Sensitivity analysis on the technical and economic performance of thermal and PV driven solar heating and cooling systems

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Abstract

Solar heating and cooling is proposed to be an environmental sound alternative to conventional systems. Both, solar electrical and thermal driven systems can be a suitable solution and are currently under a controversial discussion. Therefore, the comparison of technical and economic performance of Solar Heating and Cooling (SHC) systems becomes a major issue. The assessment 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.

Ten case studies and best practice plants were analyzed and compared. All systems can achieve non-renewable primary energy savings greater than 40%, and some can show up a cost ratio lower than 1. Trend wise the PV and ST system are compared for southern and northern locations. Although the differences are rather small solar thermal seems to have advantages against PV driven systems. But in certain cases the situation is reversed and PV is advantageous.

A comprehensive sensitivity analysis on boundary conditions is showing the technical and economic performance in the same range for solar thermal and PV. Finally the analysis points out that both technologies - solar thermal and PV driven systems - can become an economic solution.

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

1. Introduction

The growing comfort demand and the increasing number of highly glassed buildings will provoke a further increase of the energy demand for cooling in future. Therefore the usage of an environmentally friendly cooling technology is inevitable. Solar cooling is an interesting alternative to conventional cooling systems when considering a significant reduction of non-renewable energy consumption. An increase on realized solar cooling systems could be observed in the past.

Solar cooling systems have a high diversity of different system designs including different cooling technologies as well as different combinations with renewable or non- renewable backups and storage tanks. In addition the systems are often designed to cover space heating or domestic hot water demand as well.

The IEA SHC Task 53 “New generation solar cooling and heating systems” is dealing with the cost effectiveness and performance of the latest solar cooling and heating systems to make them competitive on the market. (Mugnier, 2016).

One focus is on the analysis and benchmark of solar heating and cooling systems (SHC) against a reference system but also against other renewable technologies. Therefore an overview of realized as well as simulated systems in field tests or laboratory tests has been collected. The most important design issues are described and summarized. Some representative systems are selected for the detailed technical and economic analysis with a tool developed in the Task.

The T53E^4-Tool is an enhanced Version of earlier developments in IEA SHC Task 48 and enables the

doi:10.18086/swc.2017.28.15 Available at http://proceedings.ises.org

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.

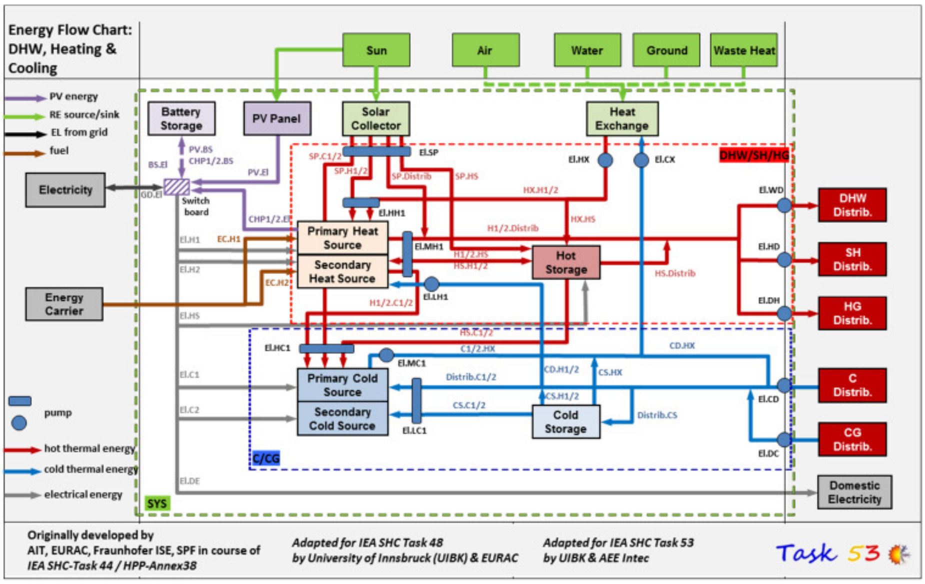

Fig. 1. Energy-flow-chart of all system components that can be taken into account for the assessment by consideration of the different subsystems in T53E^4-Tool (Neyer et al. 2016)

The main focus of the analysis is on the comparison of solar-thermal and PV driven SHC systems. In the last years more and more conventional compression chiller/heat pumps are combined with a PV system, which is less complex and difficult to control than a solar-driven system. The assessment of the plants should lead to the conclusion which system is more cost effective and can lead to higher reduction of non-renewable energy sources. A number of simulated and demonstrated systems were selected and analyzed with the T53E^4-Tool. In total 18 SHC systems are considered; their apportionment between technologies and data source is shown in Fig. 2.

