Technical and Economic Performance of Best Practice SHC Plants – A Compilation of IEA SHC Task 53 Results

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Abstract

Assessing the performance of solar heating and cooling (SHC) systems in a common comparable format is complicated by the numerous alternative energy sources and design possibilities. A generalized technical and economic assessment methodology was developed and tested in the course of IEA SHC Task 53 and is implemented into an excel tool called T53E4 Tool.

Finally, IEA SHC Task 53 is ending and twenty-eight best practice plants are analyzed and compared in a comprehensive format. The systems represent a wide mixture of technologies, applications and locations. All plants are analyzed and assessed regarding their technical and economic performance and a sensitivity analysis to identify the importance of the main boundary conditions is performed.

The results are showing interesting trends, (i) under certain conditions SHC can be cost competitive and show levelized costs of energy below those of pre-defined reference systems, (ii) from technical and environmental point of view, most of the plants can reach non-renewable primary energy savings greater 50% and up to 95%, depending on their solar fraction (thermal or electrical).

Keywords: Solar heating and cooling, technical and economic assessment, benchmarking, solar thermal, photovoltaic,

1. Introduction

On global level the energy demand for space cooling is rising rapidly. Actual 2’000 TWh electricity are used to drive air-conditioner or fans. This demand could rise up to three times till 2050 if energy efficiency is not increased strongly. Even with this increased efficiency the demand will still increase by a factor of roughly 1.5. Main reason for that rising demand are the economic and population growth and thus rising living standards (OECD/IEA 2018). In the last decade this trend was indicated by the increase of sales of air-conditioners already (JRAIA 2017).

The number of solar cooling and heating (SHC) systems is increasing permanently (Mugnier and Jakob 2015) new technologies and different solutions are available on research level but also on the market (Mugnier, 2015). These systems are characterized by a high diversity of design possibilities including not only different cooling and heating technologies, but also a great variety of different renewable and non-renewable energy sources. Main obstacles for a wider and faster spread of solar cooling and heating are based on (i) lack of knowledge. (ii) technical issues but mainly on (iii) economics.

Merging the quintessence of these IEA Task 48 activities led to the verbalization of 10 key principles. These qualitative principles are the core of a compendium including three build, monitored and optimized systems in a Guide called “The Solar Cooling Design Guide: Case Studies of Successful Solar Air Conditioning Design” (Mugnier et al., 2017). The design guide is intended as a companion to the IEA Solar Cooling Handbook (Henning et al., 2013). Three selected examples are used to explained step by step the design in different ranges of scale and technology. Nevertheless, it should be noted that there are many other attractive solar cooling technology solutions. More details on the scientific background and links to past and latest research results are published by Neyer et al. (2018).

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To encourage a strong and sustainable market for solar, photovoltaic and new innovative thermal cooling systems the IEA SHC Task 53 (T53) was initiated. It is building up on earlier IEA SHC work (e.g. Task 38 & Task 48) to support solutions to make solar driven heating and cooling systems cost competitive. A special focus of the SHC Task 53 is on tested and demonstrated systems (Subtask C). The aim is to analyze the performance of tested and demonstrated new generation solar cooling and heating systems. Therefore, examples of solar cooling systems which are successfully demonstrated, operated or simulated in detail are listed and information about the designs is gathered (Neyer et al., in print). Representative solar cooling systems are selected which will be analyzed within (Köll and Neyer in print) and summarized in this paper. The systems are analyzed on technical and economical basis with the developed T53E4-Tool (Neyer et al., 2016).

Assessing the performance of solar heating and cooling (SHC) systems is challenging because of the wide range of applications and possible technical solutions. It is important to elaborate common standards for a fair and holistic assessment but also for benchmarking against other renewable (solar, etc.) or conventional technologies. A set of technical and economic key performance indicators and the therefore needed data base including conversion factors, efficiencies and investment as well as operational cost are fully discussed and defined in the IEA SHC Task 48 and 53.

A generalized methodology enables the assessment of renewable heating and cooling for a wide range of market available systems. An existing Excel spreadsheet was enhanced to calculate the key figures to evaluate and benchmark the systems; it also contains technical and economic background data. The extended assessment and evaluation tool was tested with best practice examples of both types: (i) solar thermal and (ii) solar electrical driven systems.

2. Technical and economic assessment

The T53E4-Tool is an enhanced Version of earlier developments in IEA SHC Task 48 and enables the comparison of different system designs. It considers several renewable and non-renewable energy sources as primary heat source or backups, as well as different types of heating and cooling technologies in combination with hot or cold storages. A more detailed analysis is separating the results by their applications (e.g. space heating, domestic hot water or cooling). This ensures that the analysis distinguishes further optimization potentials, but the analysis also highlights good performing subsystems. An overview of considered energy flows and division of the subsystems is shown in Fig. 1.

