SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Monitoring data analysis on technical issues & on performances

IEA SHC TASK 53 | NEW GENERATION SOLAR COOLING & HEATING SYSTEMS (PV OR THERMALLY DRIVEN)

Monitoring data analysis on technical issues & on performances

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1. Introduction

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.

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.

These objectives of IEA SHC Task 53 are tackled through following five activities (Mugnier, 2016):

1. Investigation of new small to medium size PV & solar thermal driven cooling and heating systems, as well as development of best suited cooling and heating systems technology with a focus on reliability, adaptability and quality.
2. Demonstration of cost effectiveness of the above mentioned solar cooling and heating systems.
3. Investigation on life cycle performances on energy and environmental terms (LCA – Life Cycle Assessment) of different options.
4. Assistance with the market deployment of new SHC systems for buildings worldwide.
5. Increasing energy supply safety and influencing the virtuous demand side management behaviours.

A special focus of the SHC Task 53 is on tested and demonstrated systems (Subtask C). The aim is to analyse 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. An overview of the available systems is prepared within the activity C2 “system descriptions for field tests and demonstration projects” (Neyer et al., in print, 2018).

Representative solar cooling systems are selected which will be analysed within activity C3 “Monitoring data analysis on technical issues & on performances” in detail and summarized in this deliverable. The systems are analysed on technical and economical basis with the developed T53E4-Tool (Neyer et al., 2016), which enables the assessment and benchmarking of the different SHC but also references system.

The main aim of this activity is to

(i) compare the system performance and costs against standard reference systems but also
(ii) to analyse the difference of solar thermal and PV-driven cooling and heating systems.
(iii) and to gain a comprehensive insight on boundary conditions of the assessment and their main results
(iv) to deviate rules of thumb for design and operation to support the development of efficient, reliable, and cost competitive SHC systems.

2. Overview analyzed plants

The SHC systems present a great variety of different system design 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. Figure 1 gives an overview on the distribution of the 28 analysed systems, more details are listed in Table 1 and a detailed description of each plant and its performance can be found in chapter 4.

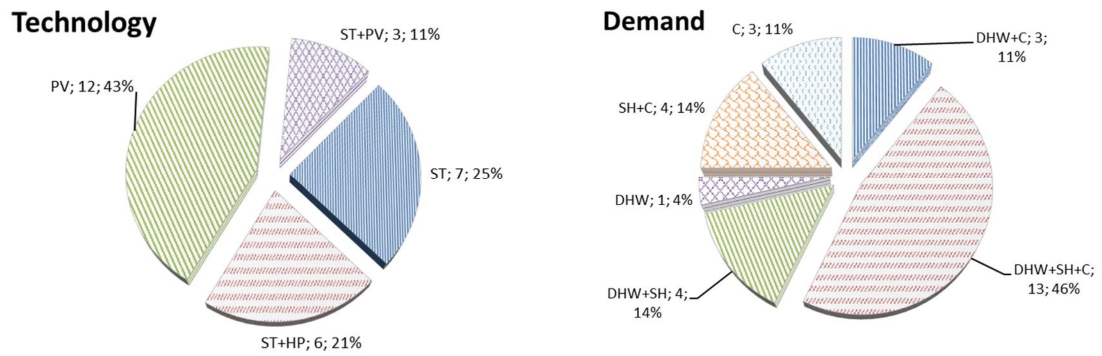


Figure 1: Overview of chosen SHC systems for the assessment summarized by the used technology (left) and the application / energy demand (right)

Roughly half of the SHC systems use a solar thermal collector (13, 46%) to support the HVAC system. Six use the solar thermal system in combination with an electrical driven heat pump, another seven ST systems are used in combination with thermal backup's. Twelve of the analysed systems are PV (43%) supported systems and another three (11%) use both technologies, solar thermal collectors and PV.

The majority of the systems has more than one energy demand, most often the systems apply for a combination of all three demands (DHW+SH+C; 46%), another seven apply for a combination with domestic hot water (three DWH+C – 11%, four DHW+SH -14%), the combination of cooling and space heating also appears four times (14%). Only four SHC plants serve for a single demand of cooling (three, 11%) and domestic hot water (one, 4%).

The analysed systems are dominated by small scale systems with a total heating/cooling capacity of below 10 kW (c.f. Figure 2) and hence also deliver rather small amount of energy over the year of below 10 MWh. 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 (c.f. Figure 3). The medium sized systems are dominated by systems using heat pump in combination with solar thermal collectors and PV systems.

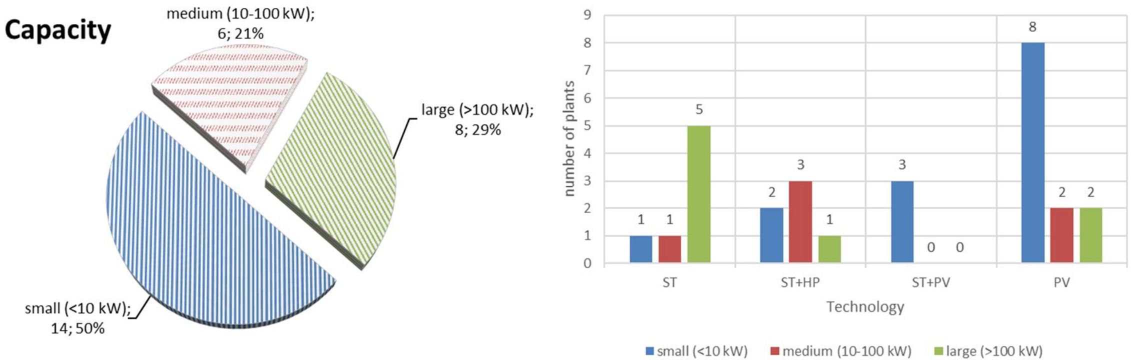
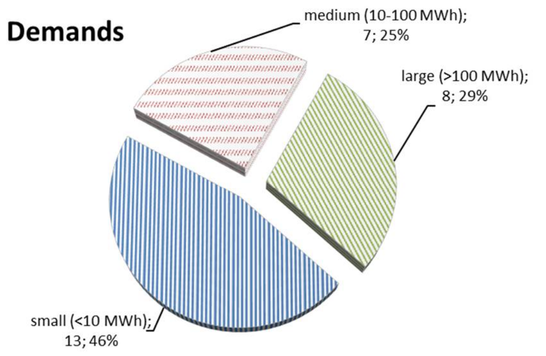


Figure 2: Plant distribution categorized by the system heating and cooling capacity



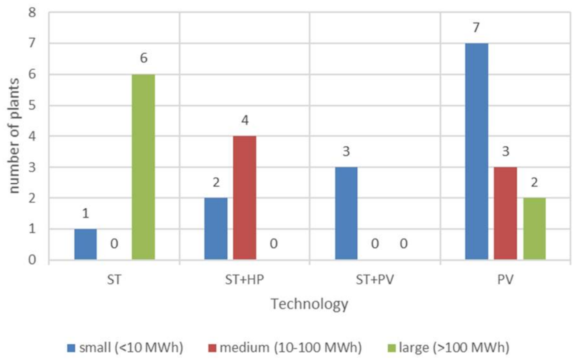


Figure 3: Plant distribution categorized by the total yearly energy consumption

Figure 4 is showing the differentiation of the analysed plants into their design and data available for the analysis. Typical designs can be grouped into full load or base load and is summarized as solar fractions. 18% of the systems are design for typical base load with solar fractions <30%. The majority (17, 61%) is designed for moderate solar fraction (still base load). Six systems (21%) reach the upper limit of solar fraction >70% and can be treated as full load design, whereas three (11%) of them are designed for solar autonomous operation.

The calculation of the solar fraction needs to be distinguished between electricity or thermal based systems. The solar fraction for thermal based systems is calculated as solar input divided by solar + energy carrier input. If solar thermal is supporting an electrical driven heat pump, the thermal input of the heat pump is used to calculate the solar fraction. For PV supported systems the PV yield less the grid feed in is divided by the overall grid + PV electricity used for the HVAC system.

The data available for assessment is crucial especially for the economic analysis. Only if data of one full year is available the calculation of levelized cost of energy and derivative economic key figures is reasonable. 24 (86%) of the plants can provide this annual energy balances and data. The remaining four systems (14%) are only analysed under technical considerations, although the comparison of the technical key figures might lag because of profitable boundary conditions under the period.

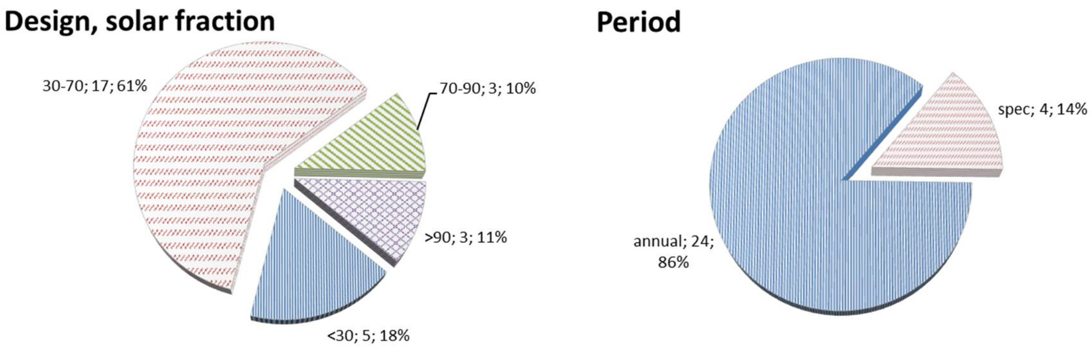


Figure 4: Overview of chosen SHC systems for the assessment summarized by the used design, solar fraction in % (left) and the period under consideration of monitoring or simulation (right)

Simulated and monitored systems are analyzed in this assessment study. Nine systems (32%) are already built and in operation and thus monitored data is available. The majority of nineteen system (68%) are theoretical results of simulations.

Half of the systems are located in more northern climates and half in more southern sites.

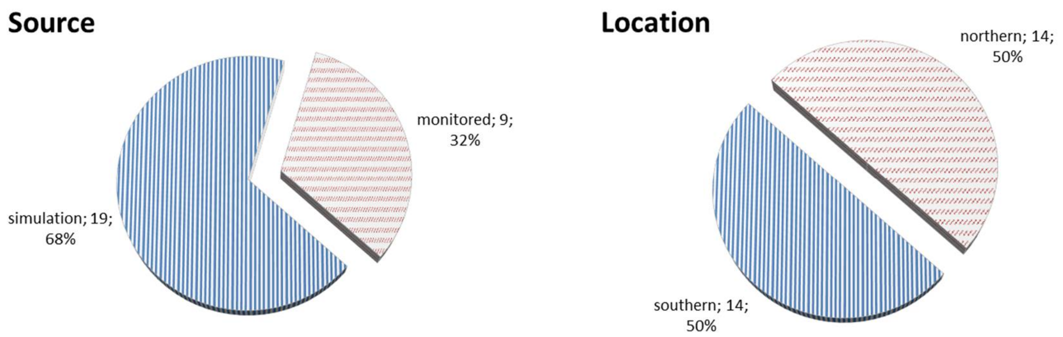


Figure 5: Overview of chosen SHC systems for the assessment summarized by the source of data (left) and location (right)

The overview of the most important characteristics of all 28 SHC systems is shown in Table 1. It appears that 17 different system are analysed but overall 28 configuration or cases were analysed. The derivative systems are number by lowercase letters accordingly.

Table 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 (m^2). PV (kW_p)	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	Reversible 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	reversible 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				

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)
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 cooling	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

Figure 6 is showing the relative distribution of energy demands that were satisfied by the SHC systems. The figure is arranged according to the technologies (cf. Figure 1) and ordered by increasing capacity (from left to right). The corresponding plant number and the absolute energy demand (in MWh) are shown on the x-axis and the bar caption accordingly.

In general, it can be seen that the larger systems typically satisfy more than one and often more than two different demands. Contrary smaller systems are often designed for only one single application. The majority of the larger systems are solar thermal supported systems using hot backups (boiler). None of the PV supported but also of heat pump-based systems serves for more than 60 MWh, on the other hand seven of eight ST systems covers more than 100 MWh of energy demands.

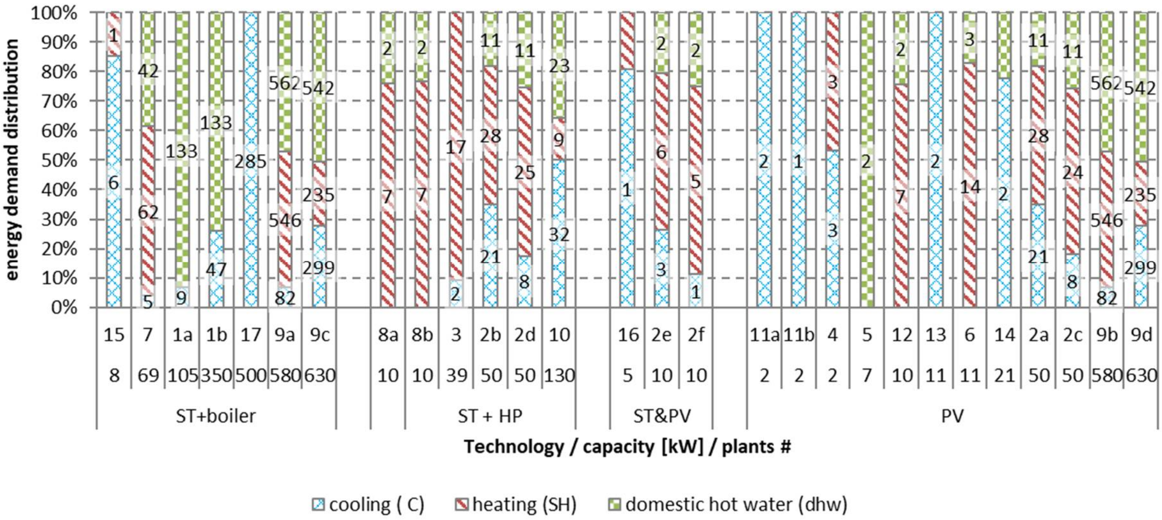


Figure 6: Relative distribution of energy demands satisfied by the SHC systems arranged according to their basis technology and capacity. Numbers in the bar refer to the absolute energy [MWh] delivered by each system.

3. T53E4 Tool: Assessment / benchmarking – Methodology

Assessing the performance of different SHC systems, in a common comparable format, is complicated by the numerous applications (e.g. space heating – SH. domestic hot water – DHW and cooling), alternative energy sources and design possibilities. Furthermore, there are a number of different energy units with different thermodynamic or greenhouse gas emissions implications (e.g. primary energy. thermal energy and electrical energy). An evaluation procedure can be applied across a number of alternative system boundaries. These system components are interacting with each other and influencing the system performance.

To analyse the system performance and perform a comparison between completely different system designs and sizes a holistic analysis is necessary. Therefore, an evaluation tools, named T53E^4-Tool (Task 53 Energy-Ecology-Economy-Evaluation-Tool), was developed within the SHC Task 53 (Neyer et al., 2016) for assessing solar cooling and heating systems on technical and economic level based on monthly energy balances. The tool is based on prior work of IEA SHC Task 38 (Napolitano et al., 2010; Fedrizzi et al., 2012), IEA SHC Task 44 ((Malenkovic et al., 2013) and IEA SHC Task 48 (Neyer et al., 2015).

The T53E4-Tool assessment is based on energy balances provided by simulations or monitored data on monthly and yearly basis. It provides a wide range of fundamental data for several technologies and components such as efficiencies, investment and maintenance cost but also country specific information like energy prices and primary energy conversion factors. A wide variety of sources such as PV, solar thermal collectors, natural gas boilers, heat pumps, pellet boilers or even district heating as well as different cold sources such as compression chillers, district cooling, absorption or adsorption chillers and cooling towers can be considered. It also includes information about hot and cold as well as battery storages.

Furthermore, the energy flows and system layouts are defined by including the different energy quantities that are transferred from one to the other component. An overview across possible component connections is shown in Figure 7 illustrated as energy flow (EF) chart. This EF-chart, that can be simplified according to the entire system and its layout and provides an overview of traded (non-renewable) energy, renewable sources and energy demands. Defined key performance indicators are calculated for the overall system but also for subsystems to have a better understanding and comparison of the different systems.

A wide range of key performance indicators for evaluating technical and economic, quality and cost effectiveness are fully discussed and defined in the IEA SHC Task 48. For simplicity, only the main key figures are referenced in this paper. Generally, more than one metric will be required to capture a complete picture of system performance.