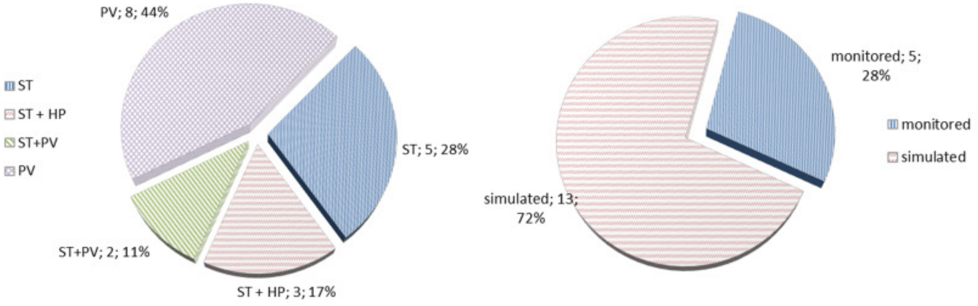

Fig.2: Overview of chosen SHC systems for the assessment summarized by the used technology (left) and the source of annual data for the assessment (right).

Eight of the selected systems are solar thermal driven systems, whereas 5 have thermal backups and 3 an electrical (HP). Eight systems are PV-driven and the remaining 2 include both, PV and solar thermal collectors. Most of the data analyzed is a result of simulation which offers the advantage to compare the same load-profile with different technologies. Five plants are in operation and the monitored data were analyzed.

Tab. 1: Nomenclature and Subscripts

ACM	Absorption chiller	in	input	Qout,cold	Useful cold
AHP	Absorption heat pump	MON	Monitored	Qout,heat	Useful heat output
AWHP	Air water heat pump	NRE	Non-renewable energy	QPV,in	Electricity from PV system
C	Cooling	out	Output	QSolar,in	Heat from solar collector
Can.i	Annualized costs of i categories	PER	Primary Energy Ratio (-)	QWD.sys	Domestic hot water demand
Can.tot	Total annualized costs	$PER_{NRE.ref}$	Non-renewable primary energy ratio of reference system	ref	reference system
CR	Cost ratio (-)	PER_{NRE}.sys	Primary energy ratio of solar system	SEER	Seasonal Energy Efficiency Ratio (-)
Ctot,ref	Total levelized costs of reference system	Q	Energy	SF	Solar Fraction
Ctot.SHC	Total levelized costs of solar heating and cooling system	QBackup	Energy from backup source	SH	Space heating
DE	Domestic electricity	QCD.sys	Cold water demand	SHC	Solar Heating and Cooling
DHW	Domestic hot water	QDC.sys	District cooling demand	SIM	Simulated
ε	Primary Energy Factor (kWh/kWh_{PE})	QDH.sys	District heating demand	SPF	Seasonal Performance Factor (-)
EC	Energy Carrier (=fuel)	Qel,ref	Electrical demand of reference system	SPFc,ref	Seasonal performance factor of cooling for reference system
el	Electrical	Qel.sys	Electricity demand	sys	Overall system (C & DHW & SH)
equ	equivalent	Qgrid	Electricity from grid	VCC	Vapour compression chiller
fsav.NRE	Non-renewable primary energy savings	QHD.sys	Heat demand	ηHB,ref	Efficiency of reference boiler
HP	Heat Pump	Qloss,ref	Heat losses of reference system		

2. Methodology

2.1 Assessment – T53E^4-Tool

The T53E^4-Tool enables a technical and an economical comparison of renewable and non- renewable systems for heating and cooling. The analysis is based on monthly energy balances of heat and electricity. For an entire assessment the values have to include annual measured or simulated energy quantities. 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.

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

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 (2011) 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.

$$\mathrm{PER}_{\mathrm{NRE.ref}} = \frac{\sum \mathrm{Q}_{\mathrm{out}}}{\sum\left(\frac{\mathrm{Q}_{\mathrm{out.heat}}+\mathrm{Q}_{\mathrm{loss.ref}}}{\varepsilon_{\mathrm{in}}*\eta_{\mathrm{HB.ref}}}+\frac{\mathrm{Q}_{\mathrm{out.cold}}}{\mathrm{SPF}_{\mathrm{C.ref}}*\varepsilon_{\mathrm{el}}}+\frac{\mathrm{Q}_{\mathrm{el,ref}}}{\varepsilon_{\mathrm{el}}}\right)} \qquad \text{(eq. 2)}$$

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

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

$$\mathrm{f}_{\mathrm{sav.NRE}} = \frac{\mathrm{PER}_{\mathrm{NRE.sys}} - \mathrm{PER}_{\mathrm{NRE.ref}}}{\mathrm{PER}_{\mathrm{NRE.sys}}} = 1 - \frac{\mathrm{PER}_{\mathrm{NRE.ref}}}{\mathrm{PER}_{\mathrm{NRE.sys}}} \qquad \text{(eq.3)}$$

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})

$$\mathrm{SPF}_{\mathrm{equ}} = \frac{\mathrm{PER}_{\mathrm{NRE}}}{\varepsilon_{\mathrm{el}}} = \frac{\sum \mathrm{Q}_{\mathrm{out}}}{\sum\left(\mathrm{Q}_{\mathrm{el,in}}+\frac{\mathrm{Q}_{\mathrm{in}}}{\varepsilon_{\mathrm{in}}}*\varepsilon_{\mathrm{el}}\right)} \qquad \text{(eq.4)}$$

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.