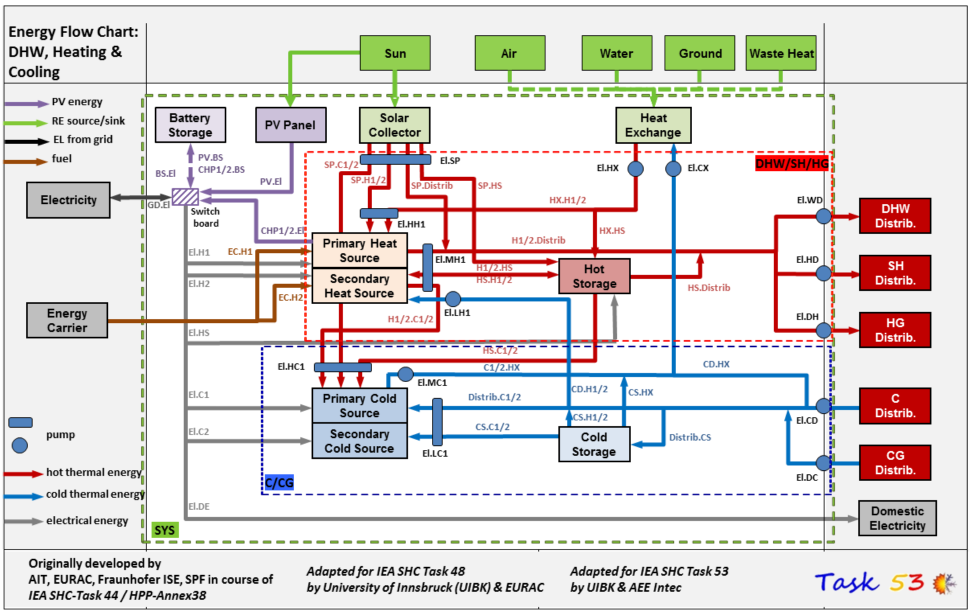


Fig. 1. Energy-flow-chart of all system components that can be taken into account for the assessment by consideration of the different subsystems in T53E4-Tool (Neyer et al. 2016)

The defined KPI's are compared to a reference system defined in Neyer et al. (2016). The reference system uses a natural gas boiler for heating and an air-cooled vapor compression chiller (VCC) for cooling. The efficiency of the reference system is depending on the size (technology), energy delivered (full load) and other parameters. The reference system is used to compare the technical and economic performance of the entire SHC system and to calculate the primary energy savings and cost competitiveness.

Technical Assessment

The key performance indicators (KPI) that are calculated are the non-renewable Primary Energy Ratio (PER_{NRE}), the non-renewable primary energy savings ($f_{sav,NRE}$) and the electrical equivalent Seasonal Performance Factor (SPF_{equ}). They are considered as appropriate indicators for the comparison of the high diversity of SHC systems analyzed with the T53E[4]-Tool. The KPI's are calculated by the tool for the overall system, as well as the subsystems.

- Non-Renewable Primary Energy Ratio

The non-renewable primary energy ratio (PER_{NRE}) is calculated over a longer period of time (annual or monthly). It is defined as the ratio of useful energy, supplied to satisfy the needs of the application (DHW, SH, Cooling), to non-renewable primary energy input from any energy source (electric or thermal) used within the defined system boundaries.

$$PER_{NRE} = \frac{\sum Q_{out}}{\sum\left(\frac{Q_{el,in}}{\varepsilon_{el}}+\frac{Q_{in}}{\varepsilon_{in}}\right)} \quad \text{(eq. 1)}$$

The higher the PER_{NRE} (in a magnitude of 1 to 2.5) the less non-renewable energy is used by the SHC system to cover the heat and cold demand.

