. Results of the first validation step are reported in Figure 5: a quite large difference for T*m lower than 0,06 corresponding to low working temperature differences that typically arise during transient conditions at system start. The model employed cannot efficiently tackle such occurrences, therefore it was updated to take into account inertia during transients.

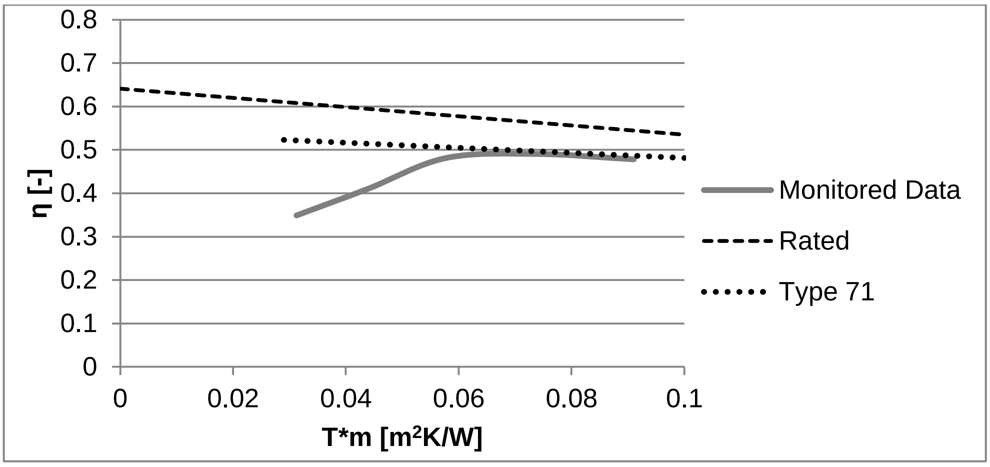

Figure 5 – Comparison of simulated data (Type71) with monitored ones.

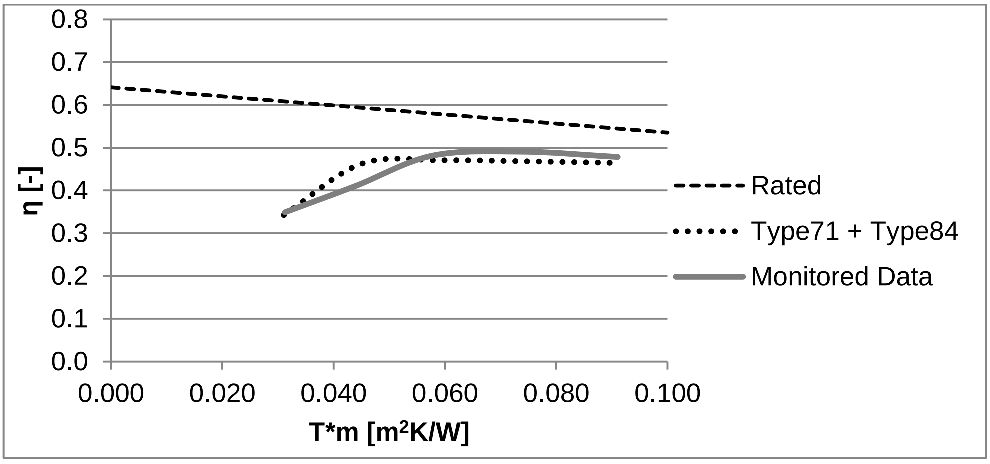

Figure 6 – Comparison of simulated data (Type71+Type84) with monitored ones.

In order to simulate the inertia of the water in the pipes, a moving average Type84 has been used before the solar collectors type. The moving average roughly (but also simply) approximates the effective thermal capacity C_{eff} of the solar collectors and pipes, which, using an electric analogy, is acting like a low band-pass filter. The comparison of the efficiency curves in Figure 6 shows a good agreement, with a RMSE between the two curves of around 3%.
After validation, the comparison based on instantaneous data shows a very good agreement as well, as can be seen in Figure 7. The same procedure was applied to all system's components.