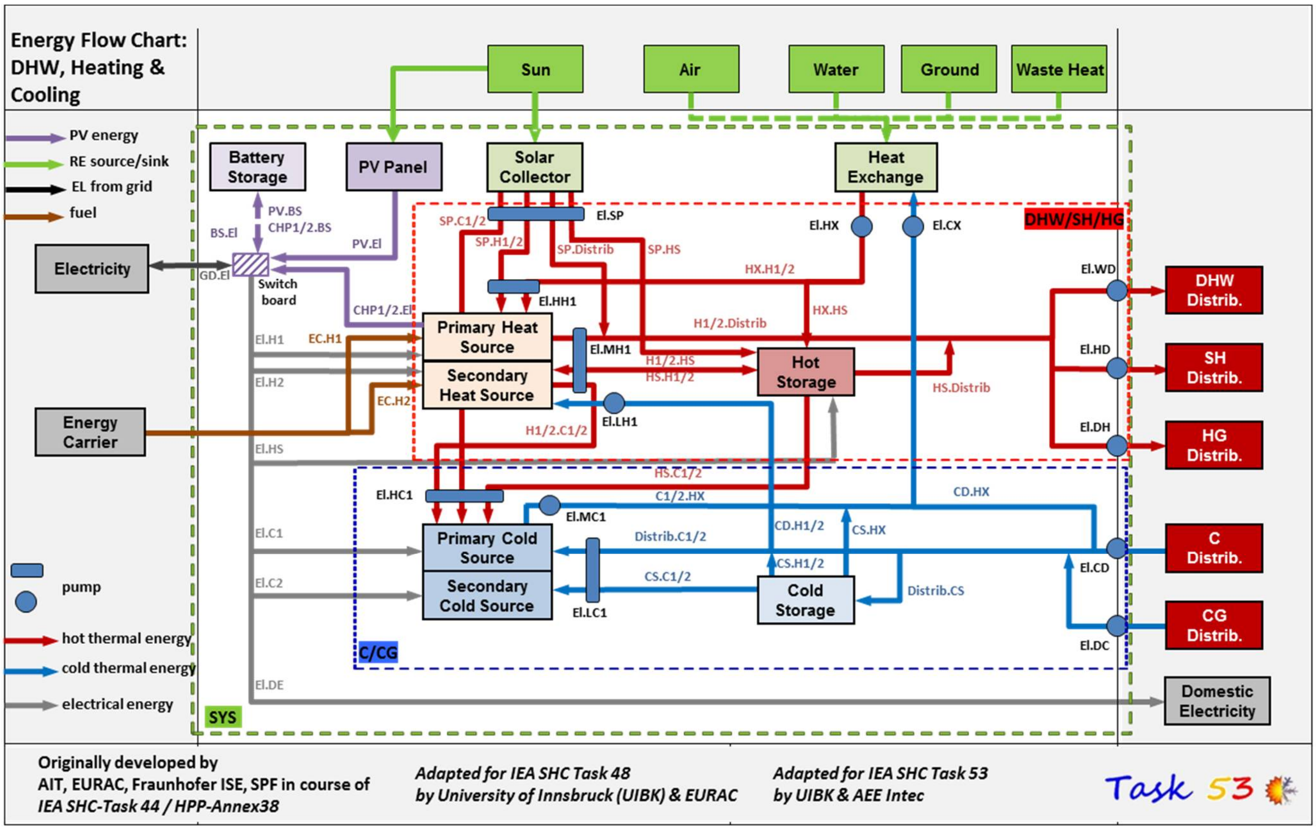


Figure 7: Energy-flow-chart of all system components that are taken into account for the evaluation and the division of the subsystems in T53E4-Tool (Neyer et al., 2016)

Table 2: Nomenclature and Subscripts used in the T53E[4] Tool

Nomenclature					
ε	Primary Energy Factor (kWh/kWh_{PE})	HE	Half effect	SF	Solar Fraction
ACM	Absorption chiller	HP	Heat Pump	SFH	Single family house
AHP	Absorption heat pump	HST	Hot storage	SH	Space heating
AWHP	Air water heat pump	HVAC	Heating. ventilation and air conditioning	SHC	Solar Heating and Cooling
C	Costs	KPI	Key Performance Indicator	SIM	Simulated
CHST	Chilled water storage	LCOE	Levelized costs of energy	SPF	Seasonal Performance Factor
COP	Coefficient of Performance	LCA	Life cycle assessment	ST	Solar thermal

CR	Cost ratio (-)	MFH	Multifamily house	T	Temperature
DE	Domestic electricity	MPG	Methyl propylene glycol	T53	IEA SHC Task 53
DHW	Domestic hot water	PER	Primary Energy Ratio (-)	TABS	Thermos-active building component
DOD	Depth of discharge	PV	Photovoltaic system	VCC	Vapour compression chiller
EC	Energy Carrier (=fuel)	Q	Energy	η	Efficiency
EER	Energy efficiency ratio	RH	Relative humidity		
fsav	Primary energy savings	SE	Single effect		
GWP	Global warming potential	SEER	Seasonal Energy Efficiency Ratio (-)		
Subscripts					
an	Annualized	MON	Monitored	HD	Heat Demand
tot	Total	out	Output	cold	Cold
ref	Reference system	loss	Losses	heat	Heat
SHC	Solar heating and cooling (system)	backup	Backup heating system	solar	Solar
el	Electrical	sys	Solar system	WD	Domestic hot water
equ	Equivalent	CD	Cold water demand	C	Cooling
sav	Save	DC	District cooling demand	HB	Heat boiler
NRE	Non-renewable	DH	District heating demand	EC	Energy carrier
in	Input	grid	Grid (electricity)		

The T53E[4]-Tool includes a technical as well as an economic analysis. Instead of showing absolute results, which are depending on a lot of different boundary conditions, the performance of the entire SHC system is compared to a predefined reference system. The reference system ensures that the results of a wide range of solar cooling and heating systems are comparable.

The reference system defined in T53 uses a natural gas boiler as heat source and an air-cooled vapour compression chiller for cooling. The analysed systems are compared to this reference system, but the tool also provides the possibility to compare the values with a specific (user defined) reference system, which can be chosen individually.

3.1.Technical key performance indicators

The technical assessment is based on the efficiency of the system that is calculated from monthly energy balances of the heat and electricity. In addition to the overall performance of the complete solar heating and cooling system, the T53-E4 tool divides the results in further subsystems (cooling, space heating, domestic hot water, district heating, district cooling)

Appropriate key performance indicators (KPI) are used for the comparison of the overall SHC systems with the corresponding design. The **Seasonal Performance Factor (SPF)** for a given system boundary is generally defined as the ratio of useful energy (supplied to satisfy the needs of the application) to energy effort from any source. The SPF can include several auxiliary components within the defined boundary and is calculated over a defined period of time (e.g. annual or monthly). Well known SPFs are based upon thermal or electric energy inputs.

However, the electrical SPF_{el} can be misleading when a system with different energy inputs (thermal and electrical) is analysed. The SPF_{el} might show high results even when large amounts of fossil fuel (e.g. gas) back up is consumed with overall poor environmental performance. Therefore, the **Primary Energy Ratio (PER)** and derivative key figures like the electrical equivalent SPF_{equ} and **non-renewable primary energy savings ($f_{sav.NRE}$)** are calculated and provide a better base for assessing different SHC systems.

- Non-renewable Primary Energy Ratio (PER_{NRE})

The non-renewable Primary Energy Ratio (PER_{NRE}) converts all non-renewable energy flows into primary energy equivalents. This provides appropriately comparable quality ratings for energy derived from alternative electricity, solar and fossil fuel heat energy sources. It is defined in Eq. (1) as the ratio of useful energy ($\Sigma\ Q_{out}$ supplied to satisfy the needs of the building) to non-renewable primary energy (electricity $Q_{el.in}$ and other Q_{in} energy carriers) scaled by the corresponding primary energy conversion factor ε. It considers all energy required for production of the energy carrier, such as extraction, generation, transformation, or transport and therefore takes their influence on the environment into account. The PER_{NRE} is calculated for all non-renewable energy inputs, for the different subsystems and also for the entire reference system ($PER_{NRE.ref}$).

$$PER_{NRE} = \frac{\Sigma\, Q_{out}}{\Sigma\left(\frac{Q_{el.in}}{\varepsilon_{el}} + \frac{Q_{in}}{\varepsilon_{in}}\right)} \tag{1}$$

A high value for PER_{NRE} indicates that the heating and cooling services can be obtained with a relatively small amount of fossil derived energy and the system is environmentally friendly. However, values for PER_{NRE} (in a magnitude of ca. 1 to 2.5) are not directly comparable with any widely available industry figures of merit such as the EER or SEER of a vapour compression chiller.

For comparison with conventional technologies, a simple reference system can be defined based on known useful heat consumption (measured or simulated results) for DHW, SH and cooling. The reference system of Task 53 contains a natural gas boiler and an air-cooled vapour compression chiller. A small hot water tank for domestic hot water is included as well as a cold-water storage volume. No hot water storage is considered. The specific reference system can be chosen including biomass boilers, water storages, etc. Additionally, the parasitic electricity consumption for the reference system (e.g. boiler. pumps. etc.) in kWh_{el} is defined. Heat losses of a reference domestic hot water tank are calculated. Eq. 2 shows the calculation of the $PER_{NRE.ref}$.

$$PER_{NRE.ref} = \frac{\Sigma\, Q_{out}}{\Sigma\left(\frac{Q_{out.heat}+Q_{loss.ref}}{\varepsilon_{in}*\eta_{HB.ref}} + \frac{Q_{out.cold}}{SPF_{c.ref}*\varepsilon_{el}} + \frac{Q_{el.ref}}{\varepsilon_{el}}\right)} \tag{2}$$

Certain primary energy conversion factors (ε) for each type of energy source have to be provided to calculate the PER_{NRE}. The primary energy factors depend on local conditions (e.g. the source from which local electricity is derived) and can vary over the entire year. Especially when PV or other fluctuating renewable electricity is included, the yearly trend should be used.

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

The non-renewable primary energy saving ($f_{sav.NRE}$) represents the percentage of reduction in non-renewable primary energy for the application compared with the reference (business as usual) system. Generally, the reference system can also be another renewable system. The $PER_{NRE.ref}$ uses the same calculation method as PER_{NRE} but takes the standardized component information to calculate its non-renewable primary energy demand. The non-renewable primary energy savings ($f_{sav.NRE}$) can be calculated as follows (Eq. (3)).

$$f_{sav.NRE} = 1 - \frac{PER_{NRE.ref}}{PER_{NRE}} \tag{3}$$

The $f_{sav.NRE}$ cannot exceed a value of 1 but can be negative, depending on the choice of reference system (standard or renewable) and the performance of the SHC system (auxiliary electricity demand and fossil backup). A high $f_{sav.NRE}$ indicates that a high solar fraction is given in the entire SHC system (if its compared to a non-renewable reference system).

The savings are used to generate a labelling to express the quality of the SHC systems. The labelling is based on the European energy labelling guideline 2010/30/EU (2010). The rating levels start from A+++ (best rating) to G (worst rating). If the considered SHC system has a lower primary energy demand than the reference system the $f_{sav.NRE}$ is greater than zero. The energy label is calculated for all subsystem (SH, DHW, C, etc.) and the total system.

- Electrical equivalent Seasonal Performance Factor (SPF_{equ})

The "Electrical equivalent SPF" (SPF_{equ}) combines all non-renewable final energy sources (both electrical – Q_{el} and energy carrier – Q_{EC}) by converting them into primary energy flows expressed in electrical equivalent units. This is achieved by using the relevant non-renewable primary energy factors for electricity (ε_{el}) and energy carrier (any kind of fuel) input (ε_{EC}). The SPF_{equ} is calculated by using Eq. 4.

$$SPF_{equ} = \frac{PER_{NRE}}{\varepsilon_{el}} = \frac{\sum Q_{out}}{\sum\left(Q_{el}+\frac{Q_{EC}}{\varepsilon_{EC}}*\varepsilon_{el}\right)} \tag{4}$$

The electrical equivalent Seasonal Performance Factor for a subsystem (e.g. cooling $SPF_{equ.c}$) can thus be used to compare the application performance with a commonly used SEER value, even when hot backup is used as part of the heat supplied to a thermal driven chiller. The SEER declares the efficiency of a component under standardized testing conditions. The actual system performance is often much lower than these SEER values (cf. Wiemken and Elias (2013), Nocke et al. (2014) and many more). Same SPF_{equ} indicates finally an equal primary energy demand, although the systems are supplied by different energy quantities.

3.2. Economic key performance indicators

The economic analysis is based on the cost ratio. Therefore, the total annual costs for investment. replacement and residual value, maintenance, energy and water cost are calculated automatically by the T53E[4]-Tool based on pre-defined values representing cut off values defined in Task 53. The annualized costs for the entire system are calculated by means of the annuity method, derivative key figures (e.g. primary energy avoidance costs. etc.) can be calculated easily.

- Investment & replacement costs

Specific costs for the main components include economy of scale investment prices. The greater the capacity of a certain component the cheaper is the specific investment cost. Examples for different types of chillers are included in Figure 8. The investment curves indicate typical average and cut off values mainly valid for central Europe. For each component the estimated lifetime, costs for maintenance, service and inspection are defined under consideration of VDI 2067 (2012). It has to be noted, that significant deviations of investment and energy prices to specific projects may occur. Therefore, all values may be changed, and user defined values can be implemented in the T53E[4]-Tool.

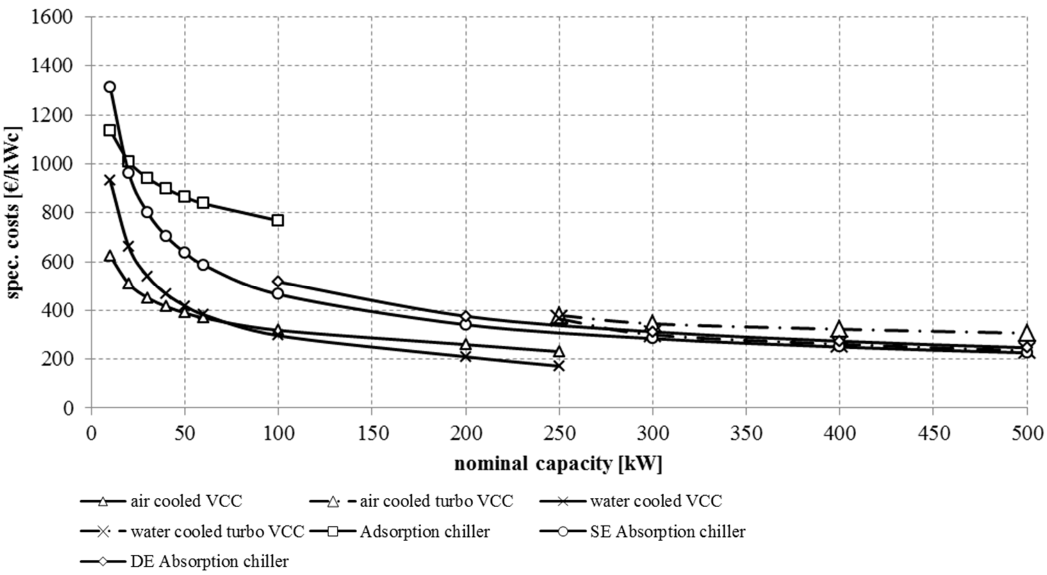


Figure 8: Example of specific investment costs used for T53 standard calculation of investments for thermal and electrical driven chillers (Neyer et al., 2015)

Replacement cost and residual values for each main component considering the lifetime of the components and the inflation rate is included for all main components.

- Consumption based cost: maintenance / energy / water

For each component, a percentage for maintenance costs per year is fixed in relation to its investment costs, following the suggestions of VDI 2067. Huge differences occur at domestic, commercial or industrial costs for different energy quantities. Domestic prices are higher but are mainly based on energy consumption. Commercial and industrial prices have low energy-based costs but can include capacity prices. Table 3 is showing the prices used for electricity and natural gas.

Table 3: Main prices for electricity and natural gas (T53 Standard calculation)

Electricity – energy	10 ct/kWh	Natural gas – energy	5 ct/kWh
Electricity – power	80 €/kW	Natural gas – annual	70 € / a

- Levelized costs of energy – LCOE

The costs for each category (9 categories: investment, replacement, maintenance, electricity, feed-in, energy carrier, water and domestic electricity) are summed up and discounted to an annualized value (C_{an}) according to the defined economics (including inflation rate, credit rates, etc.). The total annualized cost ($C_{an.tot}$) is the sum of yearly annualized costs using the set of standard costs in the assessment tool.

$$C_{an.tot} = \sum_{1}^{9}(C_{an})_i \tag{5}$$

The **Levelized Costs of Energy of the SHC ($LCOE_{SHC}$)** and also the one of the reference system ($LCOE_{REF}$) are the ratio of annualized costs to the overall useful energy provided to the application (Eq. (6)).

$$LCOE = \frac{C_{an.tot}}{Q_{CD.sys}+Q_{DC.sys}+Q_{HD.sys}+Q_{WD.sys}+Q_{DH.sys}+Q_{el.DE}} \tag{6}$$

Nevertheless. to avoid the discussion of absolute costs (e.g. when only taking sub systems into assessment) a cost ratio is calculated by comparing the Levelized Costs of Energy of the renewable systems with the Levelized Costs of the reference systems.