The reference System $PER_{NRE,\ ref}$ is also calculated for the equal heat and cooling demand. The reference system calculation follows Napolitano et al. (2010) and has a natural gas boiler for covering the heat demand and an air-cooled VCC system for cooling. It includes a small hot water storage for domestic hot water (DHW) purposes and a cold storage volume for a smooth operation of the air cooled VCC. The T53E[4]-Tool also provides the possibility to define a specific reference case for individual assessment, but here the defined standard reference system is used.

$$\mathrm{PER_{NRE.ref}} = \frac{\sum \mathrm{Q_{out}}}{\sum\left(\frac{\mathrm{Q_{out.heat}+Q_{loss.ref}}}{\varepsilon_{in}*\eta_{HB.ref}}+\frac{\mathrm{Q_{out.cold}}}{\mathrm{SPF_{C.ref}}*\varepsilon_{el}}+\frac{\mathrm{Q_{el,ref}}}{\varepsilon_{el}}\right)} \quad \text{(eq. 2)}$$

- Non-renewable primary energy savings ($f_{sav.NRE}$)

The $f_{sav.NRE}$ compares the $PER_{NRE.sys}$ of the entire SHC system to the $PER_{NRE.ref}$.

$$\mathrm{f_{sav.NRE}} = \frac{\mathrm{PER_{NRE.sys} - PER_{NRE.ref}}}{\mathrm{PER_{NRE.sys}}} = 1 - \frac{\mathrm{PER_{NRE.ref}}}{\mathrm{PER_{NRE.sys}}} \quad \text{(eq.3)}$$

The result for $f_{sav.NRE}$ is always below 1 and shows the non-renewable primary energy savings of the SHC system compared to the reference system. A high value indicates also a high solar fraction and low energy input from fossil derived fuels. A negative value points out that the SHC system has a higher non-renewable primary energy consumption than the reference system and no savings could be achieved with the SHC system.

- Electrical equivalent Seasonal Performance Factor (SPFequ)

However, values for PER_{NRE} are not directly comparable with any widely available industry figures of merit such as the EER or SEER of a vapor compression chiller. Therefore, the electrical equivalent Seasonal Performance Factor was introduced and enables a comparison with the SEER of VCC systems or the SPF of electric driven heat pump systems. All energy flows are converted into electrical equivalent units by dividing the PER_{NRE} with the primary energy factor of electricity (ε_{el})

$$\mathrm{SPF_{equ}} = \frac{\mathrm{PER_{NRE}}}{\varepsilon_{el}} = \frac{\sum \mathrm{Q_{out}}}{\sum\left(\mathrm{Q_{el,in}}+\frac{\mathrm{Q_{in}}}{\varepsilon_{in}}*\varepsilon_{el}\right)} \quad \text{(eq.4)}$$

Economic assessment

The bases for the economic assessment are the total annual costs of the system. This is the sum of the annual costs for investment, replacement, residual value, maintenance, energy and water costs and is calculated by the T53E[4]-Tool by inserting information of the type and size of system components. If the real costs are known the tool enables the possibility to enter the specific values. The annualized costs for the entire system are calculated by using the annuity method. The calculation for investment costs are considering economy of scale prices, which means that the capacity of the components is taken into account when calculating the specific costs. The maintenance, energy and water costs are based on the consumption and are defined under the consideration of VDI 2067. All the costs (investment, replacement, residual value, maintenance, energy and water costs) are expressed in annualized costs C_{an} and summed up to the total annualized costs $C_{an.tot}$ of the SHC system. The Levelized Costs of Energy is the ratio of annualized costs and the overall annual useful energy provided to the application.

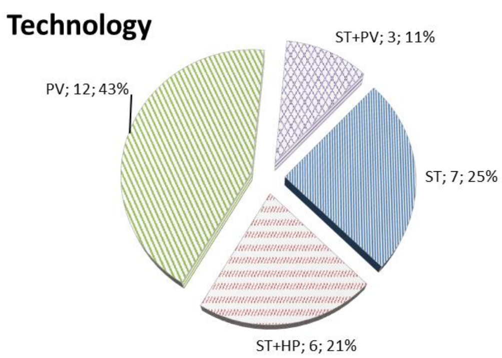
$$\mathrm{LCOE} = \frac{C_{an.tot}}{Q_{CD.sys}+Q_{DC.sys}+Q_{HD.sys}+Q_{WD.sys}+Q_{DH.sys}+Q_{el.DE}} \qquad \text{(eq.6)}$$

Since the uncertainties in cost calculation are varying, the comparison of absolute costs of different SHC systems is resigned and the economic assessment concentrates on the cost ratio by comparing the total levelized energy costs of the SHC system $C_{an.tot\text{-}SHC}$ to the total levelized energy costs of the reference system $C_{an.tot\text{-}REF}$.

$$\mathrm{CR} = \frac{\mathrm{LCOE}_{SHC}}{\mathrm{LCOE}_{REF}} = \frac{C_{an.tot-SHC}}{C_{an.tot-REF}} \qquad \text{(eq.7)}$$

3. Overview of analyzed plants

The analysed SHC systems present a great variety of different system designs and applications. The technologies are clustered according to the main component (i) PV: electrical driven and photovoltaic supported systems, (ii) ST: heat driven and solar thermal supported systems, (ii) ST+HP: electrical driven and solar thermal supported systems and (iv) ST+PV: systems supported by photovoltaic and solar thermal. The applications are clustered according to the energy demands of space heating (SH), cooling (C) and domestic hot water (DHW) and different combinations. Fig 2 gives an overview on the distribution of the 28 analysed systems.