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

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 $C_{an.tot\text{-}REF}$.

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

2.2 Examples

The 10 examples (with extra 8 variations) included in this work are described briefly and summarized in table 2.

- Example 1, SERM (Mugnier, 2015)

The SHC system of the SERM project is realized for a building with different purposes: offices, dwelling and shops in the urban zone “Jacques Coeur” in Montpellier, France. The system provides cooling mainly for the office and shops and domestic hot water for the dwellings. The centralized system consists of 240 m² flat plate collectors, 1.5 m³ buffer storage, a single stage adsorption chiller with a capacity of 35 kW and a hybrid cooling tower (adiabatic aero-cooling device) with a capacity of 85 kW. As backup for DHW purpose a natural gas boiler with a capacity of 70 kW is installed.

- Example 2, iNSPiRe (Fedrizzi et al., 2015)

The iNSPiRe project has created a simulation data-base of performance and costs of different HVAC systems at an extensive variation of boundary conditions in the field of refurbishment. Some crucial examples are selected for the analysis. A single-family house, as well as a multi-family house, with different solar thermal collector field areas or amount of PV modules or a combination of solar thermal collectors and PV at the locations Madrid and Stuttgart are analyzed. In all cases space heating (SH), cooling and domestic hot water production is provided with a centralized air to water heat pump which is connected to a 430 l tank for DHW and SH.

- Example 3, ZAE (Sipilä et al, 2017)

Within the finish-german joint research project “Solar Heating and Cooling for Central and Northern Europe” a small scale solar thermal cooling (10 kW) and heating (24 kW) plant was installed at the Savo-Solar headquarter in Mikkeli, Finland in 2016. It is designed to supply the office building of Savo-Solar. The system consists of the main components solar-thermal collectors, vacuum insulated storage tank, dry air cooler and reversible absorption chiller/heat-pump. The main heat source for driving the chiller is a solar thermal collector field with 36 m² aperture area. A wood chip fired district heating access serves as backup heat. In summertime, cooling is done by an advanced single-effect absorption process. At insufficient solar radiation, the driving heat is provided by the heat storage or the district heating network. In wintertime the system works as thermal driven heat pump, using the biofuel fired district heat to upgrade ambient heat to a useful temperature level.

- Example 4, UMH DHW (Aguilar et al., 2016)

In this example an air to water heat pump is used for the preparation of domestic hot water with a nominal heating capacity of 1.5 kW. The electricity consumption of the heat pump is covered by two PV modules with 470 Wp or electricity from the grid. The system also includes a buffer tank of 190 l and is located at the university in Elche, Spain. The DHW demand is 6.26 kWh/d distributed in 6 extractions.

- Example 5, UMH HVAC (Aguilar et al, 2017)

A PV-driven HVAC system is realized in an office with a heated/cooled area of 35 m² in Alicante, Spain. The inverter air-conditioner is used to cover the cooling and space heating demand of the office. The cooling capacity is 3.52 kW, whereas the heating capacity is 3.81 kW. It is connected to three PV panels with 705 Wp as well as to the grid to provide the necessary electricity consumed by the HVAC system. The indoor temperature was set to 23°C in cooling mode and the relative humidity was not controlled.

- Example 6, Högskolan Dalarna (Psimopoulos et al. 2016)

The simulated house is a typical Swedish single floor, single family house with a heated area of 143 m² placed in Norrköping. A variable speed, exhaust air heat pump (HP) with a capacity of 5 kW delivers heat both for SH and DHW. A hot water storage tank of 180 litres is used for DHW. If the heat from the HP is not sufficient an electrical auxiliary heater with a power of 6.5 kW is turned on. The system also includes a 5.7 kWp PV System and lithium-ion battery storage with a capacity of 7.2 kWh.

- Example 7, AEE INTEC (Fink, 2011)

The SHC system is applied for heating, domestic hot water and cooling of a small juice producer. The heat is produced by 100 m² of double-glazed flat plate collectors and as a backup-heater a wood chip boiler with a capacity of 100 kW is used. The heat is stored in a 20 m³ buffer storage and connected to a single-stage absorption chiller with a capacity of 19 kW and a dry cooling tower with a capacity of 50 kW. The chilled water is used for the juice refrigeration only. If no cooling is needed the heat is used for the juice production process, for DHW preparation or to cover the space heating demand of the residential house next to the juice production.