- CostRatio – CR

The cost ratio is calculated by comparing the total levelized energy costs (C_{tot}) of the SHC system and the total levelized costs for the reference system. The tool calculates the levelized costs (€/kWh$_{\text{useful energy}}$) based on the annualized costs (invest, replacement, maintenance, energy. etc.) and the delivered energy flows of the application.

$$CR = \frac{C_{tot.SHC}}{C_{tot.REF}} \tag{7}$$

Main assumptions for the calculation of the CostRatio are summarized in the following Table 4.

Table 4: Main assumptions for the LCOE and CostRatio calculation (T53 Standard calculation)

Period under consideration	25 a	Inflation rate	3%
Credit period	10 a	Inflation rate electricity	3%
Equity ratio	0%	Inflation rate others	3%
Credit interest rate	3%	Public funding rate	0%

4. Summary of technical and economic results

The economic assessment is based on standard values defined in the T53E4 Tool with standardized costs (investment, energy, feed-in, economics, etc.) and efficiencies (SPF_{ref}, boiler, etc.). Individual costs can be calculated by the tool but are not considered here in order to generate a base to benchmark the systems. The economic assessment of the analyzed SHC systems is based on different levels of detail.

4.1. Investment cost

The first level is based on the initial costs; thus, investment costs are analyzed only. An Invest Ratio is calculated comparing the investment of the SHC system and the standardized reference system. If the ratio results in values greater one the initial costs for the SHC system is larger compared to the state of the art accordingly. Values smaller one could be reached theoretically but are unlikely when using standardized costs, nevertheless it could be reached under consideration of investment subsidies, future costs evolution or other project specific circumstances.

The blue bars in Figure 9 and Figure 10 show the specific costs of investment for the SHC system based on their heating and cooling capacities and the entire solar collector (PV or ST); the yellow bar shows the specific investment costs for the reference system of the same capacity. The figures show that the investment costs of both, solar thermal as well as PV-driven systems, are higher than the reference system, thus the invest ratios are greater one.

In general, the specific costs for the systems get lower with a greater capacity. Same occurs for the invest ratio, which gets smaller with larger capacities, but is more depending on the specific application and the design (solar fraction) of the system than only on size. The specific investments of the solar thermal supported system start at roughly 2’000 €/kW and drops slightly below 1‘000 €/kW. The combination of solar thermal and heat pumps shows higher specific investments starting at 3’000 €/kW and dropping down to slightly above 1’000 €/kW.

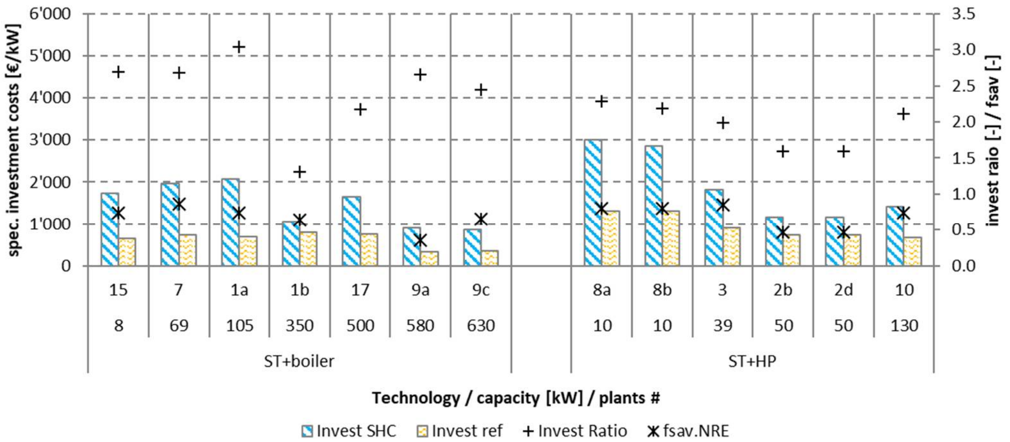


Figure 9: T53 standardized specific investment costs of solar thermal supported SHC systems, its reference system and investment ratio as well as non-renewable primary energy savings, sorted according to their capacity

The variation of the spec. investments is much higher at the PV driven systems. Some of the systems show investments greater than 4’000 €/kW (also designed to provide PV electricity for household) a large number of plants results in investments of roughly 3’000 €/kW; nevertheless, with larger systems ratios well below 1’000 €/kW are reached.

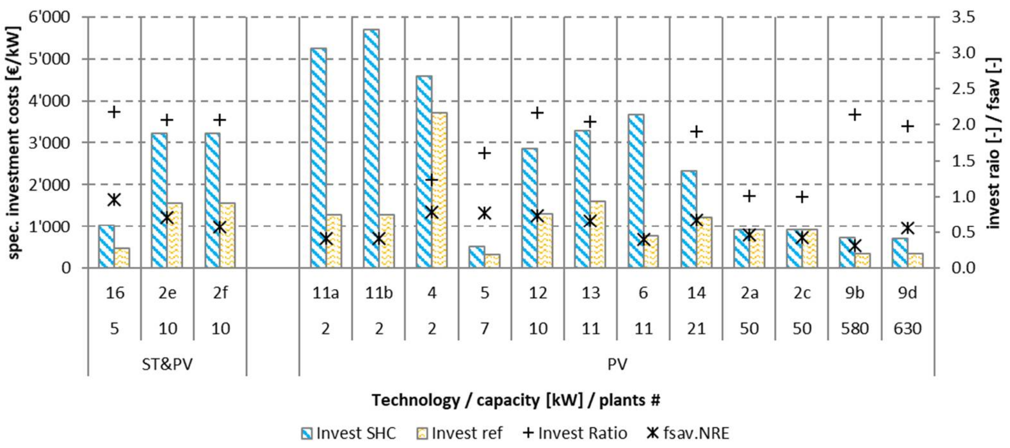


Figure 10: T53 standardized specific investment costs of photovoltaic supported SHC systems, its reference system and investment ratio as well as non-renewable primary energy savings, sorted according to their capacity

Figure 11 shows the invest ratio for all systems arranged in coherence with the achieved non-renewable primary energy savings and as frequency distribution graph (histogram). Trend wise the investment ratio is getting larger with larger solar fraction and non-renewable primary energy savings respectively. The systems designed to achieve high non-renewable primary energy savings or complete solar autonomous operation come up with the highest investment ratio. The majority of the plants reach an invest ratio between 1.8 and 2.4, above and below, there are equal numbers of plants. Three outliers, which are all PV supported systems built for household electricity supply and thus not reflecting the costs in relation to the HVAC, reach a ratio greater than 4.

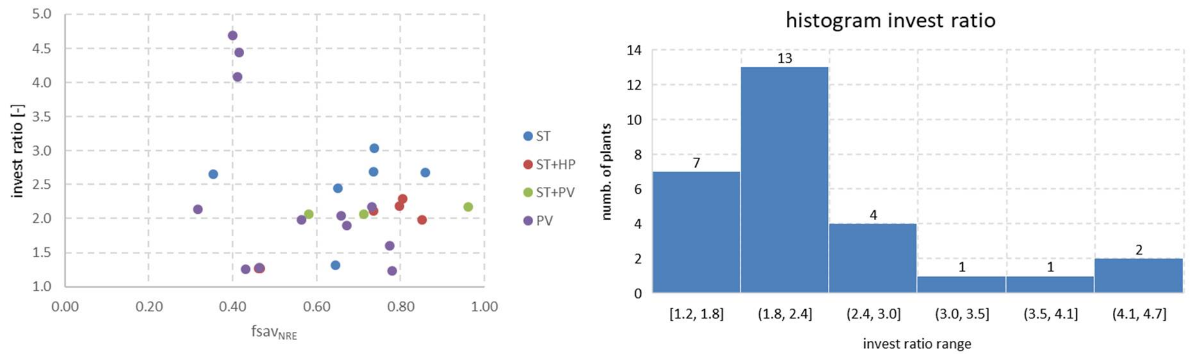


Figure 11: coherence of non-renewable primary energy savings ($fsav_{NRE}$) and invest ratio (left) and histogram of invest ratio (right)

4.2. Total annualized costs

The figures above show the comparison of investment costs, but do not consider the costs and savings during operation. Therefore, 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 12 and Figure 13 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 more energy demand is required 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.

The solar thermal driven systems come up with investment shares of 30-60% and operation-based cost (energy carrier and electricity) of 15-50%, remaining costs are used for maintenance. The solar thermal and heat pump combinations are clearly more dominated by investment as they are smaller systems and the component costs of the heat pumps are higher than ordinary backup boilers (e.g. natural gas).

The graph for electricity driven systems includes the feed-in compensation, displayed as negative values) and if present the house hold electricity costs. The investment shares for combined ST&PV systems is at the highest level of roughly 55-60%, these systems further show an operation-based cost share of 20% and maintenance costs of roughly 15%. The pure PV supported system have varying investment shares of 40-60% for smaller systems and 25-40% for larger systems. The rest of the distribution is the same as for the ST systems, dominated by operational cost (electricity) and 10-15% of maintenance. The electricity costs for the systems are put together by electricity (10 €cent/kWh) and capacity prices (80 €/kW). Depending on the country specific boundaries and the size of the system a pure energy-based price might be more realistic. If the costs of electricity equals 20 €cent/kWh and no capacity-based prices are deposited roughly the same costs would occur.

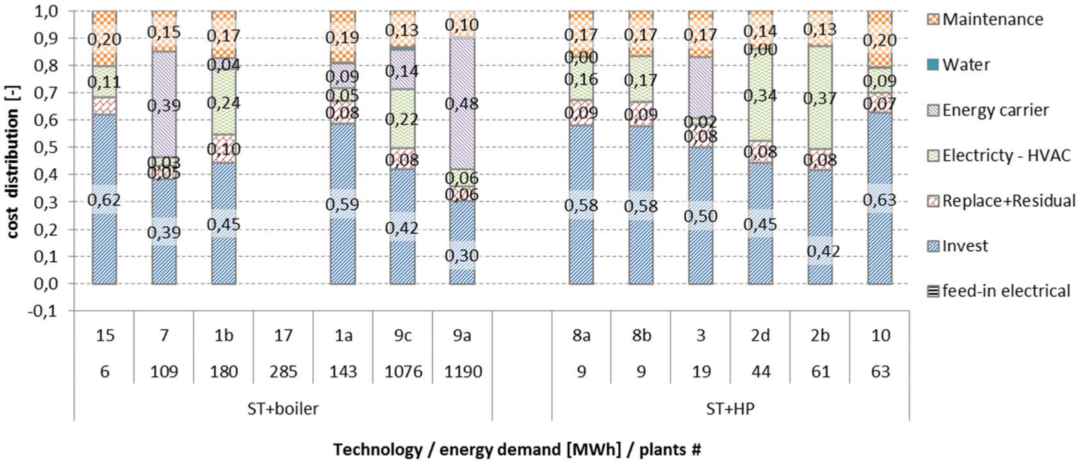


Figure 12: distribution of total annualized cost of solar thermal supported SHC systems

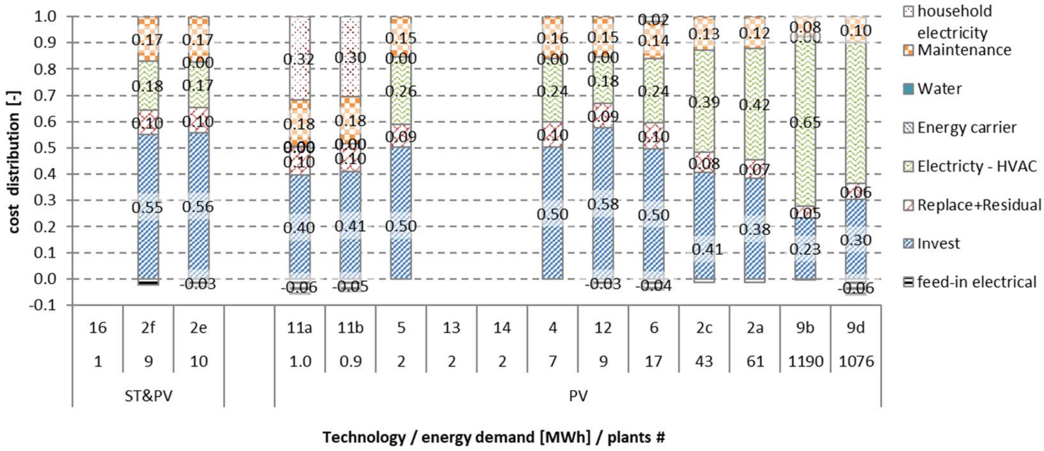


Figure 13: distribution of total annualized cost of photovoltaic supported SHC systems

4.3. $fsav_{NRE}$ vs. CostRatio

The overall assessment of the technical and economic performance of the SHC systems is shown as coherence of the non-renewable energy savings ($fsav_{NRE}$) and of the CostRatio (CR). The CostRatio 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 difference to the investment ratio is that it considers the investment costs on annual basis but also includes the costs during operation.

Following general format of Figure 14 is used often in further chapters and is showing the CostRatio in reversed order, thus the more beneficial a system the more it will appear at the top of the chart. 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 majority of the systems can achieve savings above 40%; almost half of them can reach CR smaller one! Details of the distribution are detailed in Figure 15. As Figure 14 is showing the result of all systems (ST and PV supported) the following evaluations try to separate the systems according to their main characteristics.

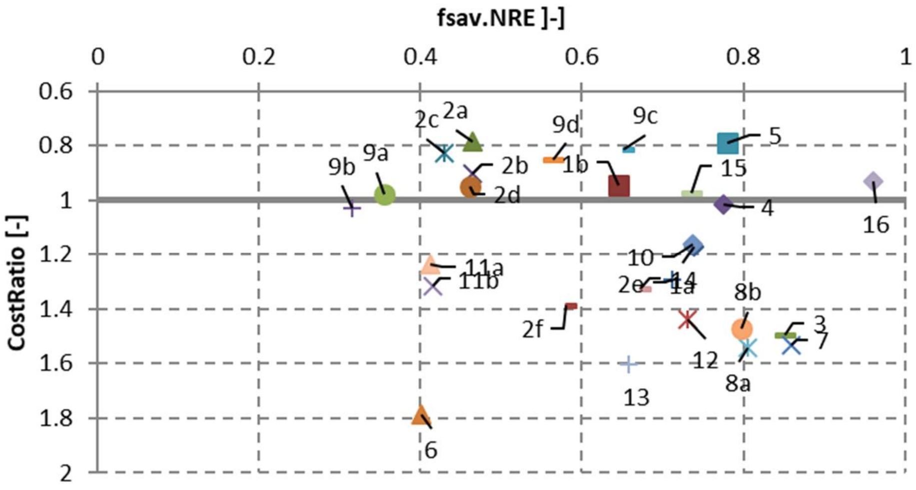


Figure 14: Cost Ratio vs. non-renewable primary energy savings of all 29 systems

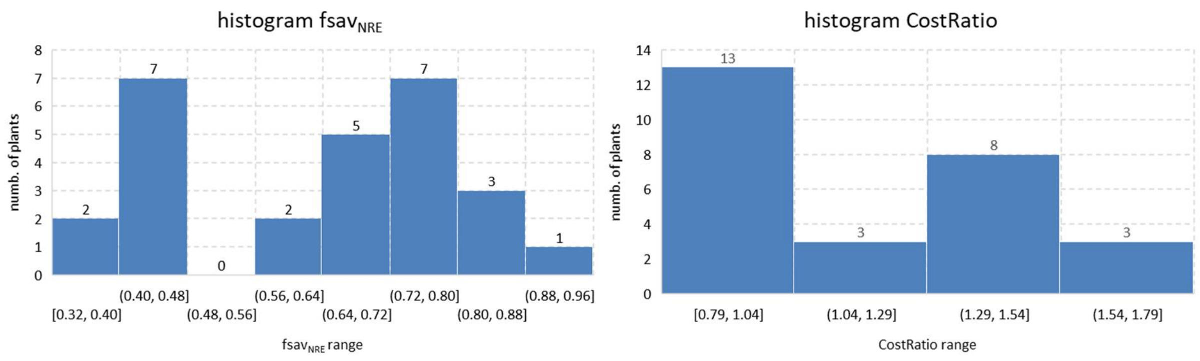


Figure 15: histogram of non-renewable primary energy savings ($fsav_{NRE}$)(left) and CostRatio (right)

4.4. Trends

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.

4.4.1. Overall

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.