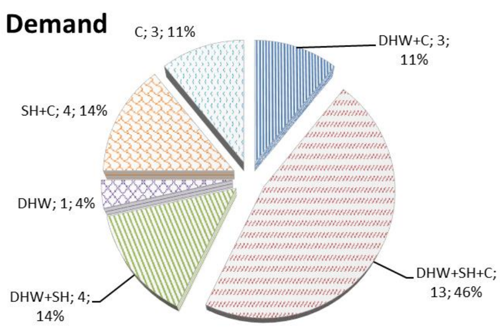


Fig. 2: Overview of chosen SHC systems for the assessment summarized by the used technology (left) and the application / energy demand (right) (Köll and Neyer in print)

The analyzed systems are dominated by small scale systems with a total heating/cooling capacity of below 10 kW (c.f. Fig 3) and hence also deliver rather small amount of energy over the year. The smaller systems in the assessment are mainly PV systems, whereas most of the solar thermal systems have an energy production of more than 100 MWh. The medium sized systems are dominated by systems using heat pump in combination with solar thermal collectors and PV systems.

An overview of the most important characteristic of all plants is displayed in Table 1, further detailed descriptions of each configuration is presented in the appendix of Köll and Neyer (in print).

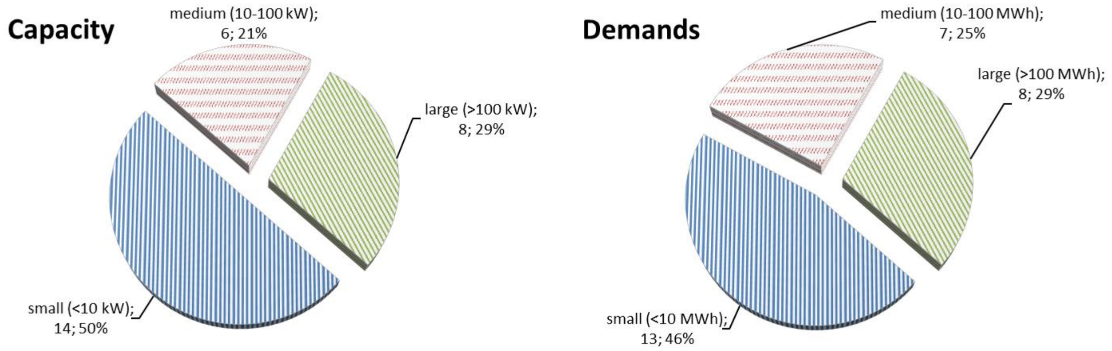


Fig. 3: Plant distribution categorized by the system heating and cooling capacity (left) and by the total yearly energy consumption (right) (Köll and Neyer in print)

Tab. 1: Characteristics of the 28 SHC system considered for the analysis

Plant #	Status	Demand		Solar			Boiler		Chiller	
	Monitored (MON) Simulated (SIM)	Type: DHW / SH / C	Energy demand (MWh)	Technology: ST / PV	Size: ST (m²). PV (kWp)	Solar fraction (%)	Type	Capacity (kW)	Type	Capacity (kW)
1a	MON	DHW C	133 / 9	ST	240	79	natural gas	70	ACM	35
1b	SIM		133 / 47	ST		64			ACM VCC	35 250
2a	SIM	DHW SH C	11 / 28 / 21	PV	4.8	21	Reversible AWHP	34	Rev. AWHP	34
2b				ST	27.6	34				
2c			11 / 25 / 8	PV	4.8	17				
2d				ST	27.6	30				
2e			2 / 5 / 3	PV & ST	9.2 & 2.4	th:49 el: 30		8		8
2f			2 / 5 / 1			th:34 el: 18				
3	MON	SH / C	17.2 / 1.8	ST	36	34	reversible AHP	24	Rev. AHP	15
4	MON	DHW	3 / 3.5	PV	0.47	71	AWHP	1.5	-	-
5	MON	SH/C	2.2	PV	0.705	54	split	3.81	split	3.52
6	SIM	SH/DHW	14.3 / 3	PV	5.7	33	air HP	5	-	-