- Example 8, TheBat (Thür et al., 2016)

In the project "TheBat" a single family house located in Innsbruck is simulated with different control concepts with the goal to maximize the PV-self consumption by using a heat pump and the available heat capacities in the building as "thermal battery". The chosen example is covering the space heating and domestic hot water demand with a brine heat pump with a thermal capacity of 10 kW. The HP can charge a water storage (TES) or directly heat the building via thermal activated building structure (TABS). The heat pump is controlled by matching the compressor speed to the available power of the PV and store the produced heat preferably in the TABS or the TES. First, the electricity from the PV is used for running the HP, the remaining electricity is fed into the grid (no household electricity consumption is considered in the simulation studies).

- Example 9, SolarHybrid (Neyer et al 2016a)

In the project SolarHybrid a solar thermal and PV driven HVAC system for a hotel located in Innsbruck and Sevilla is simulated. The cooling of the hotel is provided by a vapour compression chiller (VCC) in combination with an ammonia/water-absorption chiller (ACM). A solar thermal (ST) driven system is compared with a PV supported system. The ST feeds a hot water storage tank, which is used to ensure the heat supply and operation of the ACM. A natural gas backup boiler is used for DHW and SH only. The ACM is used to cover the base load (19 kW) and the conventional VCC (70 kW) covers the remaining demand using grid electricity. Both refrigerators operate with dry back-cooling. The PV supports the heat pump, which operates reversible and feeds the hot water storage tank for domestic hot water and a cold water storage. A PV area, which is designed exclusively for the operation of the reversible HP complements the system.

- Example 10, Yazaki (Inagaki et al. 2017)

The passive house office is located in JINAN in P.R.China, a humid continental climate. The thermal energy for the solar collector fields of 110 m² is stored in a 5 m³ hot water tank. In summer case the heat is used to run the absorption chiller (WFC10) with 35 kW nominal capacity and the heat is rejected via a wet cooling tower. The chilled water is stored in a 1.5 m³ tank and complemented by a reversible air-water electrical heat pump. The energy is delivered into the rooms over a radiant ceiling and the ventilation unit. The ventilation unit includes a heat recovery system, a pre heating/cooling coil, a 20 kW air-air heat pump as backup and the re-heating coil.

A summary of the most important information of the plants is shown in Tab. 2. The solar fraction should give a hint weather the plants are designed for full load (100%) or base load (<30%) only. The solar fraction for thermal (SF_{th}) or PV-driven systems (SF_{el}) is calculated according to Eq. 8 and Eq. 9 respectively.

$$SF_{th} = \frac{Q_{solar,in}}{(Q_{solar,in} + Q_{backup})} \quad \text{(eq. 8)}$$

$$SF_{el} = \frac{Q_{PV,in}}{(Q_{PV,in} + Q_{grid})} \quad \text{(eq. 9)}$$

Tab. 2: examples analyzed with T53E4 Tool

Plant #	**Status**	**Demand**		**Solar**			**Boiler**		**Chiller**	
	Monitored (MON) Simulated (SIM)	Type: DHW / SH / C	Energy demand (MWh)	Technology: ST / PV	Size: ST (m²), PV (kW_p)	Solar fraction (%)	Type	Capacity (kW)	Type	Capacity (kW)
1	MON	DHW C	133 / 9	ST	240	74	natural gas	70	ACM	35
2	SIM	DHW SH C	11 / 28 / 21	PV	4.8	5	Reversible AWHP	34	Reversible AWHP	34
2a				ST	27.6	39				
2b			11 / 25 / 8	PV	4.8	25				
2c				ST	27.6	46				
2d			2 / 5 / 3	PV & ST	9.2 & 2.4	th:58 el: 54		8		8
2e			2 / 5 / 1			th:56 el: 40				
3	MON	SH / C	17.2 / 1.8	ST	36	32	reversible AHP	24	reversible AHP	15
4	MON	DHW	3 / 3.5	PV	0.47	35	AWHP	1.5	-	-
5	MON	SH/C	2.2	PV	0.705	42	split	3.81	split	3.52
6	SIM	SH/DHW	14.3 / 3	PV	5.7	27	air HP	5	-	-
7	MON	SH&DHW/ process heat/C	62 / 30 / 4.5	ST	100	25	wood chip boiler	100	ACM	19
8	SIM	DHW / SH	2 / 7	PV	2.5	49	HP	10	-	-
9	SIM	DHW / SH / C	562 / 545 / 82	ST	720	35	Natural gas	500	ACM VCC	19 70
9a				PV	84.5	27			VCC	80
9b			541 / 534 / 299	ST	720	66			ACM VCC	19 100
9c				PV	84.5	52			VCC	110
10	SIM	SH / C	9 / 32	ST	111	45	Reversible air HP	61	Reversible air HP	51