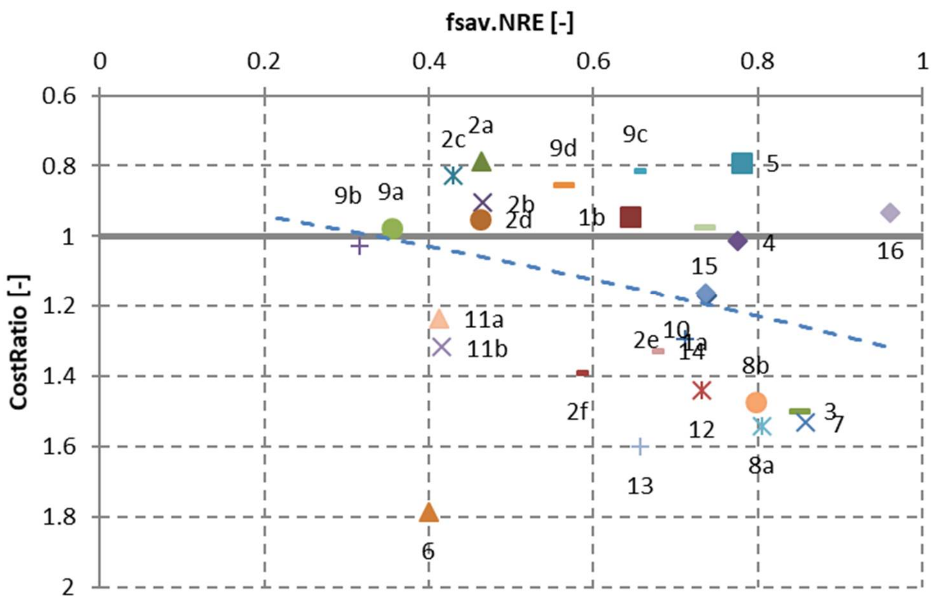


Figure 16: Overall trend of analysed SHC systems

4.4.2. Technology: ST vs. PV

For this comparison the systems are classified by the used solar technology. The distribution of the used technologies is the following:

- ST (6): #1a, #1b, #7, #9a, #9c, #15
- ST + HP (6): #2b, #2d, #3, #8a, #8b, #10
- ST+PV (2): #2e, #2f
- PV (10): #2a, #2b, #4, #5, #9b, #9d, #12 (#6, #11a, #11b)
- Not included (4): #13, #14, #16, #17

The systems #13-14 and #16-17 are not included in the evaluation since no full yearly data are available and therefore the fsav$_{NRE}$ and CR are not representative and comparable to the other systems.

SHC systems combining solar thermal collector with an additional boiler are cost competitive at lower primary energy savings (20-40 %). At higher savings (70-100 %) the cost ratio increases, but the trend shows that the increase is less compared to the solar thermal systems combined with a heat pump. The reason is that combining solar thermal collector with a boiler enables an efficient use of both technologies. As the SHC system are characterized by relatively high investment costs but very low operational costs they can be used efficiently to cover the base load. On the other hand, boilers are characterized by low investment costs, but relatively high fuel costs and therefore are more efficient to cover the peak demand. SHC systems using solar collectors in combination with a heat pump, on the other hand, show a stronger increase of costs with higher primary energy savings, since these systems are mainly investment costs driven.

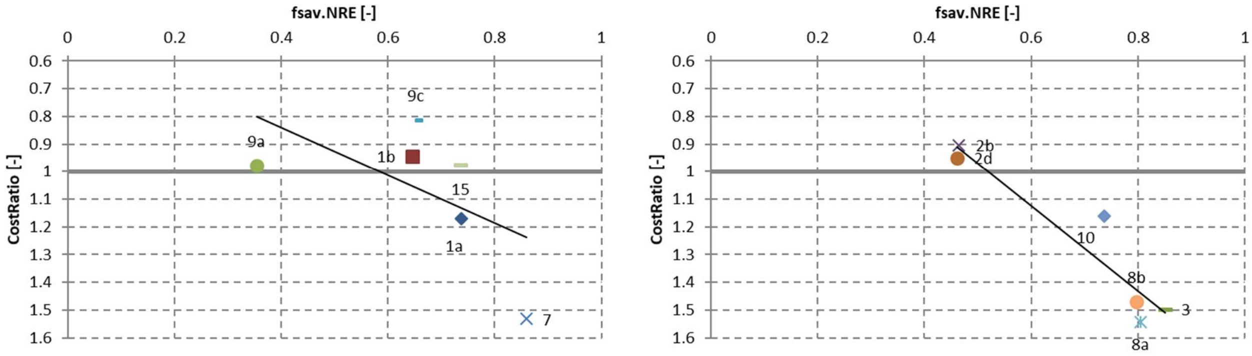


Figure 17: Trends of solar thermal & boiler (left) and solar thermal & heat pumps (right)

In Figure 18 SHC systems with combined used of PV and solar thermal are displayed. Since the number of representative systems is very low no trend could be shown. On the right-hand side the trend for the PV-driven systems can be seen. It is shown that the CR is increasing slightly with the increase of non-renewable primary energy savings. Some examples show that well-designed PV-driven systems can be cost competitive also at higher environmental performance. Plants #6, 11a, 11b are excluded from that trend as the serve for domestic household electricity.

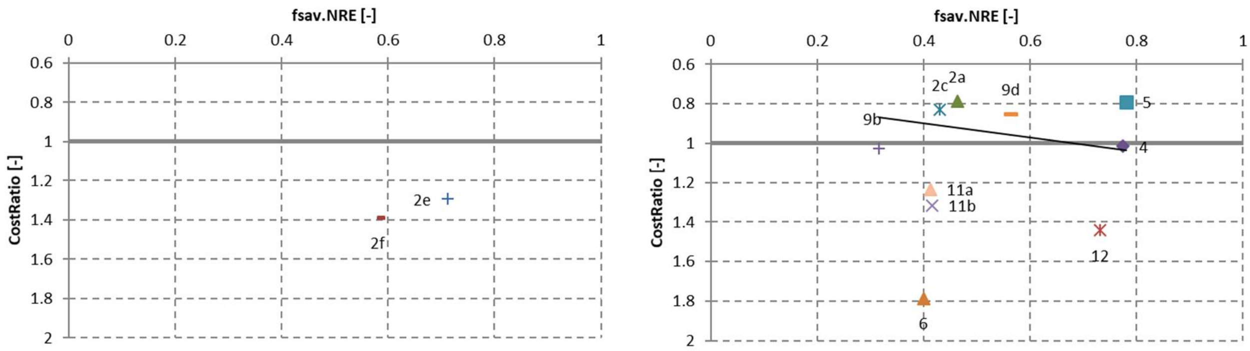


Figure 18: Trends of solar thermal + PV systems (left) and photovoltaic supported systems (right)

4.4.3. Location: North vs. south

The comparison is classified by the location of the SHC system. The systems are separated in southern and northern climate with typical heating and cooling loads. The distribution of the used technologies is the following:

- Southern (11): #1a, #1b, #2a, #2b, #2e, #4, #5, #9c, #9d, #10, #15
- Northern (13): #2c, #2d, #2f, #3, #7, #8a, #8b, #9a, #9b, #12 (#6, #11a, #11b)
- Not included (4): #13, #14, #16, #17

The comparison in Figure 19 clearly shows the difference between the locations. Whereas the systems located in the south can compete cost-wise with the reference system also for higher primary energy savings the CR for northern systems is increasing strongly. The main reason for the good performance of the southern region is the higher solar yields over the entire year, as well as a longer cooling season with higher loads to use the abundant available solar energy more efficient in summer.

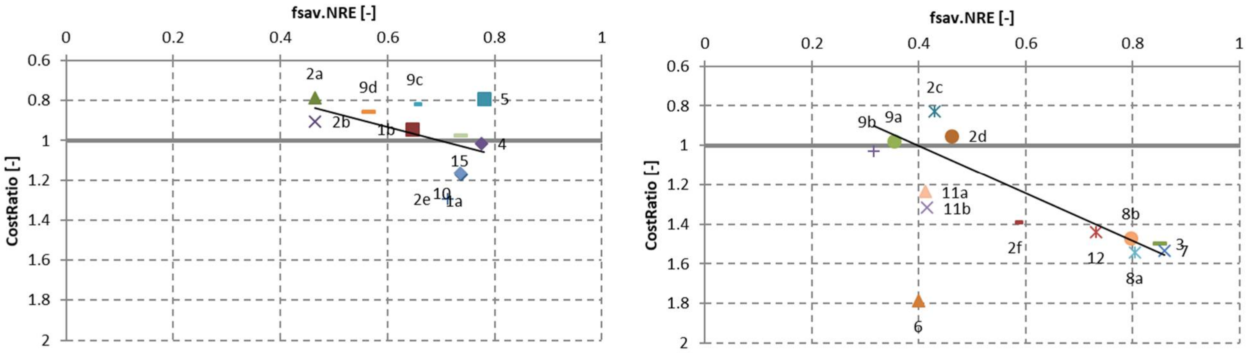


Figure 19: Trend of southern located (left) and northern located (right) systems

4.4.4.Combination: Technology and Location

The two previous trends are combining a lot of different boundaries either for location or for technology, thus this comparison is combing the two categories accordingly.

- ST-South (6): #1a, #1b, #2b, #9c, #10, #15
- PV-South (5): #2a, #2e, #4, #5, #9d
- ST-North (6): #2d, #3, #7, #8a, #8b, #9a
- PV-North (4): #2c, #2f, #9b, #12
- Not included (7): #6, #11a, #11b, #13, #14, #16, #17

The trend in Figure 20 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 like above very clear; showing that for southern location the CR are below a CR of 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.

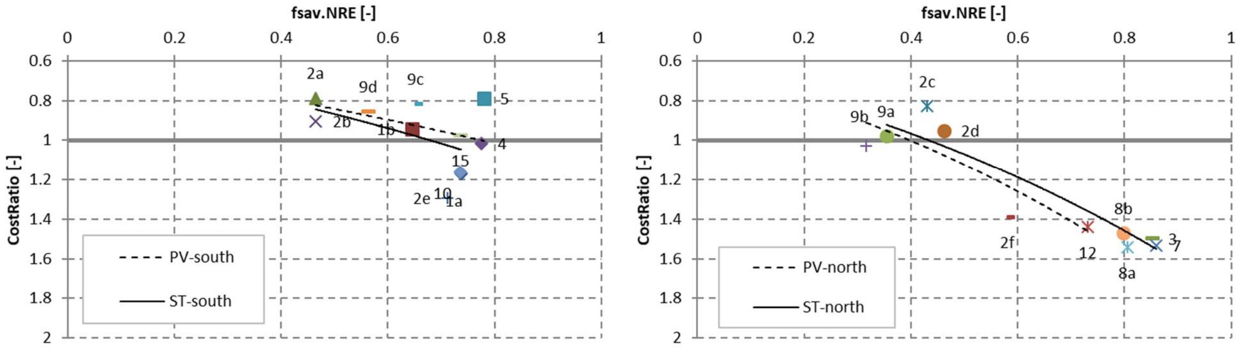


Figure 20: Trend of the combined technology / location for southern located (left) and northern located (right) systems

4.4.5.Base vs. full

The heat or cooling load which is covered by the SHC system has a strong influence on the annualized costs. Therefore, the systems are classified in 4 sections based on their solar fraction with the following distribution:

- SF<30 (4): #2a, #2c, #7, #9b
- SF 30-70 (15): #1b, #2b, #2d, #2e, #2f, #3, #5, #6, #8a, #8b, #9a, #9d, #11a, #11b, #12
- SF 70-90 (3): #1a, #4, #9c,
- SF > 90 (2): #10, #15

- Not included (4): #13, #14, #16, #17

A few systems are designed for low solar fractions <30% and the majority of them can reach CR smaller one or close to one. Only system #7 is showing with its biomass backup boiler results in relative higher costs. Most of the SHC systems (15) are designed for a solar fraction between 30 and 70%. There are several systems that achieve cost savings, whereas others have significantly higher costs compared to the reference system. The trend is showing a lower gradient, indicating lower cost increase to reach the same savings as with lower solar fraction, nevertheless it is obvious that the more base load the cheaper a system.

Figure 22 show the trend for higher solar fractions. The trends are shown only for 70-90% category but as only three systems are including no comparison should be performed. Nevertheless, all systems show a CR lower than 1.2 or even below 1 indicating very efficient designs.

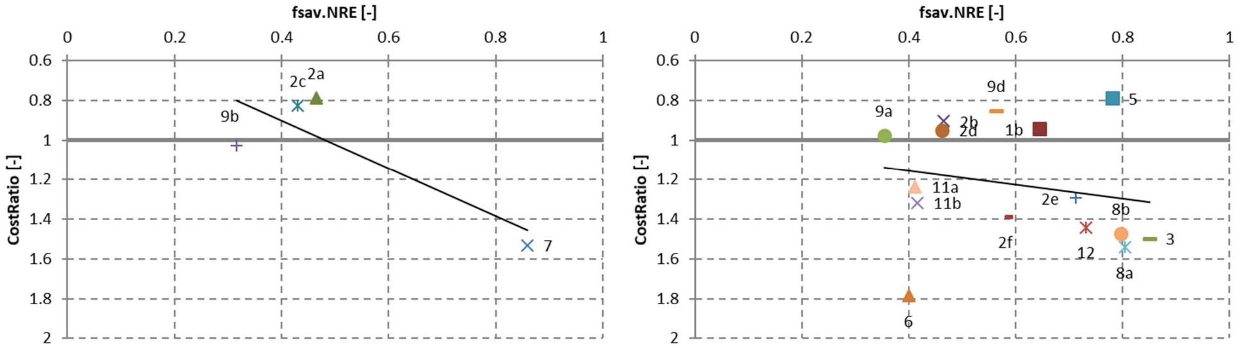


Figure 21: Trend for plants with SF <30% (left) and SF 30-70% (right)

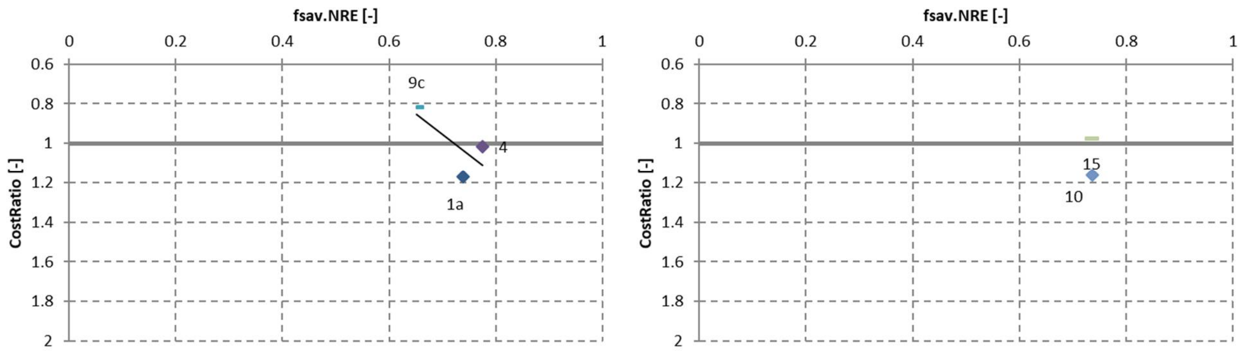


Figure 22: Trend for plants with SF 70-90% (left) and SF >90% (right)

4.4.6. Number of application

In principle SHC systems are able to cover the space cooling, space heating and domestic hot water demand or several different applications, but not all of the analyzed systems cover all three demands.

- One application (1): #4
- Two applications (9): #1a, #1b, #5, #8a, #8b, #11a, #11b, #12, #15
- Three applications (14): #2a, #2b, #2c, #2d, #2e, #2f, #3, #6, #7, #9a, #9b, #9c, #9d, #10
- Not included (4): #13, #14, #16, #17

There is only one system that is designed to cover only one demand (#4 DHW only). The systems covering two demands show a slight cost increase with increasing primary energy savings, whereas the systems covering all three demands show a stronger cost increase with increasing primary energy savings. Nevertheless, the absolute results show more economic successful results if three demands are handled.