7	MON	SH/DHW/ process heat/C	62 / 30 / 4.5	ST	100	23	wood chip boiler	100	ACM	19
8a	SIM	DHW / SH	2 / 7	ST	20	63	Brine HP	10	-	-
8b						59				
9a	SIM	DHW / SH / C	562 / 545 / 82	ST	720	35	Natural gas	500	ACM VCC	19 70
9b				PV	84.5	22			VCC	80
9c			541 / 534 / 299	ST	720	81			ACM VCC	19 100
9d				PV	84.5	35			VCC	110
10	SIM	SH / C	9 / 32	ST	111	99	Reversible air HP	61	ACM air HP	35 51
11a	SIM	C	1	PV	3.68	41	-	-	split	2.5
11b						42				
12	SIM	DHW / SH	7 / 2	PV	2.5	50	Brine HP	10	-	-
13	MON	C	2	PV	5	38	-	-	HP	10.76
14	MON	DHW/ C	2 / 0.5	PV	11.1	50	HP	10.6	free coolin g	10
15	MON	SH/C	6 / 1	ST	8	100	DEC	4	DEC	6.2
16	MON	SH/C	0.5 / 0.1	PV & ST	2.4	el:80 th: 100	DEC	2.5	DEC	1.5
17	MON	C	284	ST	406	15	-	-	ACM	500

4. Results

The systems are also compared on basis of the total annualized costs including fuel, electricity costs based on the energy production, maintenance, water and replacement costs over the whole life time of 25 years. In Figure 4 the cost distribution based on annualized costs is shown for the solar-thermal and PV-driven systems. If the data available is less than one year (for 4 plants: #13-14, #16-17) the cost distribution is not shown as it would distort the analysis. The systems are sorted according to their amount of supplied energy (demands), the more energy supplied the further right they are arranged. In general, the share of investment, replacement and maintenance (as both are calculated depended on investment) is gets less the higher the energy supplied by the system.

The main cost driver of the investigated SHC systems are the investment and energy costs. For the solar-thermal systems the fuel costs for the backup (energy carrier for heating, electricity for cooling) can get larger shares, whereas for systems combined with a heat pump (ST+HP, PV) the electricity costs are dominating.

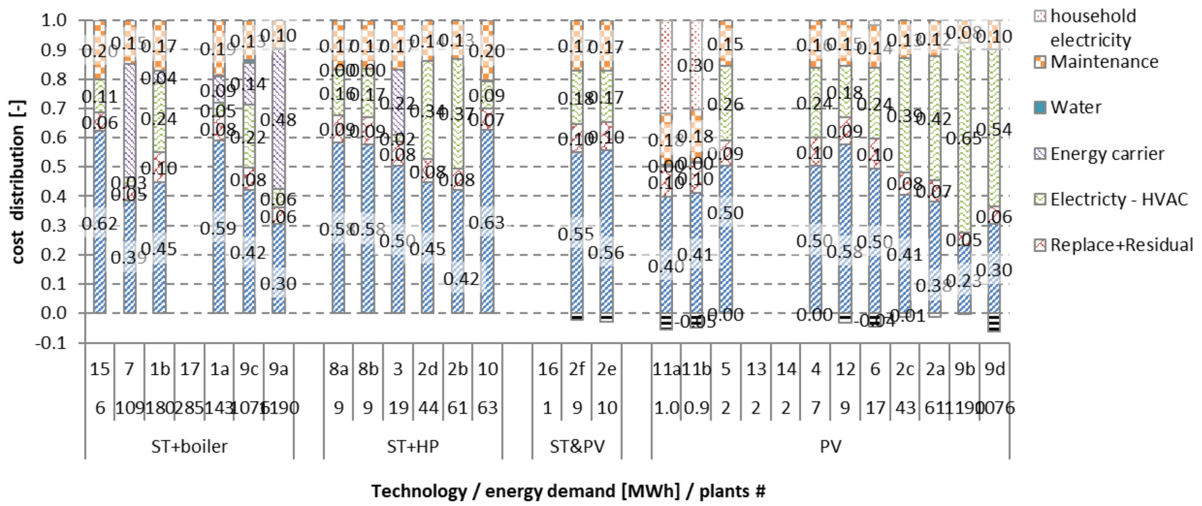


Fig. 4: distribution of total annualized cost of solar thermal supported SHC systems (Köll and Neyer in print)

The overall assessment of the technical and economic performance of the SHC systems is shown as coherence of the non-renewable energy savings ($f_{sav.NRE}$) and of the CostRatio (CR). The chart is showing the Cost Ratio in reversed order, thus the more beneficial a system the more it will appear at the top of the chart. The Cost Ratio shows the ratio between the total annualized costs of the SHC system compared to the total annualized costs of the reference system. A CR greater one indicates higher annualized costs for the SHC system and a CR lower one annualized cost savings for the SHC system. The non-renewable primary energy savings are arranged in normal order, thus the more savings a system can achieve the more it will appear at the right-hand side. The reference system is present at cero savings and a CR of one.