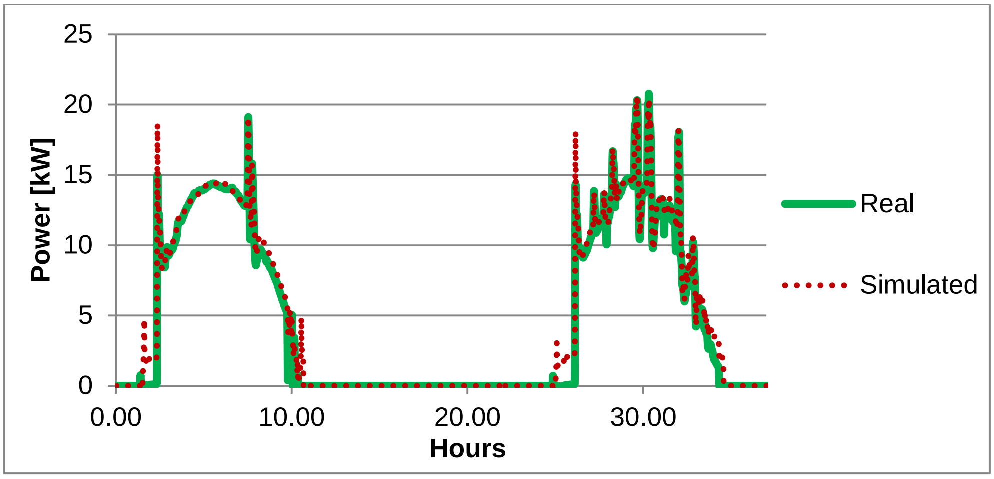

Figure 7 – Solar collectors power comparison after validation procedure

5 Results

A parametric analysis of the SHC system set points was carried out in order to optimize the system operation [5]. Stated the control strategy, a comparison was performed between the system performance before and after the models validation.
A comparison of total amount of incident energy on the collectors (Q_{rad}), total amount of collected energy (Q_{coll}), cooling (Q_{cold}), heating (Q_{heat}) and DHW (Q_{DHW}) delivered to the building are reported in Table 1 for some representative cases. With regards to the nomenclature, the first two numbers represent the dead band values of the hysteresis enabling the harvest of solar energy to the storage tank: in case A, pumps are switched on when storage mid temperature drops below 75 °C and off when storage mid temperature rises above 90°C. the third number represents the DHW delivery temperature (40 °C with reference to the same case).

CASE		Q_{rad} [kWh/y]	Q_{coll} [kWh/y]		Q_{cold} [kWh/y]		Q_{heat} [kWh/y]		Q_{DHW} [kWh/y]	
			before	after	before	after	before	after	before	after
A	90_75_40	58680	27953	24294	2036	1443	466	262	17945	15911
B	75_60_40		28025	24251	2589	2038	846	503	16369	13651
C	60_45_40		27419	23507	3290	3057	1248	1174	13586	9591
D	90_75_60		29788	25383	787	307	130	103	24299	21092
E	75_60_60		30105	25476	908	353	198	103	24055	21007

Table 1 – Collected and delivered energy for different simulation cases

The yearly incident radiation on the surface of the collectors is 58 MWh/y.
Looking at the date before the validation, the yearly harvested energy varies between 27 and 30 MWh/y depending on the temperature sets. The heat requested for the DHW preparation is widely influenced by the control sets temperature. Moreover, due to the storage size (75 l/m^2 collectors) a change in set temperatures for the tank charging influences considerably the system's performance Q_{DHW} increases of about 25% from C to A. Q_{cold} and Q_{heat} decrease respectively of 38% and 63%.

After validation, the yearly harvested energy amounts to 23 and 25.5 MWh/y: the collectors' efficiency is overestimated of 13% with respect of the real behavior by using datasheet parameters. Similar results are obviously obtained for the energy values conveyed to the building.
The solar fractions for cooling, heating and domestic hot water preparation (SF_{cool}, SF_{heat}, SF_{DHW}) are reported in Figure 8 for other representative cases before and after the validation procedures. Using the first model the SF_{DHW} ranges between 75%, for 90_65_60 (priority is given to the preparation of the DHW), and 45%, for 60_40_50 (a balanced use of the solar energy is foreseen); if the validated models are used values of 67% and 28% respectively are obtained instead.
The SF for cooling varies between 5% for the case 90_65_60 and 24% for the case 60_40_50. With validated models, the first values drops to almost 2% while the second remains about the same. The second result is a consequence of the reduced SF_{DHW} assessed in the validated model. Same trends are obtained for the SF_{Heat}.