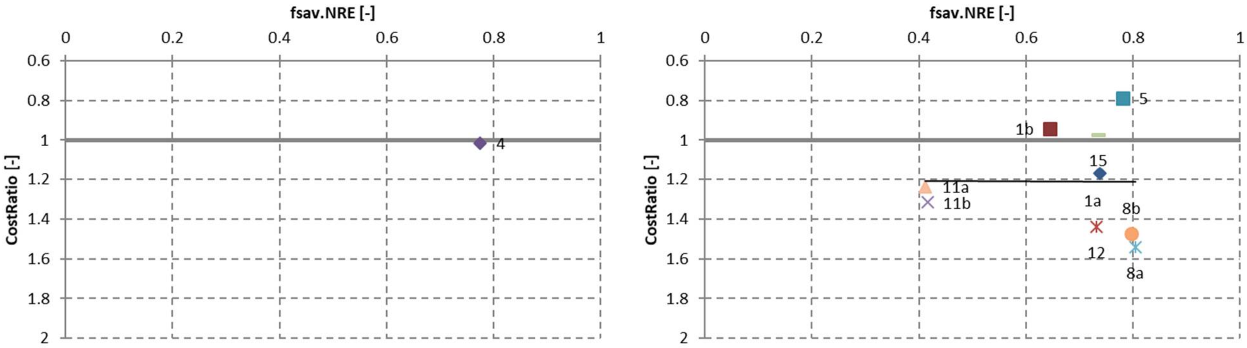


Figure 23: Trend for plants with only one application (left) and two applications (right)

A possible explanation can be found in the complexity of the systems in comparison to the year around demand. Satisfying two demands is less complex but might end up in less demand. Increasing the non-renewable primary energy savings seems to be less effort, thus leading to lower gradients in the trendlines.

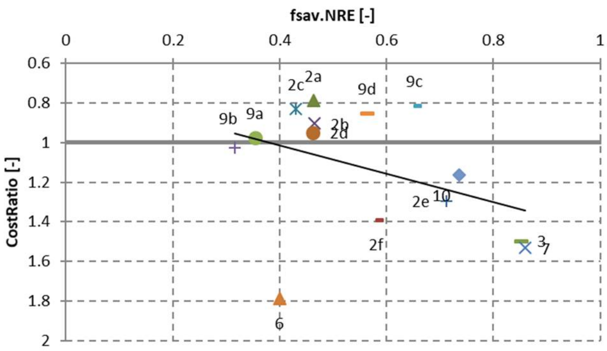


Figure 24: Trend for plants with three applications

4.4.7.DHW vs. SH vs. C

The analysis of the specific application is aligned the same direction as the trends according to the number of applications. The systems distribution is almost even, thus the trends can be compared in all conscience, although the system performance is depending on the ratio of the particular demand and its sub-system efficiency.

- DHW (20): #1a, #1b, #2a, #2b, #2c, #2d, #2e, #2f, #3, #4, #6, #7, #8a, #8b, #9a, #9b, #9c, #9d,
- #12
- SH (18): #2a, #2b, #2c, #2d, #2e, #2f, #3, #5, #6, #7, #8a, #8b, #9a, #9b, #9c, #9d, #10, #12
- #15
- C (20): #1a, #1b, #1c, #2a, #2b, #2c, #2d, #2e, #2f, #3, #5, #7, #9a, #9b, #9c, #9d, #10, #11a, #11b, #15
- Not included (5): #13, #14, #16, #17

In the following Figure 25, Figure 26 and Figure 27 the trends are shown on system level (left) and for the entire sub-system only (right). The trends of the sub-systems show lowest CR and lowest gradient for DHW (year around usage), followed by cooling and heating. The trends of system show a very similar behavior for DHW, SH and C. Each line reaches cost parity between 40 and 50% non-renewable primary energy savings. Thus, the systems design for each of the demands can lead to very economic systems but also to high savings.

The lowest gradient can be achieved by systems including cooling, followed by systems with domestic hot water and space heating. In any case it should be noted that the overall gradient is very depending on the ratio of the subsystem and its respective efficiency.

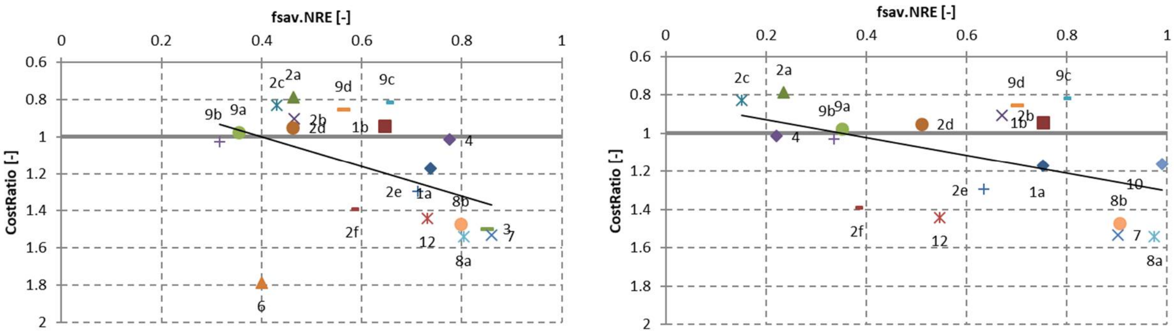


Figure 25: Trend for plants covering the DHW demand, left: based on system key figures, right: based on sub-system key figures

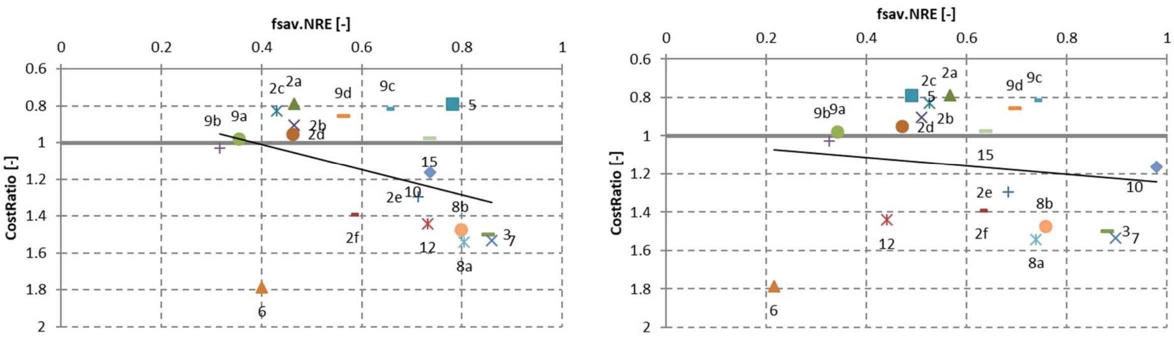


Figure 26: Trend for plants covering the space heating demand, left: based on system key figures, right: based on sub-system key figures

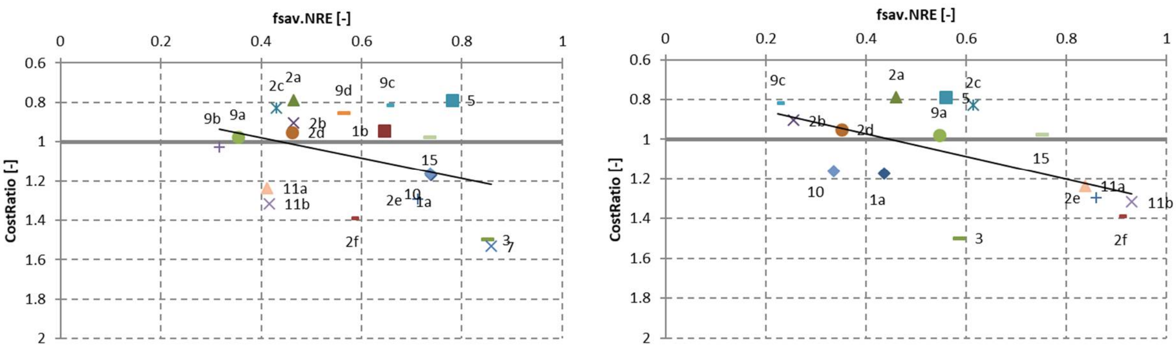


Figure 27: Trend for plants covering the cooling demand, left: based on system key figures, right: based on sub-system key figures

4.4.8. Monitored vs. simulated

In the following trend the comparison of monitored and simulated systems is performed.

- Monitored (5): #1a, #4, #5, #7, #15
- Simulated (19): #1b, #2a, #2b, #2c, #2d, #2e, #2f, #3, #6, #8a, #8b, #9a, #9b, #9c, #9d, #10, #11a, #11b, #12
- Not included (4): #13, #14, #16, #17

The results of the monitored plants are in the higher range of savings (>70%) but still show comparable low CostRatio's. The trend is mainly driven by plant #7 and its expensive biomass backup. Not included plants are all monitored but cannot provide yearly data up to now. All remaining plants are simulated and are summarized in Figure 28 (right hand side).

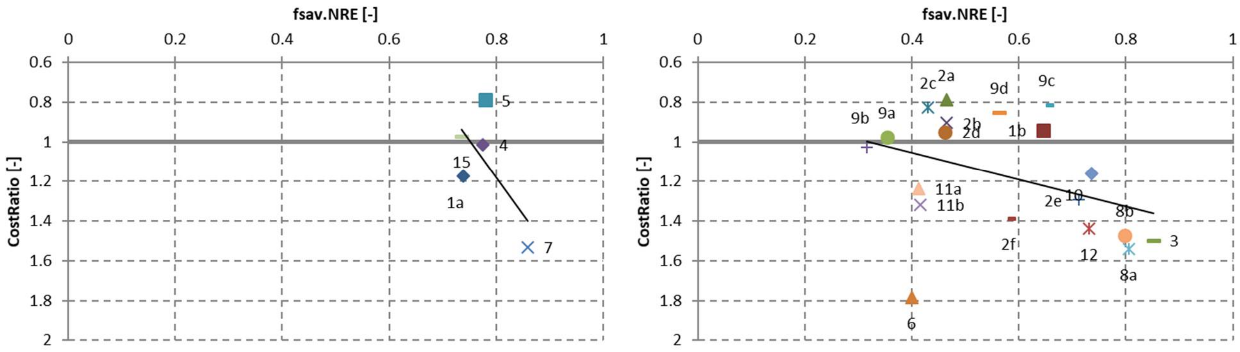


Figure 28: Trend for plants monitored (left) and simulated (right)

4.4.9. Size: small vs. medium vs. large Capacity

The size (its capacity and energy demand) is highly influencing the results of CostRatio, thus the comparision of the three categories small (<10 kW), medium (10-100 kW) and large (>100 kW) is performed next. The results would be almost the same for the categorizing according to the energy demand and is therefore not shown.

- Small size, <10 kW (8): #2e, #2f, #4, #5, #7, #8a, #8b, #12, #15
- Medium size, 10-100 kW (5): #2a, #2b, #2c, #2d, #3,
- Large size, >100 kW (7): #1a, #1b, #9a, #9b, #9c, #9d, #10
- Not included (7): #6, #11a, #11b, #13, #14, #16, #17

The trend of the small-scale plants shows that the design is rather aimed on high savings, thus it results on higher CostRatios. The medium range plants show that with smaller savings (40-60%) cost equity can be reached for many cases, if the savings are getting higher the CostRatio is increasing up to 50%. The trend of large-scale plants is showing the lowest CR for the complete band width of results of savings.

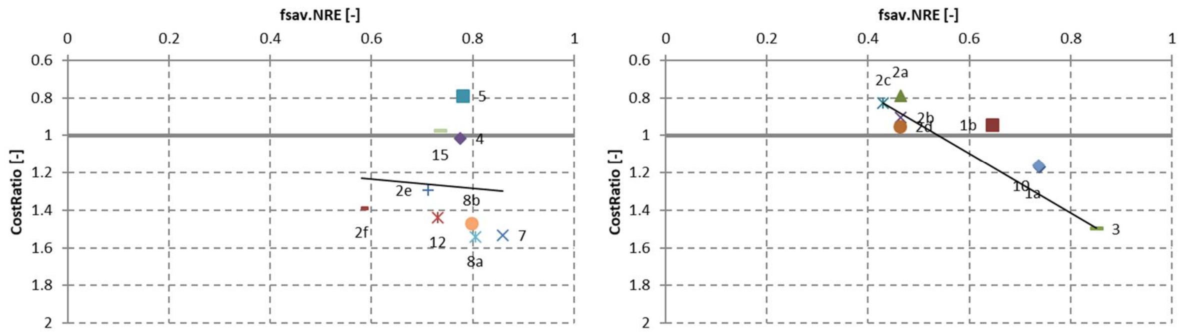


Figure 29: Trend for plants with small size (<10 kW: left) and medium size (10-100 kW: right)

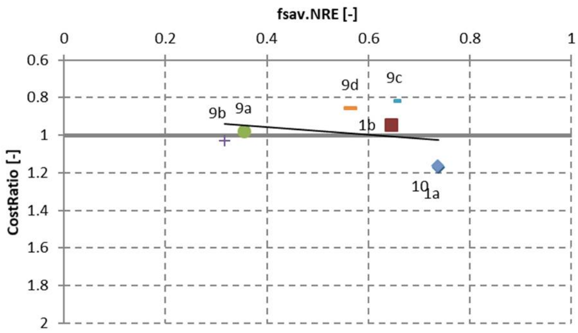


Figure 30: Trend for plants with large size (>100 kW)

4.4.10. Specific time period

Systems #13-14 to #16-17 do not contain full yearly data and therefore cannot be compared to the other systems. The analysis is based on measured data over several days or months. Since the system performance is not constant over the year the achieved results very much depend on the measured time and season. Further, the results for the CostRatio needs to be taken with care, since the CostRatio is based on the total annualized costs including operation-based cost but the total energy demand is not known the CR's might be higher than for full annual data. Nevertheless, these systems under development present a very promising initial position coming up with high non-renewable primary energy savings at comparatively low costs.

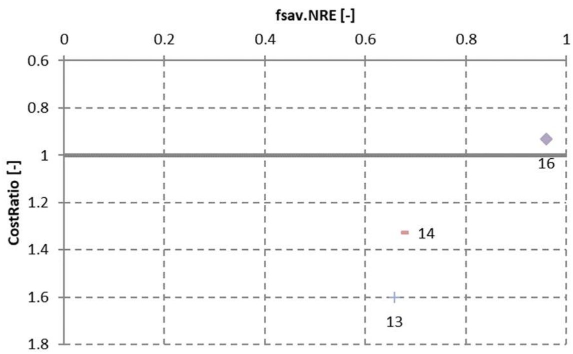


Figure 31: plants not included in the trends because of specific time period

5. Sensitivity analysis on boundaries

All above 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 5. 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. Concluding the chapter, the interpretation of changing reference technology is briefly explained.

Table 5: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

5.1.Investment

The investment cost for all components (SHC + Ref) were changed according to Table 6, in the graphs four selected results are presented. The investment costs are changed in 15% steps from increased costs (115%) to decreasing investments (85, 70%) accordingly. If the levelized cost are more investment dominate the effect of this sensitivity is larger. Investment costs are only affecting the CostRatio, the energy savings of the entire system does not change.

Figure 32 is showing the results of changing investment costs on the overall trend of all 28 analyzed SHC plants. The impact of the change is more relevant at higher savings, this is congruent to prior findings, that higher savings require higher investment cost (larger solar fraction with larger collector fields).

The origin trend (blue) starts with a CR of 1 at 30% savings and reaches a CR of 1.25 at roughly 90% savings. The change of ±15 % in investment is having more effect when the investment costs are higher (115% compared to 70%). Accordingly, the trend lines are not equidistance and have higher divergence at higher energy savings. If costs can be reduced by -15% (green) energy savings of 65 % can be achieved with a CR below 1 and thus representing costs lower than that of the reference system. If the costs can be reduced by -30% (orange) the gradient of the trendline is getting smaller, starting at a CR of 0.85 and ending at a CR of 0.9. Thus, the costs of the SHC systems are lower than the reference system also when high savings can be achieved.

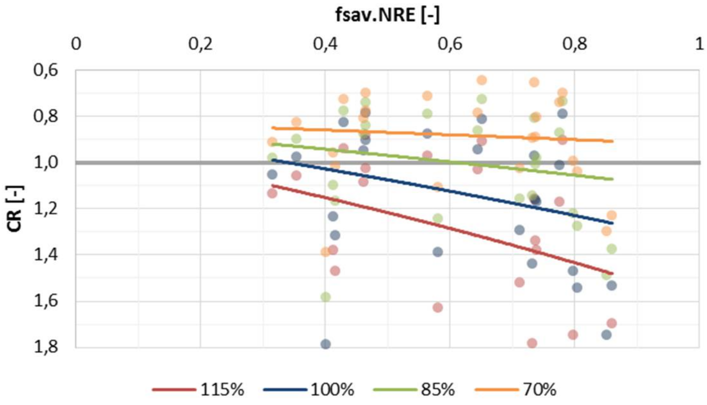


Figure 32: Sensitivity analysis on investment cost for the overall trend

The sensitivity on investment costs for the southern and northern locations separated in ST and PV supported systems is represented in Figure 33. The effect 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 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 gets equal 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 CostRatio'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.