The comparison of the economic and technical performance of the systems shows in general that higher primary energy savings result in higher cost ratio. There are also examples showing that with a well-designed system it is possible to achieve both, high primary energy savings as well as a cost competitive system. The trend analysis of all plants shows that both, solar thermal as well as PV driven SHC systems are cost competitive at lower solar fraction and lower primary energy savings respectively. The cost ratio increases with the increase of primary energy savings. Nevertheless, it can be seen that the variation in this area is much higher and there are several examples showing also cost savings at high solar fraction.

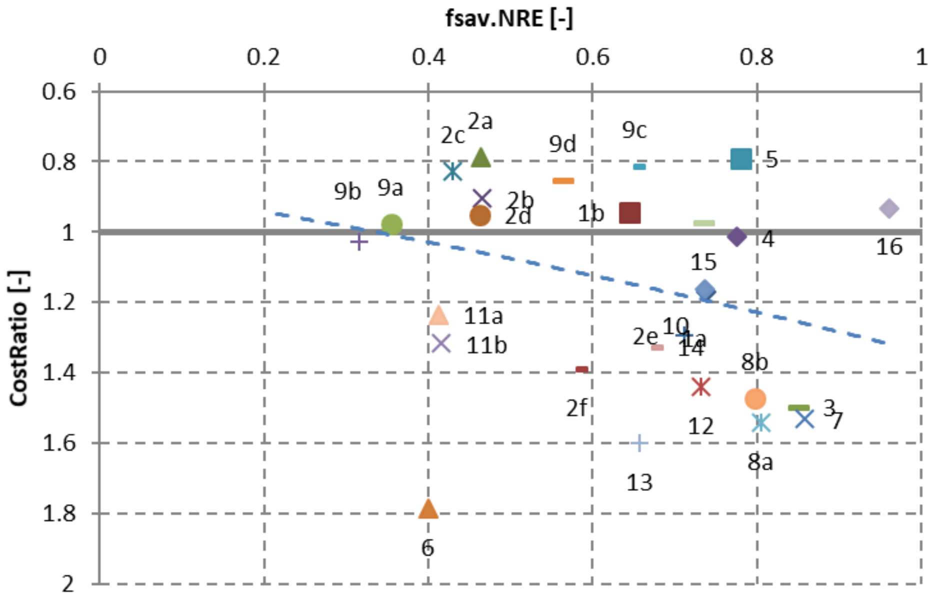


Fig 5. Cost Ratio vs. non-renewable primary energy savings of all 28 systems and the overall trend of the analyzed SHC systems (Köll and Neyer in print)

Since it is difficult to draw the right conclusion of a high number of individual systems, they are clustered by different characteristics like technology, location, application and load and compared trend wise according to their technical and economic performance. However, all presented results are based upon some predefined technical and economic boundary conditions. If one of these boundaries is changing the results might change more or less significantly. Thus, the crucial boundary conditions are evaluated with a sensitivity analysis. Accordingly, six boundaries are changed in a wide range and the results are summarized for the overall trend, and the trends for northern and southern location separated according to the underlying technology (PV or ST).

The six parameters and their range of variation are shown in Table 2. Each parameter is varied seven times in a selected range to represent a reasonable and market relevant series. The variation is given in % compared to the base case (100 %). The results of each single sensitivity analysis are discussed below accordingly.

Tab. 2: Sensitivity parameter and range of variation

Parameter	Unit / Value	Variation [%]						
		1	2	3	4	5	6	7
Investment Cost	(€/kW)	40	55	70	85	100	115	130
Electricity price	(10 ct/kWh)	50	100	150	200	250	300	350
Natural gas price	(5 ct/kWh)	50	75	100	125	150	175	200
Auxiliary demand	(kWhel)	50	60	70	80	90	100	110
Energy output	(kWhuse)	80	90	100	110	120	130	140
Conversion factor	(0.4 kWh_{el}/kWh_{NRE})	80	90	100	115	130	145	160

In the following only one example is shown, more results of the comprehensive trend and sensitivity analyses is presented in Köll and Neyer (in print). The trendlines are combining a lot of different boundaries e.g. for location or for technology, thus the following figure is combing the two categories accordingly.