3. Results

A wide variety of SHC systems is included in the assessment. Systems with different heating and cooling technologies, with different capacities, with simulated and monitored data base as well as a mixture of cooling, space heating and domestic hot water application were selected. An overview of the selected systems on basis of the total capacity and the type of heat source technology is shown in Fig. 3:

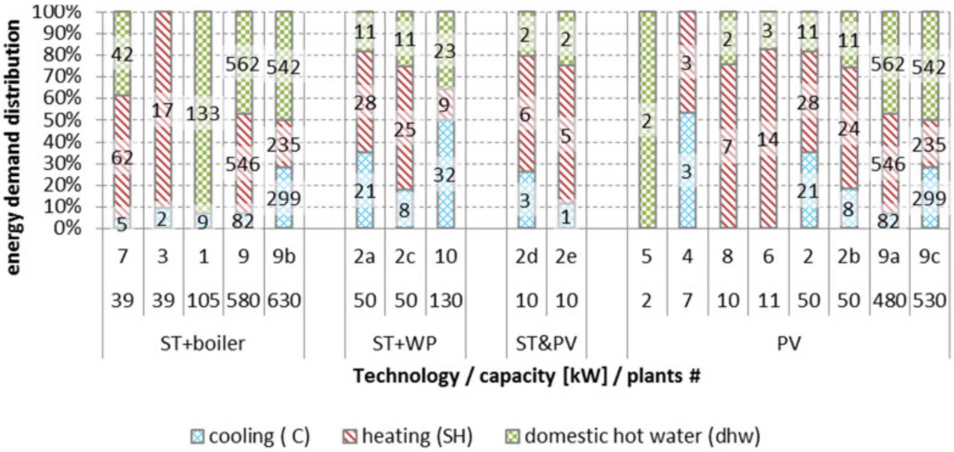

Fig.3: distribution of annual energy demand between cooling (C), heating (SH) and domestic hot water (dhw); numbers in the bars are in MWh; arranged according to the Technology used and total installed heating and cooling capacity (kW)

Seventeen systems include DHW demand, fifteen systems include cooling and sixteen systems include SH. In total eleven systems cover all three demands: SH, DHW and cooling. There is also a wide spread in the size of the systems. The total installed heating and cooling capacity of the systems is between 2 kW and 630 kW, but more than half of the systems are in the range between 10 kW and 130 kW. The graph also illustrates the total yearly energy demand in MWh. Whereas the smallest system covers a heat demand of 2 MWh/y the highest total energy demand which is covered by a system is 1190 MWh.

The base of the economics is presented in Figure 4 by showing the specific investment cost of the entire system and the related reference system. The ratio of investment ($\text{Invest}_{\text{SHC}}/\text{Invest}_{\text{REF}}$) is calculated and shown in connection with the achieved non-renewable primary energy savings ($f_{\text{sav.NRE}}$).

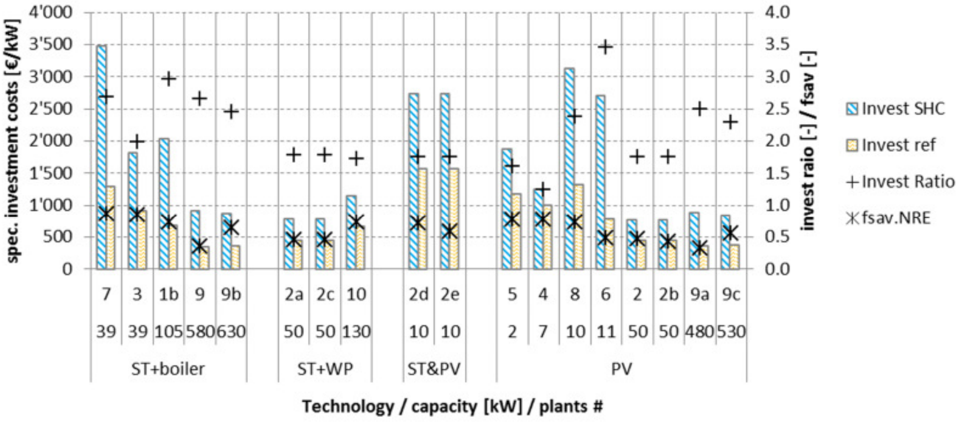

Fig.4: specific Investment costs for each SHC plant and corresponding reference system according to T53E4 Standard (left axis); Investment ratio (SHC/REF) and non-renewable primary energy savings (right axis); arranged according to the Technology used and total installed capacity (kW);

All costs are compiled with the Task 53 Standard values. Trend wise the smaller systems and those with higher savings show higher absolute investment costs and higher investment ratio. But both values are further influenced by the design (size of components, storages…) and the choice of components (HP vs. boiler, etc.). Comparing ST and PV systems produces an equal picture. Roughly half of the plants present investment costs higher 1’500 €/kW, the other half costs below 1’000 €/kW.