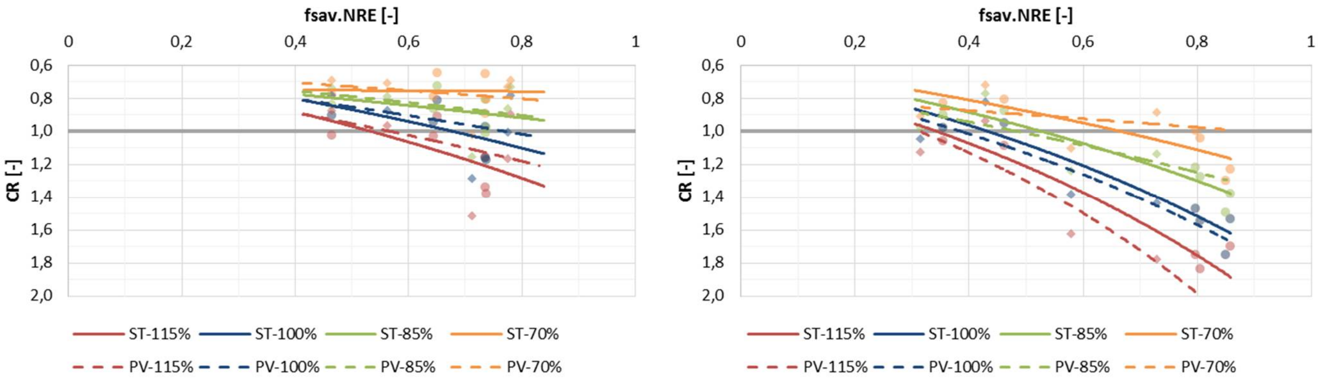


Figure 33: Sensitivity analysis on investment cost for the southern (left) and northern (right) location separated for PV and ST

5.2.Electricity costs

The electricity cost (only affecting energy costs) for all systems (SHC + Ref) is changed according to Table 6, in the graphs four selected results are presented. The electricity costs are changed in 50% steps from decreased (50%) to increasing electricity costs (200, 300%) accordingly. The base value before change is an energy price of 10 €ct/kWh$_{el}$. The electricity costs are only affecting the CR, the savings cannot change due to this sensitivity analysis. The more electricity is used in a system, the more sensitive the CR.

The overall trends in Figure 34 are showing slight changes only. The effect is greater at lower savings, because more electricity is used in these systems. If the electricity costs are increasing the CR is getting larger.

Nevertheless the effect is very small and the change of CR is in a range of 10% at low savings and almost neglectable at higher savings.

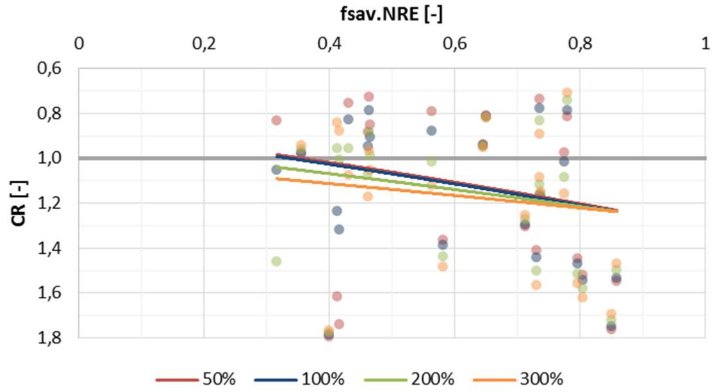


Figure 34: Sensitivity analysis on electricity cost for the overall trend

If the trends are separated for ST and PV supported systems, the changes are getting more noticeable. In Figure 35 the shown variation is smaller than in the overall trend. The change of electricity price is -50% and up to +100%, representing an already realistic range, depending on the country and the conditions (private vs. commercial prices). The PV supported systems are combined with electricity driven devices, thus they are more sensitive on the change of electricity prices than ST supported systems. Nevertheless, also some of the ST examples are combined with heat pumps and vapour compression chillers respectively and the difference gets balanced.

For the southern location, the ST and PV trend gets more equalized if the electricity price is increasing. Whereas the change for ST supported systems is larger at higher savings compared to PV supported system. Thus, the auxiliary electricity demand of ST is larger compared to the PV systems. However, if the electricity price rises up to 20 €ct/kWh the trendline is below a CR of 1.

For northern location the picture is quite different. The ST systems do not show a noteworthy sensitivity on the change of electricity costs. The change of CR is below 10% at low savings and a few percent at high savings. In contrast the CostRatio of PV supported systems changes by almost 30% (0.9 to 1.2) at low savings with increasing electricity costs.

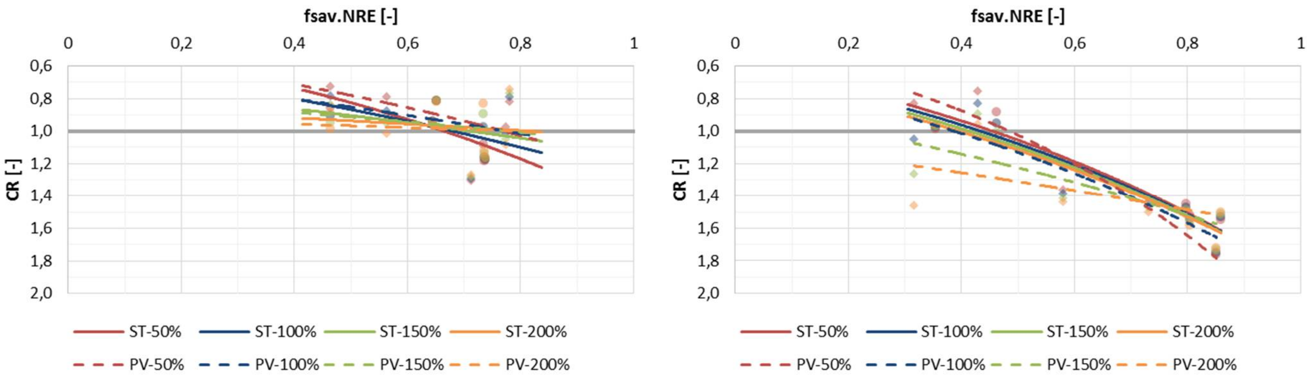


Figure 35: Sensitivity analysis on electricity cost for the southern (left) and northern (right) location separated for PV and ST

5.3. Natural gas cost

The natural gas costs (only affecting energy costs) for all systems (SHC + Ref) is changed according to Table 6, in the graphs four selected results are presented. The electricity costs are changed in 25% steps from decreased (75%) to increasing natural gas costs (125, 150%) accordingly. The base value before the change is an energy price of 5 €ct/kWh$_{gas}$. The natural gas costs are only affecting the CR, the savings cannot change due to this sensitivity analysis. The higher the share of costs for natural gas used in a system (St + boiler or reference), the more sensitive the CR.

The overall trend in Figure 36 is changing significantly with the change of natural gas costs. The original trend line is shifted almost in parallel depending on the direction of change. If natural gas costs are decreased the CR is increasing, if the costs are increasing, the CR is decreasing. When natural gas costs reach 7.5 €ct/kWh cost parity can be reached at roughly 60% of non-renewable primary energy savings.

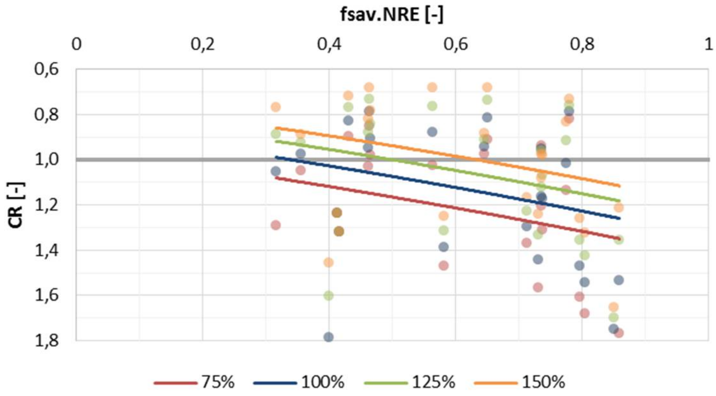
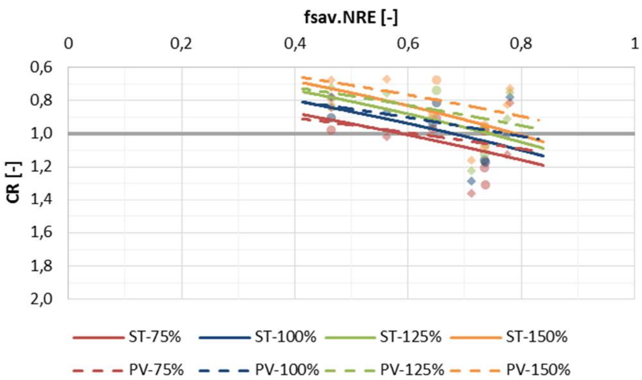


Figure 36: Sensitivity analysis on natural gas cost for the overall trend

The separated view on southern and northern locations is shown in Figure 37. The picture is changing slightly for ST and PV supported systems. For southern locations the change for ST is pushing the trendline at highest costs of natural gas toward cost parity at high savings (orange line). The stepwise change of gas price is again leading to almost parallel shift of the lines, indicating that the majority of ST supported systems is working with gas backup und thus the ratio of fuel costs is not affecting. For PV supported system the effect of changing gas prices is larger at lower savings than at higher savings. Overall the effect is more positive for PV supported system than for ST systems. The PV systems reach a maximum CR of 0.9 at high savings.

Same is occurring at northern locations, the effect of changes in natural gas costs is affecting the CR more at lower savings than at higher savings. In these cases, the only change is the fuel cost of the reference system. The ST supported systems are less sensitive on the lower side of savings than at the higher end. The positive effect is larger than for PV driven systems, the CR at maximum savings is almost 20% lower. This characteristic can occur when the SHC system itself is also affected by the change of costs (natural gas backup).



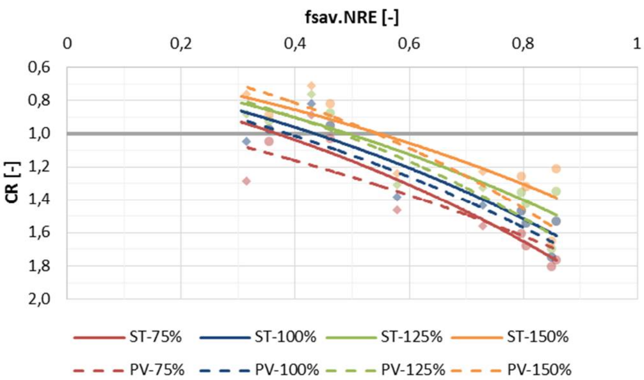


Figure 37: Sensitivity analysis on natural gas cost for the southern (left) and northern (right) location separated for PV and ST

5.4. Auxiliary demand

The electrical auxiliary demand for all SHC systems is changed according to Table 6, in the graphs four selected results are presented. The electricity demand is changed in 10% steps from increased auxiliary demand (110%) to decreasing electricity (80, 60%) accordingly. For the separated view the decrease is kept in a smaller range of 90 and 80% of the original demand respectively. The auxiliary demand is affecting the CR (electricity costs) but also the savings (non-renewable primary energy share of electricity).

The change of the overall trend is shown in Figure 38, the less auxiliary electricity is necessary, the higher the non-renewable primary energy savings and the lower the CostRatio. The change in savings is more significant than the change in cost and the changes are higher at lower savings than at higher ones. This points on the fact that plants that reach higher savings are already optimized in respect to the electrical auxiliary demand and thus the effects are lower compared to systems designed for lower solar fraction and non-renewable primary energy savings respectively.

The separated analysis of southern and northern location in Figure 40 is showing slightly different sensitivity on the change of auxiliary demands. For PV supported systems that are all based on electricity the change of electrical auxiliary demand is almost neglectable. Its changing the CR at lower savings about 5% while there is almost no change at higher savings; same neglectable behaviour is occurring for changes in the savings itself. The effect for ST supported systems is not much more evident. There is almost no change at lower savings and but a slight decrease in CR (~5-7%) and increase of savings (5-7%).

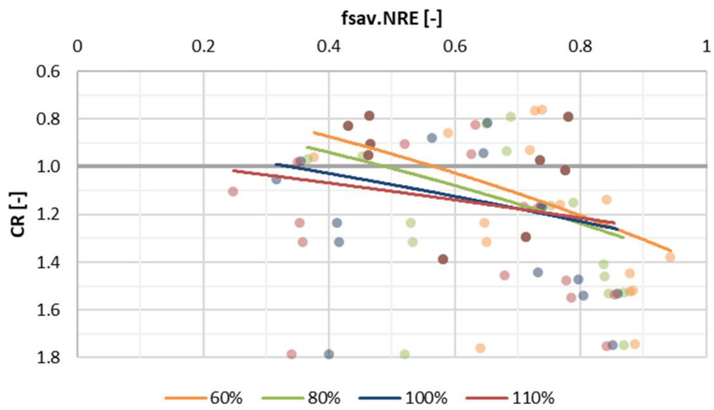
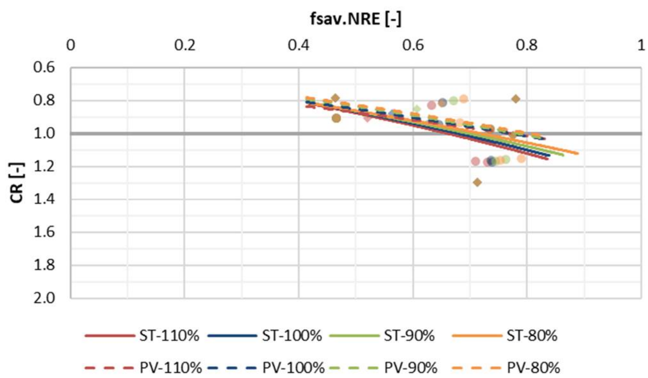


Figure 38: Sensitivity analysis on auxiliary (electricity) demand for the overall trend

For the northern plants the changes are different. The PV supported systems present a larger change in savings (~15%) at low savings with only small effects on the CostRatio. The effects at higher savings are from minor priority and almost neglectable. The effect on ST supported systems seems to be again neglectable at low savings and in the magnitude of 5% at higher savings in both direction (savings and CR).



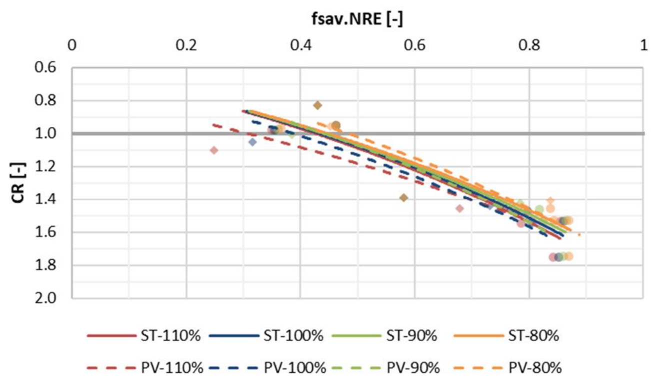


Figure 39: Sensitivity analysis on auxiliary (electricity) demand for the southern (left) and northern (right) location separated for PV and ST

5.5.Energy Production

The energy production (equivalent to more energy demand at a constant auxiliary demand) for all systems (SHC + Ref) is changed according to Table 6, in the graphs four selected results are presented. The production is changed in 10% steps from decrease (90%) to increasing production (120, 140%) accordingly. For the separated view the increase is kept in a smaller range of 110 and 120% of the original respectively. The energy production is affecting the CR but also the savings, systems that satisfy rather low energy demands are more sensitive than large scale systems.

The change of the overall trend is presented in Figure 40, the more a system can supply the lower the CostRatio and the larger the non-renewable primary energy savings. The change is more significant from financial than from environmental point of view. Systems at the lower end of savings are less sensitive to the change than systems at the upper end, as they are more investment dominated and thus the change of produced energy is more affecting.

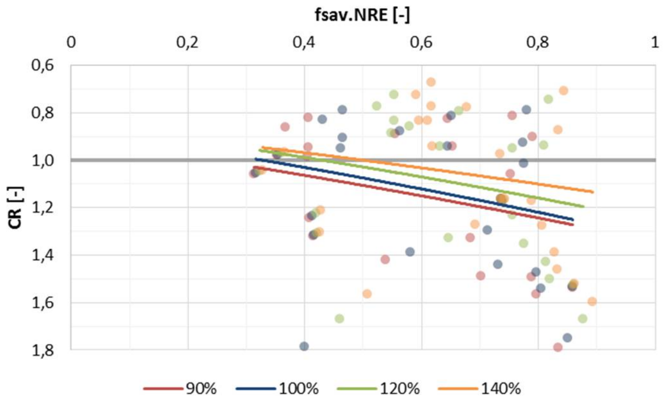


Figure 40: Sensitivity analysis on energy production (output) for the overall trend

The separated sensitivity analysis is shown in Figure 41 and representing differences for ST and PV supported systems. The southern located systems are generally less affected as they mainly have larger energy demands and thus can operate already more than in the northern locations. The effect on savings is more relevant at lower savings and more relevant for PV supported systems. One major factor is the size of the systems, in which the majority of PV supported are significantly lower in capacity but also in energy demands that are satisfied than the ST supported systems.