The trend in Figure 6 for PV and ST are almost equal in that arrangement. For the southern location the PV trend is showing slightly lower CR, for the northern locations is reversed and ST is showing the lower CRs. The general trend for southern compared to the northern locations is very clear; showing that for southern location the CR are below one for almost all plants, whereas for the northern location only system with low savings can reach cost equity and additional cost of >40% occur when savings of 80% should be reached.

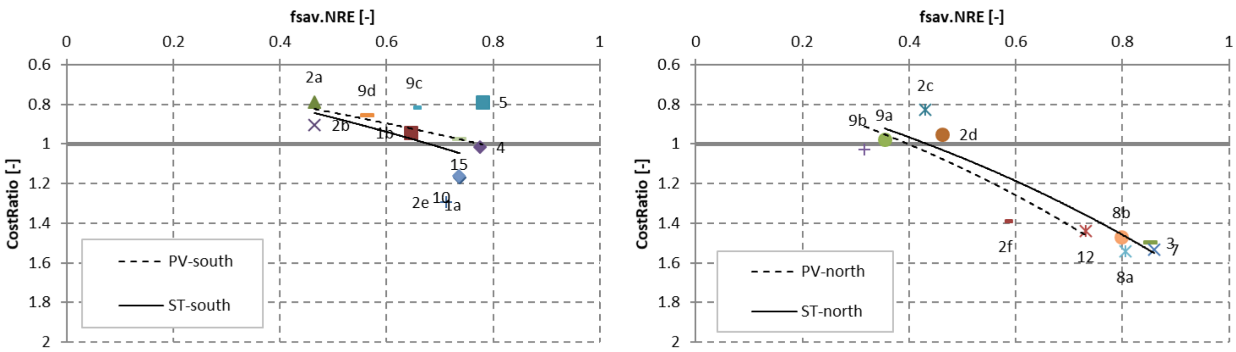


Fig. 6: Trend of the combined technology / location for southern located (left) and northern located (right) systems

A rrepresentative results of the sensitivity analysis is the variation of investment cost shown in Fig. 7. The effect of changing investment costs is larger in northern located SHC systems as they are more investment dominant compared to the southern location, were the (cooling) demand and thus the fuel costs are more important. The blue 100 % lines indicate the initial state (boundary condition).

The southern origin trend (left) starts at a CR of roughly 0.8 and reaches 1.1 for ST supported and 1.05 for PV supported systems. If the investment costs can be decreased this small advantage of PV is equalized. The trends for ST and PV equals at -15%, ST shows a small advantage at -30%. This change is pointing on the fact that ST is slightly more investment dominated compared to PV driven systems at the same level of savings.

The northern trend is representing a much stronger gradient compared to the southern locations. Its original trend starts at a CR of roughly 0.9 with savings of 30% but is ending at higher savings at a CR of 1.6. In the northern locations the PV is showing slightly higher Cost Ratio's. If the costs are reduced accordingly, the CR drops and a large part of the trendline is ending at CRs smaller than 1. The change in trendlines shows that for northern location the PV supported systems are much more investment dominated than the ST supported ones. This is especially driven by the demands (heating and cooling) and its coincidence of solar irradiation but also due to the design of the systems

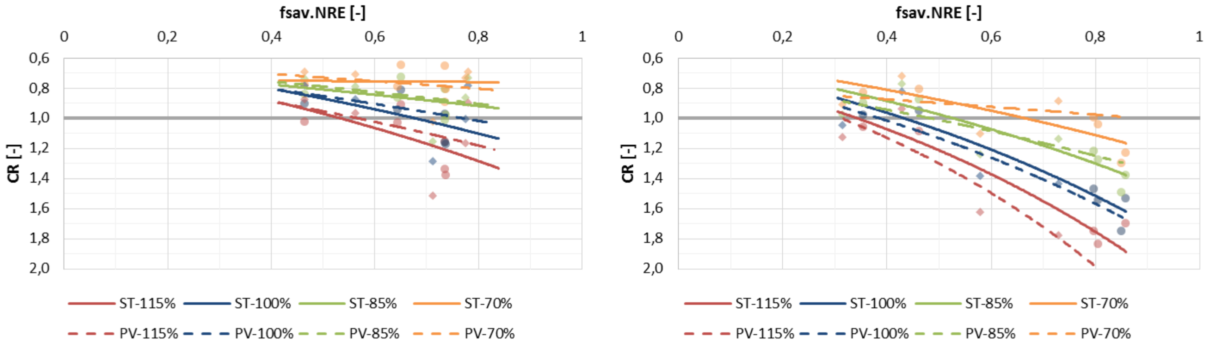


Fig. 6: Sensitivity analysis on investment cost for the southern (left) and northern (right) location separated for PV and ST (Köll and Neyer in print)

The most significant influence on economics (other sensitivity results are not shown here) is driven by the investment costs. With standard investment costs parity of levelized costs of energy (CR = 1) is reached by systems designed for less than 30% non-renewable primary energy savings. With an investment cost reduction of 15 % already systems achieving 65% savings can reach parity. If a cost reduction of 30% (not unrealistic, c.f. ROCOCO (Preisler et al. 2008) can be reached the trend line considerably undermatches a Cost Ratio of 1. Thus, the SHC systems can provide an economic benefit over its life time and can possibly assure more than high non-renewable primary energy savings.