The investment is usually the main cost factor, but the total cost also include cost for replacement, electricity, energy carrier, water, maintenance and for grid connected PV systems the feed-in remuneration. The total annualized cost distribution of all systems is shown in Figure 5. The more energy a system is providing the higher the ratio of energy costs; the smaller the system the huger is the ratio of investments. The ratio of investment costs varies from roughly 30% up to almost 60%; if replacement costs are considered the ratio related to investment adds another 5-10%. Maintenance cost ratios are slightly higher for the solar thermal driven system compared to PV supported system. A high PV self-consumption can be observed in almost all system thus the feed-in remuneration does play a minor role.

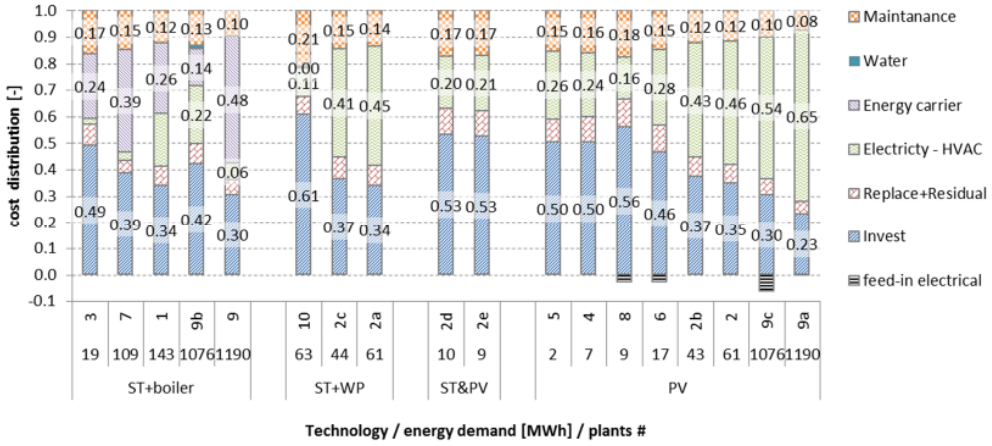

Fig.5: annualized cost distribution for each SHC plant; the fraction for investment, electricity, energy carrier and maintenance are stated in the bars; arranged according to the Technology used and total energy demand (MWh)

Figure 6 presents the summary of non-renewable savings in relation to the entire costs, expressed as CostRatio (CR). Each plant is represented as individual dot. The CR is displayed in reversed order thus the more cost effective and the higher the savings the more the results appear in the upper right side. Further 4 trend lines are drawn summarizing the results technology and location wise.

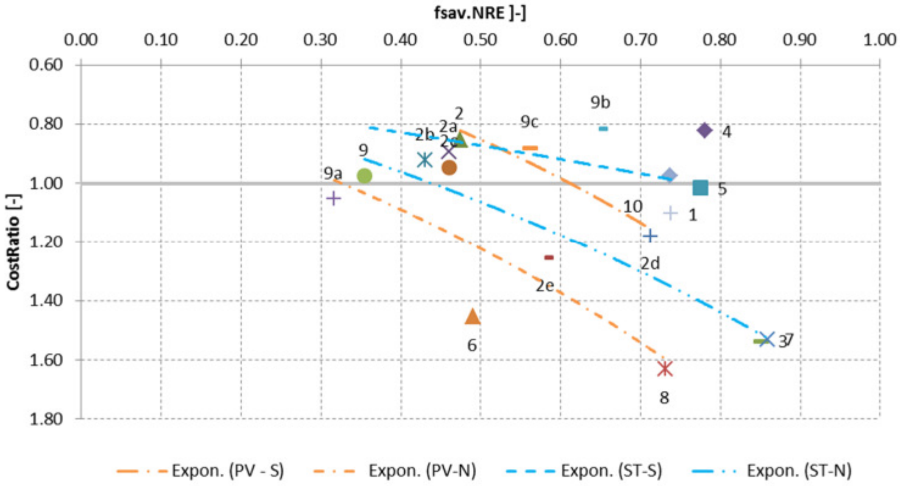

Fig.6: CostRatio (CR) in reverse order vs. non-renewable primary energy savings ($f_{sav.NRE}$); cluster in four groups (i) PV supported system in southern climate (PV-S), (ii) PV system in northern climates (PV-N), (iii) solar thermal supported system in south (ST-S), (iv) solar thermal system in north (ST-N)

The clustering for the trend lines of the results is arranged in the following order (i) PV-S: #2, #2d, 9c; (ii) PV-N: # 2b, #2e, #6, #8, #9a; (iii) ST-S: #1, #2a, #9b, #10; (iv) ST-N: #2c, #3, #7, #9. Only plant #4 and #5 cannot be clustered as they are a not comparable in size and technology used. The quantity of examples is not high enough to dare on the trend lines; nevertheless they can be used for general statements and to show the results of the sensitivity analysis.