For the northern located systems, the effect is varying a lot, depending on the entire systems. The trend shows a larger sensitivity on the CR for ST at lower savings compared to PV. At larger savings the effect is larger for PV supported systems compared to ST.

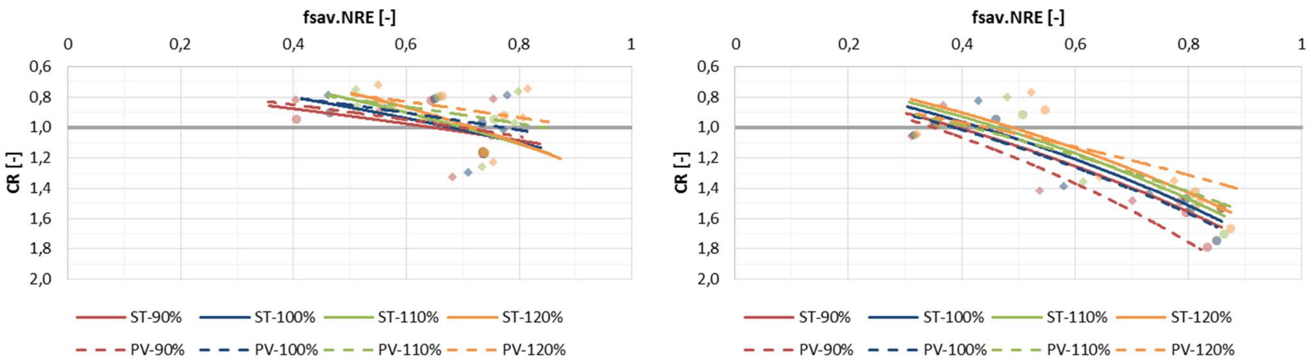


Figure 41: Sensitivity analysis on energy production (output) for the southern (left) and northern (right) location separated for PV and ST

5.6. Conversion factor electricity - □$_{el}$

The conversion factor for electricity for all systems (SHC + Ref) is changed according to Table 6, in the graphs four selected results are presented. The conversion factor is needed to calculate the non-renewable primary energy demand for allocation of each kWh electricity. The more renewable electricity (water, wind, PV, etc.) is in stock the larger the value. As T53 standard a value of 0.4 kWh_{el}/kWh_{PE} is used. At present the value is already larger for some countries (Austria, Germany, …). Further this value is depending on the season (e.g. hydro power or PV in winter / summer) or even on smaller time periods (e.g. Wind). However, a constant annual mean value is used for the standard T53E4 analysis, but the tool offers the possibility to use / input monthly changing values. Up to now only Austrian values were implemented as monthly values (Stadler 2015), as they need to be calculated and are not available by default. Thus, the monthly analysis is an open issue to be done in future work.

The factor is decreased down to 90% (lower value, e.g. in China) as well as increased up to 115 and 130% accordingly. For the separated view the increase is even kept in a larger range of 130 and 160% (roughly the value for Austria) of the original respectively. The conversion factor of electricity is affecting the non-renewable savings only, the CostRatio cannot be influenced by this sensitivity analysis.

Figure 42 is presenting the sensitivity on the electrical conversion factor on the overall trend. The change of savings depends on the system design and configuration. When the conversion factor is changed from 90 to 130% accordingly, single plants show a change in $f_{sav.NRE}$ of almost 20%, other plants a maximum change of 5%. The overall trendlines are moving towards higher savings if the conversion factor is increased. Whereas, due to the amount of electrical auxiliary demand the sensitivity is slightly larger at lower savings (~10%) and lower at higher savings (~5%) where the plants are already optimized.

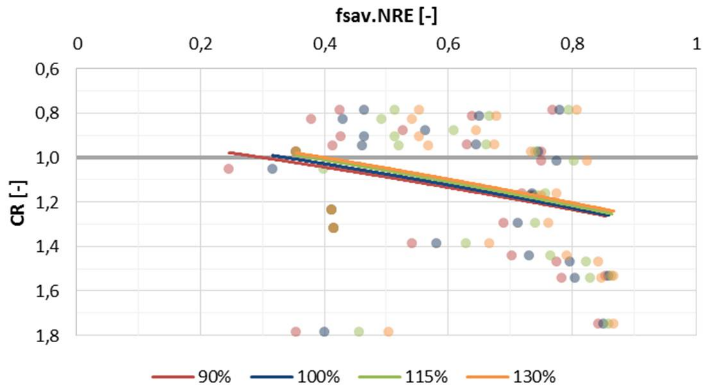


Figure 42: Sensitivity analysis on conversion factor of electricity for the overall trend

The separated trends, which are significantly showing a different attitude for southern and northern locations, is shown in Figure 43. For the southern locations the change for both, the PV and ST supported systems, in savings is up to 20% at lower savings and up to 7% at higher savings. Whereas the gradient is changing much more for the ST supported systems, indicating that the influence at higher savings is much lower compared to PV supported systems.

For the northern locations the PV systems show a higher sensitivity at lower savings (~30%) compared to ST systems (~7%). At higher savings the sensitivity is lower and reversed; ST shows a change of roughly 10% compared to PV with 8%.

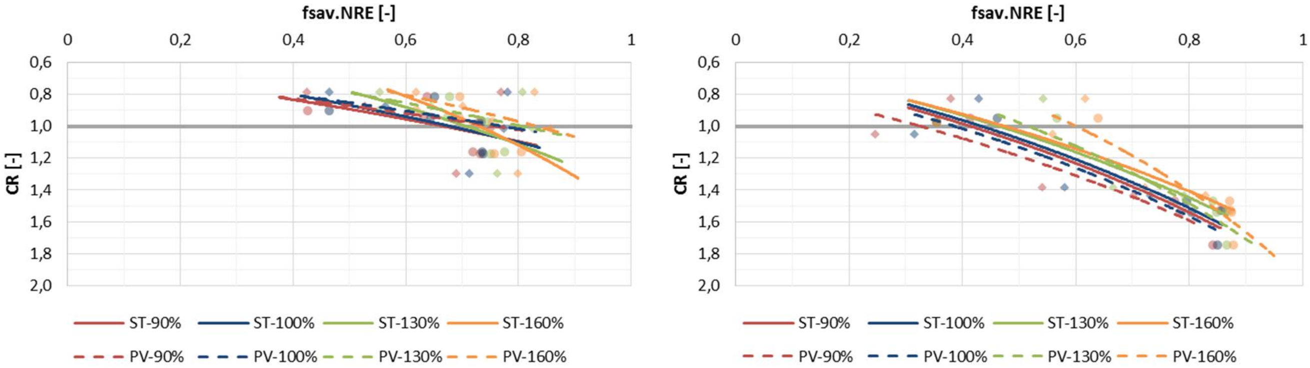


Figure 43: Sensitivity analysis on conversion factor of electricity for the southern (left) and northern (right) location separated for PV and ST

5.7.Reference system

The reference system is predefined; it consists of an air-cooled vapour compression chiller for cooling and a natural gas boiler for space heating and domestic hot water preparation. The efficiency is calculated according to the size of the chiller (different technologies with varying SEER) and the part load for the natural gas boiler.

Nevertheless, the actual reference system and its related efficiencies depend on many factors. E.g. in Spain there is a certain solar thermal fraction for domestic hot water obligatory; In other cases, a reversible heat pump for heating and cooling seems to be the correct choice of reference; etc. Thus, the reference system must be adapted on technical and economic side accordingly. If a project is analysed with the T53E4 tool, there is an opportunity to adapt the local reference system, but it is not in the focus of this analysis to adapt each analysed plant with its corresponding reference.

However, the relative presentation of the results in terms of economics (CostRatio) and environmental impact (non-renewable primary energy savings) allow a rough estimation of changes in the reference system. Although the trendlines could change its gradient and position, a single view on certain plants should be possible. Depending on the specific energy demand mixture and individual boundaries for each case a new origin can be calculated. An example is presented in Figure 44, two specific reference systems are calculated for plants #9a/b and discussed briefly.

The two specific reference systems consist of a reversible heat pump with different seasonal efficiency factors (theoretical and on total system level!) for cooling and heating. The corresponding non-renewable primary energy savings and CostRatio's are calculated with the T53E4 tool. The investment, maintenance and electricity costs are considered automatically by the T53E4 tool.

If the lower efficient heat pump (ref #1) is applied savings of 11% at 17% higher costs are achieved. If the heat pump would be more efficient (ref #2) higher savings can be achieved. The change is depending on the ratio of heating and cooling demand that is satisfied (here heating is more dominate). If the investment costs keep the same the CR is decreasing due to lower electricity costs to a value of 1.1.

- Ref #1: heat pump with system $SPF_C = 4$, $SPF_H = 3 \rightarrow f_{sav.NRE} = 0.11$, CR = 1.17
- Ref #2: heat pump with system $SPF_C = 5$, $SPF_H = 4 \rightarrow f_{sav.NRE} = 0.32$, CR = 1.10

If the results are integrated in the standard figure the difference gets obvious (c.f. Figure 44). The origin of the T53 reference is shifted accordingly. Both systems 9a (ST supported) and 9b (PV supported) account for cost parity against the original reference systems at 30-35% savings. Compared to both new reference systems the CR is lower for the renewable systems. However, if the high efficient heat pump system is implemented the system #9b would result in negative savings (~-2%); system #9a would only achieve savings of 3%.

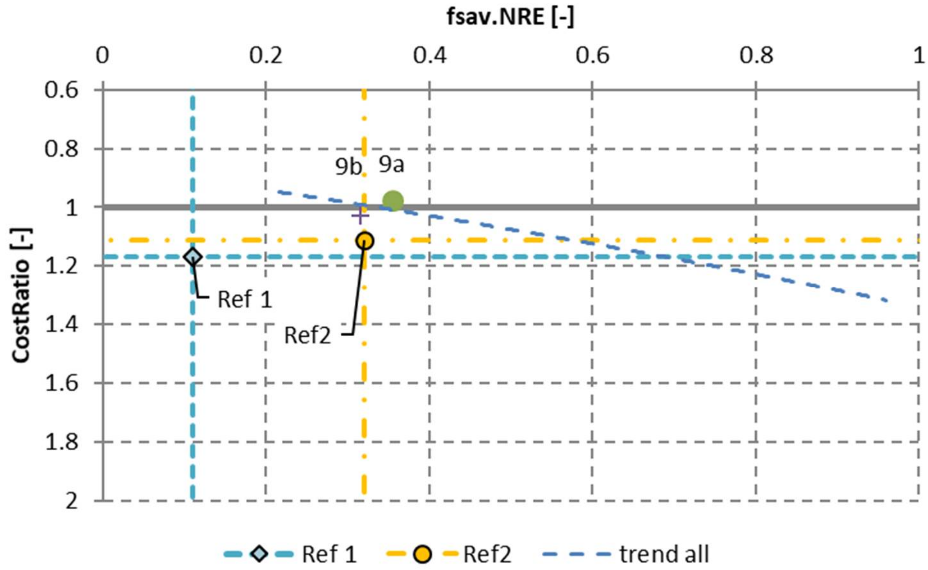


Figure 44: sensitivity on change of reference system on the overall trend

6. Conclusion

New 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.

The T53E4 assessment shows different correlations and trends between the economic and technical key figures of different kind of SHC systems. Even though 28 systems are considered for the analysis the critical mass for statistically loaded results are not achieved and thus adding new examples can have a significant influence on the specific results. It is also evident that the contributions are made by participants of the Task and thus the sunbelt region (MENA, South Asia, America, …) with its strongly growing market and interesting boundary conditions are underrepresented. Nevertheless, the amount of analyzed systems is representative to show overall trends, direct comparisons of trends needs to be taken with care.

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. For example, the SERM project (c.f. chapter 8.1) was installed under total commercial conditions but has been the very first installation for nearly all the actors and especially the installer. This led to an installation time longer than expected and thus to higher cost (especially provisions for unexpected events).

Thus, the cost analysis of all SHC systems and of the reference system performed and presented here are based on the same assumptions. The real costs may vary significantly under different boundary conditions e.g. location (countries), experiences of planers, installers, etc. Even the main characteristics of the reference system may depend on the country or a complete different reference system would be more representative. For example, if a solar thermal contribution in the domestic hot water production or space heating is established in the national regulation, then the reference system should include such solar thermal facility accordingly (e.g. like in Spain).

Nevertheless, for the assessment provided here it is important to have an independent comparison between the different technologies or systems, but when designing individual SHC system the local conditions must be considered in each detail! In the following section the results are discussed along some important headlines representing ongoing discussions around the topic of new generation solar cooling and heating systems.

6.1. T53E4 Tool & Method

- The T53E4 Tool allows to analyses a given SHC or renewable system, its post processing simulated or monitored data under predefined conditions. The technical and economic key figures are based on monthly database; seasonal effects can be considered. However, a daily analysis is unseizable and the performance is only judged under its monthly achievements. Consequently, if a system provides advantages under certain conditions but get counterbalanced over a month (e.g. due to backup’s or standby losses, etc.) the benefits does not get recognized or rated.
- The aim of the T53E4 tool is to enable a standardized analysis of individual SHC systems and therefore allow a comparison under SHC but also other renewable concepts in terms of technical and economic performance. The economic analysis is based on standardized costs and predefined efficiencies and conversion factors. The results are compared to a predefined reference system to represent all technical and economic outcomes in a normalized way, avoiding a discussion of absolute magnitudes. However, the absolute values are calculated as well and can be discussed when needed.
- To provide sufficient flexibility the T53E4 Tool is evaluating two standards in parallel, the T53 Standard and a project specific one. For designing SHC systems the consideration of local conditions

is important, and the T53E4 Tool needs to be adapted accordingly. Further the possibility of comprehensive sensitivity analysis is given and can be useful for the design process.

- During the evaluation of the 28 examples some major bug fixed have been completed but there is still a potential of unmissed bugs as the T53E4 tool can be used very general. However, the T53E4 tool will be published with all its documentation but without support and can be used for assessments of renewable heating and cooling systems.

6.2.Small vs. large scale plants

- Among the analyzed projects, the cooling capacity is in a range to be considered as small (50% <10 kW) to medium (21% < 100 kW) therefore scale effects were not really achieved, and the benefit can only be discussed theoretically.
- 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.

6.3.ST vs. PV

- 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 (Henning, 2006) and IEA SHC Task 48 (Mugnier, 2011)) are an important knowledge base.
- Regarding PV supported systems
    - A special focus should be on the coupling between the solar production and the thermodynamic converter (vapour compression chiller). Two directions are possible in general (i) either the coupling is partial and complemented by the grid, or (ii) the coupling is full and direct whereas the compressors are not manufactured for such a variable energy source. If the compressor areis not adapted expensive batteries must be used. A focus on the management of the compressor(s) must be elaborated in close partnership with the compressor manufacturer.
    - Another crucial component is the solar inverter because it gives a margin to smoothen the solar variability (especially through the MPPT tracker device but not only)
    - PV driven systems need to be designed with a control system focused on maximize the use of the PV energy in the chiller / heat pump. These systems require in general storages: thermal or electrical.

- The use of surplus PV electricity (strongly depends on the design of the system) not used for HVAC but still for self-consumption in terms of household electricity needs to be considered. This analysis is possible with the T53E4 tool but was not generally included as the examples are to various in Task 53. With the increasing number of installed PV facilities, it can be expected that regulation will focus on the PV self-consumption to reduce grid stress.

- Regarding absorption chillers/absorption heat pumps
  - Renewable backup heat sources for thermally driven SHC systems should be exhausted as much as possible. For example, northern European countries show a high potential for the use of biomass driven district heat.
  - In general, there should be a higher focus on combining the cooling and heating purpose as well (Space Heating, DHW). Systems that can fulfill both, heating and cooling, in an efficient way that can be more economic.
  - In case of small scale absorption chillers/heat pumps the focus should be to lower investment costs, for the component itself but especially for piping and external effort.
- Those system that combine ST and PV which were analyzed here are ending up with high CostRatios at moderate solar fraction und thus moderate non-renewable primary energy savings. PVT was not used in any of the 28 examples analyzed. However, it is, as it is the case for ST or PV supported systems, a matter of design and optimization in the individual case to reach technical and economic feasible and appropriate facilities.
- 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 for southern and northern location) both technologies are very close in technical and economic performance.