Furthermore, a significant influence is occurring due to changes of natural gas costs used for the references systems but also in some SHC plants for backup heater. The standard price is defined to be 5 €ct/kWh, future changes in the prices depend a lot on political, economic and exploration boundary conditions and are hardly possible to be foreseen. Thus, the price is only varied in a range that is already possible due to the change from commercial to private consumers. When the natural gas costs are increased by 50% to 7.5 €ct/kWh the parity can be achieved by systems with up to 60% savings instead of 30 %.

5. Conclusion & Summary

New generation SHC systems can be very complex, since they are combining different technologies which interact and influence each other, therefore the evaluation of the complete system as well as subsystems is challenging. Within the SHC Task 53 an assessment tool (T53E4-Tool) was developed for standardized technical and economic analysis and comparison of SHC systems. The technical analysis is based on yearly or monthly energy balance, whereas for the economic analysis standardized costs and efficiencies are considered. A limited number of solar cooling installations are available that are providing monitored data and these projects often need to be considered as demos or pilot plants rather than purely commercial systems. Therefore, the economic aspects of these projects must be considered with significant care. Thus, the cost analysis of all SHC systems and of the reference system performed and presented here are based on the same assumptions.

Among the analyzed systems, the cooling capacity is in a range to be considered as small (50% <10 kW) to medium (21% < 100 kW) therefore economy of scale effect was not really achieved. However, the main matters are the entire decrease of specific component costs but also the cost distribution. The ratio between component investment and labor cost / piping / monitoring etc. is changing for small compared to large scale plants. Thus, a focus for small scale systems needs to be on easy to install and maintain systems. Air-cooled systems, either PV or ST supported, might be one option. Especially for small scale absorption chillers/absorption heat pumps the investment costs need to be decreased significantly. The implementation of the entire external piping to the chiller shows high saving potentials (installation costs). Most of the small-scale systems analyzed are PV supported systems. The main advantage using Photovoltaic panels for small scale systems is that they can be connected to heat pumps at low investment costs. A standard solar thermal supported system on the other hand requires rather large investments like a cooling tower which can only be designed in a cost-effective way when used for large systems.

The convenience of PV or ST is strictly related to the loads to be covered: if the system does not foresee a sorption device, the application of ST has the higher savings when applied to the DHW production and space heating (if the control strategies allow this mode). On the contrary, PV applications can reduce the electricity demand for cooling and, in the same way, heating and DHW preparation. PV driven systems strongly suffer from lack of long term monitoring feedback compared to ST ones, the experiences gain in the last decade in the field of solar thermal cooling (e.g. IEA SHC Task 38 and IEA SHC Task 48) are an important knowledge base.

However, solar thermal as well as PV-driven system can be cost competitive or even save costs compared to the reference system. The right choice depends on the system configuration and the effort in optimization towards the integration of the solar energy. The sensitivity analysis shows that from a summarized point of view (trend lines and sensitivity analyses for southern and northern location) both technologies are very close in technical and economic performance.

The presented technical and economic assessment of 28 plants and configurations shows that 9 plants were able to reach cost parity or CR even lower than 1 under the present boundary conditions. If boundaries are changing according to the sensitivity analysis already up to 16 plants would reach CR lower than one. Under these conditions best cases come up with CR of roughly 0.7, presenting 30% lower levelized cost of energy for the entire systems compared to the reference system!

In general, economics of SHC systems are mainly investment cost driven whereas the reference systems are dominated by the fuel costs. Therefore, SHC systems can be considered as cost efficient if they are integrated for covering baseload and in combination with conventional system for covering peak demands. Although from environmental point of view solar autonomous systems should be from highest interest, they come up with higher costs but also with higher primary energy savings.

Thus, future R&D priority should focus on investment cost reduction (materials, mass production, simplification, etc.). Minor priority, but only from an economic point of view, is required on efficiency measures. However, efficiency and respective auxiliary demand reduction can get more significant if the first priority was successful and investment costs are getting lower.

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