Considering the cost ratio, it can be seen that the majority of systems can compete with a conventional system or are even more cost efficient. The most effective plants are PV driven #4, #5 and ST driven #9b, #10 and #1. They represent a good relationship of cost and savings. All these plants have a year around solar usage and either a low investment ratio (small plants) or a low share of investment costs of total annualized costs. ST systems in north and south represent more even gradient than the PV driven systems. The southern locations represent more efficient (higher savings) and more economic (higher solar yield) systems. In southern location the trend lines cross each other, in the northern location the trend line of ST reclines higher. This indicates that solar thermal at the same saving is cheaper than PV or at the same CostRatio the solar thermal can reach higher saving. This might be true as a general finding but individual example (especially #2) show reversed conclusions. Thus the trend line and their interpretation should be used with care!

The question arises whether the chosen boundary conditions are affecting the results or if the design and location is more important. Thus a sensitivity analysis was performed and the effect is shown by means of the shift of the trend lines. The parameters that are varied are the total investment costs (40%~130%), the electricity price (50%~350%), the natural gas price (50%~200%), the conversion factor for electricity (80%~140%) and the electrical efficiency of the systems (90%~200%). As not all results can be presented in this paper two (investment costs in Fig. 7 and electrical efficiency in Fig.8) are selected and discussed here, all other will be published in the course of IEA SHC Task 53.

The result of the sensitivity analysis on investment costs is shown in figure 7 in two diagrams separated according to the location. The results for ±15% of the initial costs are presented in figure 7 in red (+15%) and in blue (-15%). It is obvious that if the costs are dominated by investments the CostRatio will response more intense than if the investment costs ratio is smaller. The analysis will only affect the CostRatio, the non-renewable primary energy savings keep unaffected.

In the northern locations (Fig 7. left) the +15% in solar thermal and -15% in PV systems are overlapping strongly and the results get equal. The same behavior occurs in the southern locations. If the investment costs are changed in the same direction (e.g. -15%) in norther location the difference gets smaller (PV is more investment driven), in the southern locations the difference gets larger (ST is more investment dominant). The effect of minus 15% can take shape in a magnitude of -5 to 20 %points in the CostRatio

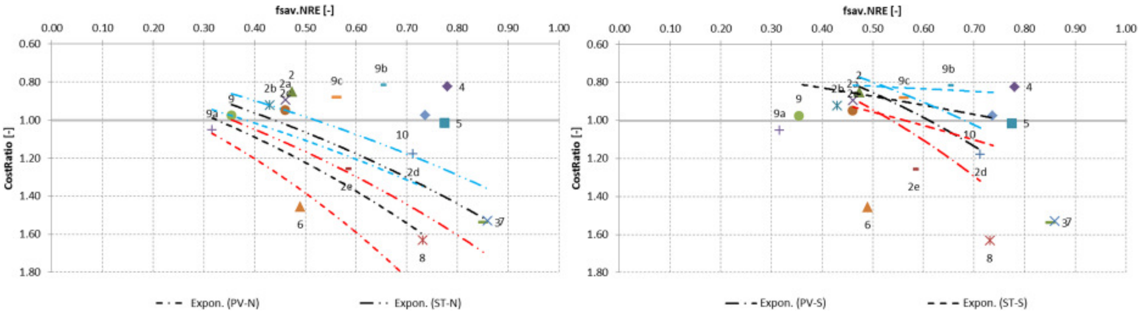

Fig.7: sensitivity analysis on investment costs; +15% investment in red; -15% investment in blue; for northern located system (left) and south located system (right)

The sensitivity analysis on the electrical efficiency of the systems is shown in figure 8. The electrical efficiency is changed by changing the total grid electricity drawn by the entire system. The effect is shown for +25% (red) and for +40% (blue). It is obvious that if the system is electricity driven and the larger the electricity costs ratio is, the more sensitive a system will be. The sensitivity analysis will affect the cost ratio (lower electricity cost) as well as the non-renewable primary energy savings.

For both locations the gap between PV driven and solar driven system gets smaller. Even with (probably unrealistic) 40% efficiency increase the solar thermal systems keep upfront the PV systems. In general the lower efficient systems (lower $f_{sav.NRE}$) benefit more than the already high efficient systems. Thus curves shift to the right and the gradients get steeper. If the efficiency could be increased by 25% the savings increase by a factor of 10 to 15%points, the CostRatio keeps almost unaffected (up -5%points).