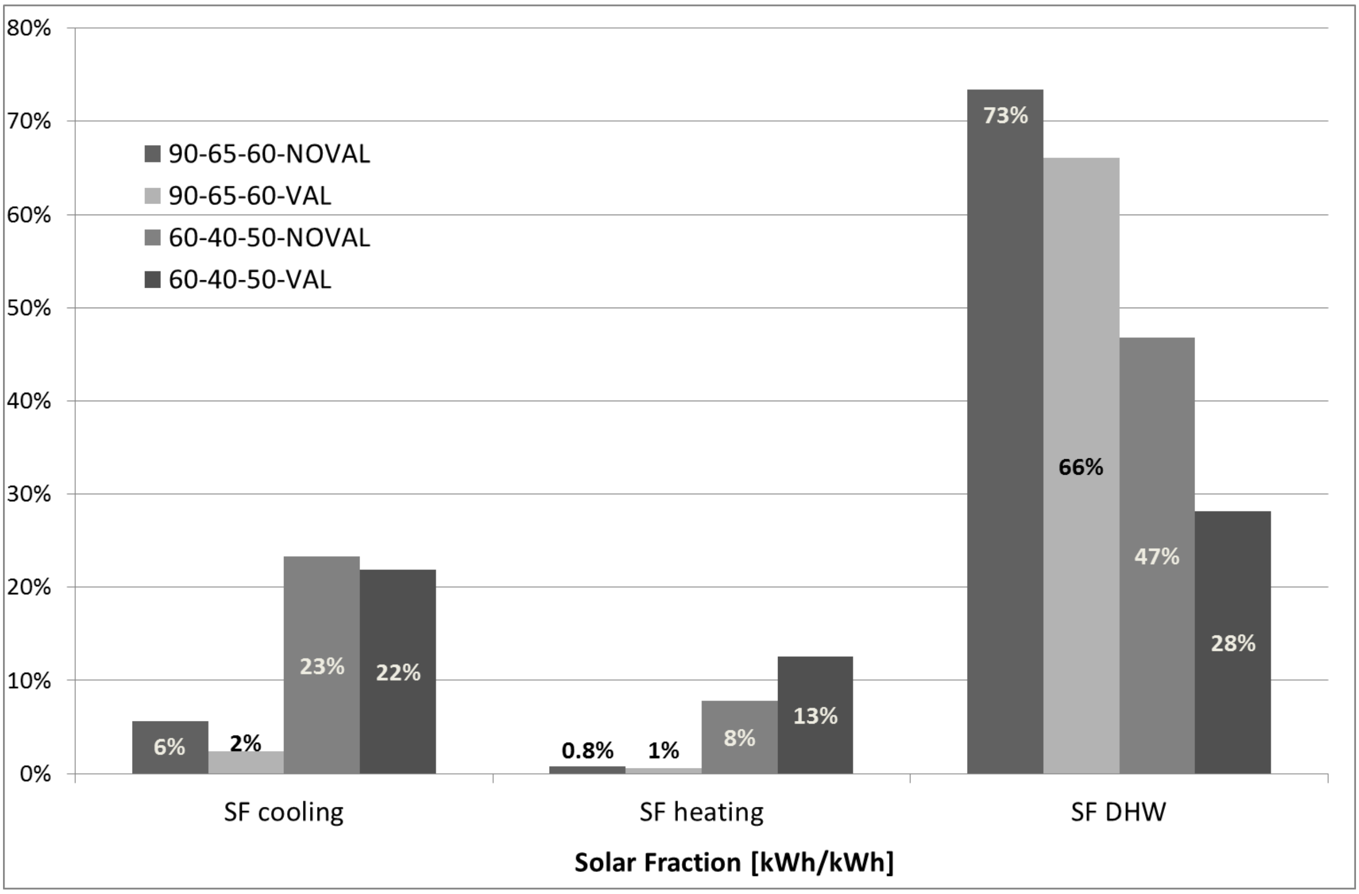

Figure 8 - Solar Fractions relative to thermal loads before (NOVAL) and after validation (VAL)

6 Conclusions

In this paper the prediction of the seasonal performance of SHC systems through numerical simulation was addressed. In particular, a procedure was described that uses monitored data to validate performance of systems' components. The adherence of the numerical model of a collectors' field with the real operation was reported as an example.
The performance of an entire system before and after components' validation was then reported. The comparison between the system's performance highlighted a reduction of solar energy harvest of about 13%. The effects of the validation process for on some selected simulation cases was also reported: the largest differences were encountered with respect to the SF_{DHW}, since priority is given in this system to the preparation of the DHW.

Optimization of the control strategy of the system is now foreseen as a further development step, by taking into consideration system final and primary energy consumption, inhabitants comfort and system maintenance costs.

Acknowledgments

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