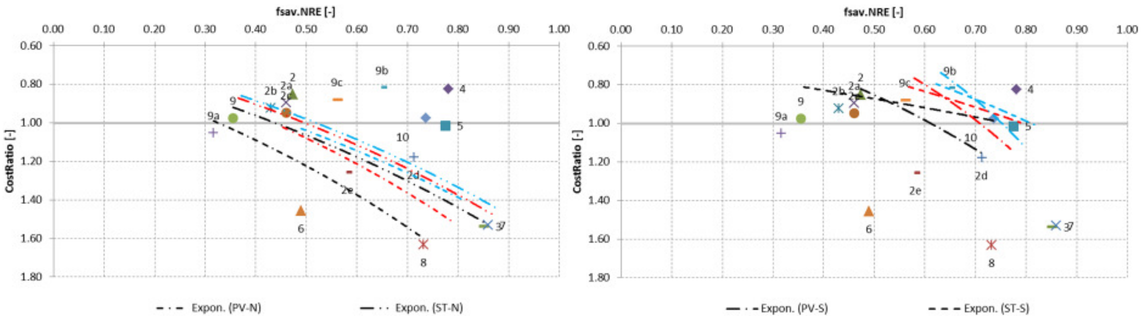

Fig.8: sensitivity analysis on electrical efficiency changes (+25 % red lines; +40% blue lines) for northern located system (left) and south located system (right)

The other sensitivity analyses are showing a similar picture. Decreasing costs lead to lower CostRatio's increasing the efficiency increases the non-renewable primary energy savings and reduces the CostRatio. The natural gas costs effects all system as the reference system is a natural gas boiler. Within a reasonable change of boundary conditions (±20~30%) the magnitude of change in key figures can be expected in the range presented within the two analyses.

Overall it falls into place that with a clever design and a decrease of investment costs the solar technologies are already less expensive than a conventional system for heating and cooling applications or can reach cost equity with minor effort.

4. Summary & outlook

A comprehensive tool was developed in the course of IEA SHC Task 53 and is available for the analysis and assessment of new generation of solar heating and cooling systems. The key figures that are calculated allow a benchmarking and simplify the comparison of different system configurations. The T53E^4-Tool can be used to benchmark against a standardized reference systems or against other renewable heating and cooling technologies. Still, the comparability is challenging if applications and configurations are mixed. Nevertheless, a trend wise comparison of magnitudes can definitely be achieved. The T53E^4-Tool is expected to be published in 2018.

The methodology presented is based on monthly energy balances and focusing on non-renewable primary energy. Thus the results are depending on the non-renewable primary energy conversion factors which depend on the season (summer / winter), daytime (peaks), on political decision (balancing methods) and the repercussion of the entire system on factors itself. Future developments of costs but also primary energy conversion factors are difficult to forecast. Thus a sensitivity analysis on the influencing boundary conditions should be performed anyway.

A majority of the systems can be classified as small or medium scale systems. The economics are investment dominated and the electrical or thermal efficiency is of minor order. Nevertheless a high efficiency is essential for acceptable non-renewable primary energy savings, being aware that the efficiency or technology of the reference system will change in future.

The southern locations represent more effective (higher non-renewable primary energy savings) and more economic systems mainly due to higher solar yields. Southern examples can already reach CostRatio's below one. Accordingly the systems are cost competitive compared to the standard reference system calculated within the T53E^4-Tool.

Summarizing the comparison of ST and PV driven system expresses a clear conclusion that ST is more effective at lower costs. Nevertheless the difference is probably within the uncertainties and when changing the boundary conditions accordingly the results are overlapping. In the end the advantage of the one or other technology is depending on local conditions, the design of the plant and its control strategies. Both Technologies can be optimized intensively to become cost competitive and an attractive alternative compared to conventional heating and cooling systems.

5. Acknowledgment

The Austrian part of the IEA SHC Task 53 is carried out within the framework of the IEA research co-operation on behalf of the Austrian Ministry of Transport, Innovation and Technology.

A special thanks to all Task 53 participants that provided examples with monthly and annual energy data and their agreement for the usage of the data for assessment, benchmarking and publication. In particular to:

- TECSOL – Daniel Mugnier
- EURAC – Chiara Dipasquale and Roberto Fedrizzi
- ZAE Bayern – Richard Schex and Martin Helm
- Universidad Miguel Hernandez – Pedro G. Vicente Quiles
- University Högskolan Dalarna – Emmanouil Psimopoulos and Chris Bales
- University of Innsbruck – Alexander Thür
- YAZAKI Energy Systems – Wei Zheng

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