6.4.Northern vs southern location

- Significant differences are observed when comparing systems and their technical and economic results separated for northern and southern locations. In northern regions lower cooling demands occur and the period of cooling is shorter compared to southern regions. However instead there is a larger heating demand in the norther location; Due to solar irradiation and the coincidence of loads the effort to reach large solar fraction and non-renewable primary energy savings respectively is disproportional for northern locations.
- Domestic hot water demand is independent of the location and more related to the building / load profile but often offers a year around and constant energy demand. Depending on the design the solar fraction in the shoulder seasons (without heating or cooling demand) can be significant and support the technical and economic performance of the entire systems accordingly.
- Thus, the maximum CostRatio’s at maximum non-renewable primary energy savings for southern locations reach 1.1 compared to 1.6 (trend wise) and the efforts to reach cost parity are much higher in northern location accordingly.
- Systems dominated by heating demand, as it is typical for northern areas, show promising results using reversible absorption heat pumps compared to electrical driven heat pumps (especially air/air heat pumps). Nevertheless, it need to be considered that an appropriate low temperature heat source needs to be provided e.g. the solar collector can operate as low temperature heat source.
- In warmer climates, high energy savings can be achieved by using PV-electricity to cover part of the domestic electricity consumption.

6.5.Peak vs base load

- The overall trend is showing that if high non-renewable primary energy savings should be achieved the CostRatio is increasing accordingly. In general, higher investment costs can be expected to cover peaks loads and thus the it is often more economical to cover peak loads with auxiliary boiler. However, the individual economic results depend on the location, energy demands, the design (investment) and many other factors.
- Nevertheless, some autonomous systems included in this study show promising results e.g. plant #15 and #16 achieve low cost ratios with its design for almost solar autonomous operation. Although the examples do not provide a full year analysis (#16) or have no annual operation (#15) CR's smaller 1 can already be reached.
- Among the 28 analyzed plants the lowest CostRatio was achieved with plants, designed for a medium range of non-renewable primary energy savings of 40-80%. The lowest CostRatio was reached at a level of roughly 0.8 under standard conditions.

6.6.Sensitivity analysis

- The sensitivity analysis illustrates how the economic and technical performance of the SHC systems is changing when different predefined boundary conditions are varied. It is the basis to find circumstances under which SHC systems can be cost competitive compared to the predefined reference system. To simplify the analysis the sensitivity is expressed for the trend lines describing the coherence of economics (CR) and environmental impact (fsav.NRE) for all systems. Further the sensitivity of trend lines separated for northern and southern location as well as separated for ST and PV supported systems are discussed.
- The utmost significant influence on economics 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% can be reached (not unrealistic, c.f. ROCOCO (Preißler, 2008) the trend line considerably undermatches a CostRatio 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 %.
- In addition, the electricity price, auxiliary demand, the energy production and the conversion factor for electricity was varied. However, all these changes did not show a very significant influence in the economic and technical results. Although the single effects are low it must be noted that a combined optimization or change of boundary condition might still be from interest, especially if a specific SHC plant under local boundaries needs to be designed and optimized.
- The sensitivity analysis of the energy output is pointing on a very important issue. The results are showing that with increased energy production (higher energy demand of the building/process) the CostRatio can be decreased and the savings can be increased. The focus of this Task and especially this work presented here is on the assessment of HVAC only. For a more appropriate and holistic statement it is necessary to include the building / process into the assessment, a detached HVAC consideration is only half of the truth!

- For the assessment the reference system is predefined as T53 Standard and consist of an air-cooled vapour compression chiller for cooling and a natural gas boiler for domestic hot water and space heating preparation. In some cases, different reference systems are more appropriate. Thus, the general relative nature of the assessment can be used easily to study the effect of changing reference systems. The change of economy or efficiency of the reference can be integrated in the diagrams and analyzed accordingly. An example is exanimated explaining the procedure and its interpretation of results.

Summing up: Both technologies, solar thermal and PV, can be integrated to support a HVAC system accordingly and both systems can be competitive against reference systems when they are well designed and boundary conditions are favorable. This study presents a technical and economic assessment of 28 plants and configurations, of which 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 can 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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8. Appendix: Detailed description of analyzed plants

In the following chapter all systems considered for the evaluation are described in more detail and their key results are discussed briefly.

8.1. SERM (by: TECSOL; ST; C+DHW)

The SERM project is applied for the building "Amiral" in the urban zone "Jacques Coeur" at Montpellier (France). It's a group of buildings used for different purpose: offices, dwellings, shops.

All the energy production devices are centralized and supply energy using a small district heating/cooling network. Cooling is mostly used by the office and the shops. Domestic hot water is mostly used by the dwellings and heating is used by all the three types of loads. The major advantage of this kind of building is the significant cooling demand in summer and the massive domestic hot water demand all year long. As a consequence, the system produces chilled water with solar energy in summer to reduce the consumption of the conventional chillers and produces solar domestic hot water all year long.

There are two possibilities: the heat can be transferred to the domestic hot water production sub-stations or it can be used to produce cold. In this case, the heat is transferred to the generator of an absorption chiller. This device produces cold which will be sent to the general chilled water distribution circuit. The absorption chiller then rejects heat to the ambient at a medium temperature via heat rejection device. The one which was chosen is an adiabatic aero-cooling device.

Usually in southern part of Europe most of the large domestic hot water systems for dwellings are sized to work with the maximum solar fraction occurring in summer time. Basically, a value of 80% to 85% is targeted leading to an average annual value of about 50% and an average of 20% to 30% in winter.

The solar collector field has been sized in order to have the highest solar fraction during inter-seasonal period. As a consequence, the solar fraction is higher in winter than usually and there is no risk of overheating in summer because the additional solar heat is used to produce chilled water to cool down the building.

Basically, the control is managed as follows:

- In winter: all the solar energy is used to produce domestic hot water. This winter mode is used as long as possible. Then in spring, when the installation is close to overheating it is switched to summer mode.
- In summer the priority is given to the absorption chiller for cooling. The large area of collectors permits to reach a sufficient temperature in the hot tank earlier in the morning. So, the installation starts producing chilled water earlier compared to a classical design for a solar cooling system (solar collector oversizing favorable). The temperature in the tank is controlled at the optimal working point of the chiller by a 3-way valve. The excess energy is transferred to the sub-stations to produce domestic hot water.

For the SERM system two different cases are analyzed. (1a) represents the monitored values of 2016 and (1b) represents a fictive case where the cold production of the overall system (a higher cold demand) is estimated. The system is serving as base load to a larger, not monitored conventional vapor compression system. Assuming that the SHC system provides 20% of the overall cooling load (c.f. 9 MWh in (1a) 47 MWh in (1b)), an overall system performance was estimated. The energy carrier input is not affected as DHW demand is kept constant, the conventional chillers only rise the electricity demand. It was assumed that the conventional system is working at an electrical seasonal performance factor of 3.

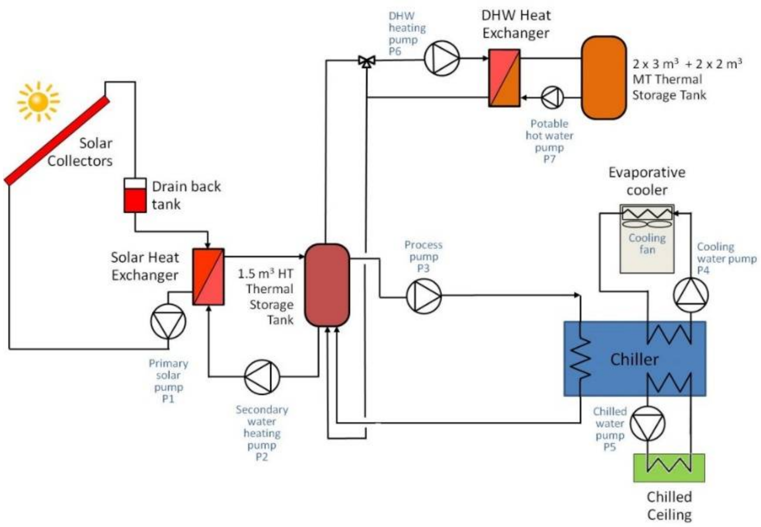

Figure 45: Hydraulic scheme of the SHC system by Tecsol in France (Mugnier and Seleme, 2017)

The non-renewable primary energy savings are calculated against the pre-defined Task 53 standard reference system. The lower the energy carrier (here natural gas) input the higher the savings. In 2016 74% savings were achieved, mainly influenced by the excess DHW consumption. If the overall system is analyzed and the conventional compression system is included in the analysis the savings drop again, but only slightly.

Table 6: Energy balance and cost comparison of the SERM 1a system

ENERGY		**1a**		**1b**	
		kWh			
EC.Sys		31’028		31'028	
SC.sys		117’802		117'802	
GD.sys		5’489		14'883	
WD.sys		133’173	0.93	133'173	0.74
SH.sys		0	0.00	0	0.00
CD.sys		9'394	0.07	46'970	0.26
$f_{sav.NRE}$		0.747		0.65	
SPFequ		7.39		6.28	
COST		**SHC**	**REF**	**SHC**	**REF**
Annualized cost	€	17'389	14'842	38'729	41'073
LCOE	€/kWh	0.122	0.104	0.215	0.228
CR	-	1.17		0.94	

The excess consumption for DHW and the conventional compression system are influencing the CR positive as the ratio of investment to consumption (energy) based cost is changing. The additional costs recline between 17% (1a) and -6% (1b). The LCOE behave different, reflecting the difference in heat and chilled water cost. The more DHW demand is satisfied the smaller the LCOE, if chilled water production is analyzed the LCOE rise, although the CostRatio reaches lower costs than the reference system.

In the following 2 figures the breakdown to the entire subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($f_{sav.NRE}$) and SPFequ is presented as added annual figures but also the annual course. The annual values are dominated by the DHW subsystem efficiencies as the ratio of DHW is greater than 90% in the monitored cases (1a). The annual course of PER for the SHC and the reference system is indicating that the solar fraction of DHW was very high in March to July, where the savings reached roughly 90%. In contrary the $PER_{NRE.ref}$ is almost constant over the entire year, slightly smaller in summer when the degree of capacity utilization is smaller compared to winter operation.

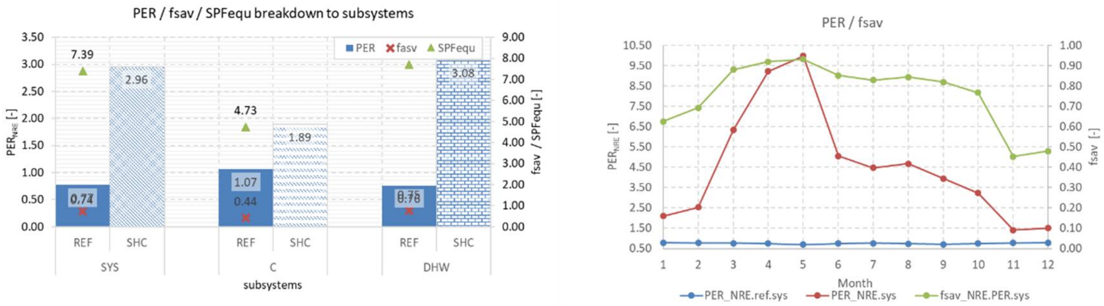

Figure 46:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the SERM 1a system

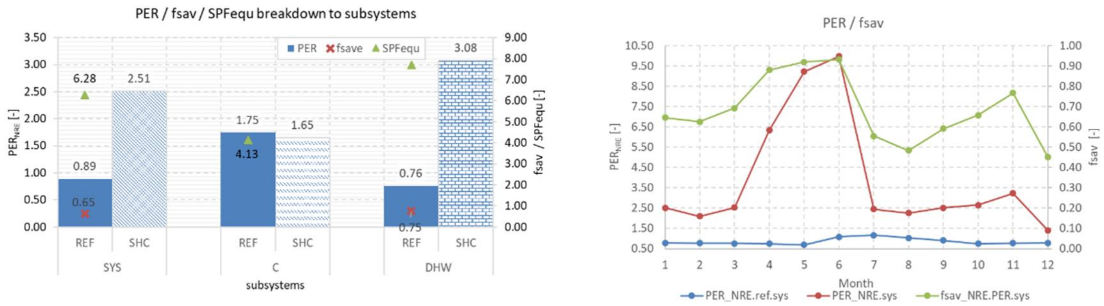

Figure 47: Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the SERM 1b system

If the overall system is analysed, the reference system efficiency and $PER_{NRE.ref}$ is increasing as the EER_{ref} is depending on its size (35 kW (1a) vs. 280 kW (1b); as compressors get more efficient, refer to (Neyer et al., 2015)). This is leading to negative savings, which get balanced by the positive DHW values. In this case the assumption of EER for the conventional system might be too low, but anyway showing the effect that need to be taken with care if an overall system is analysed. If the entire SHC system is small compared to the overall system, the economics can get attractive but the non-renewable primary energy savings can suffer.

The following two figures below present the annualized cost of the entire systems. The cost analysis shows that the SHC system has higher investment costs, but lower fuel costs compared to the reference. In addition, the reference system has relatively high costs for electricity of the HVAC system compared to the SHC system.

Investment cost change from 59% in (1a) to 45% in (1b) but the absolute investment is growing if the conventional system is taken into account from 10 k€ to 17 k€. The excess in electricity is visible in the rising share respectively. On the other hand, the maintenance costs of the SHC systems are higher compared to the ones of the reference system. The overall annualized costs of the SERM SHC system are 17 % higher as the ones from the reference system (CR=1.17) if the total system is taken into account cost savings of 6% can be achieved (CR = 0.94).

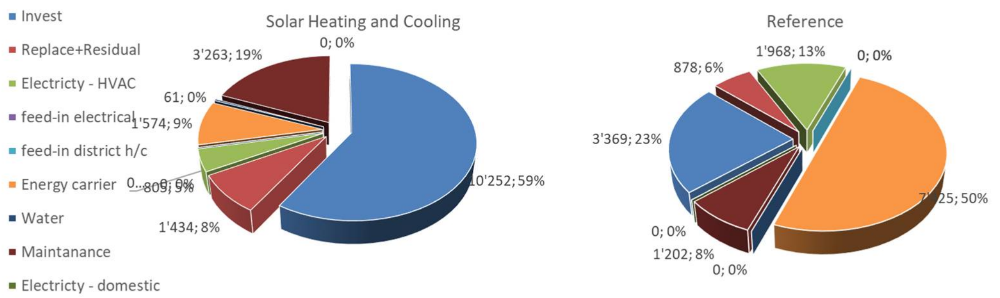

Figure 48: Annualized cost distribution of the SERM 1a system

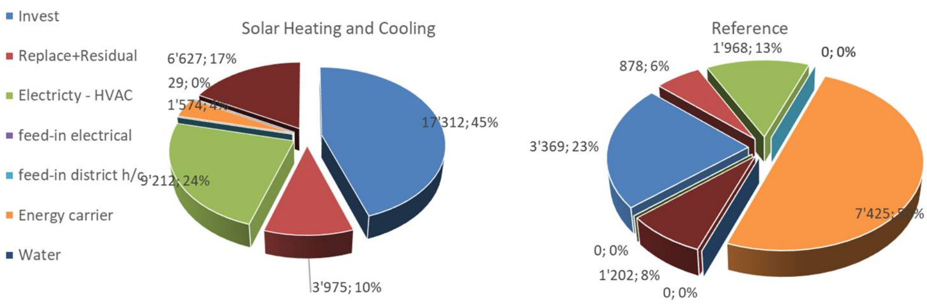

Figure 49: Annualized cost distribution of the SERM 1b system

8.2. Inspire (by: EURAC; ST vs. PV; SH+C+DHW)

The example reported here is one of the cases studied within the iNSPiRe project (Fedrizzi, 2015) in the field of the refurbishment of existing buildings. One of the outputs of the project is the development of a simulation-based database with energy performance, investment and running costs of a wide range of combinations of different building typologies and HVAC system configurations.

A 5-floors small multifamily house (sMFH) with ten dwellings of about 50 m² each as well as a single-family house (SFH) is used. The houses are simulated in different climates: Madrid and Stuttgart and therefore have different cooling and heating demands. The SHC system covers the DHW, space heating and cooling demand of the house with a centralized air to water heat pump in combination with PV or solar thermal collectors or a combination of both technologies. It is also connected to a sensible storage tank.

Firstly, the heat pump charges a tank to satisfy the DHW demand. In this case, the tank size is 430 l for the MFH and 140 l for the SFH to cover the DHW demand. This same tank is also used for storing solar energy in case a solar field is used but then the volume is larger and results from a design of 50 l/m² of the solar panels area (Fedrizzi, 2010). The yearly DHW demand is assumed to be around 20-22 kWh/m².

Six different cases are evaluated, varying the climate, load profile and heat source. The stored solar energy can be used for the DHW demand or for heating. The surplus of electricity from the PV system is fed into the grid. The capacity of the renewable energy generation for the MFH is either 4.8 kWp (31.2 m²) in case of PV or 27.6 m² collector area in case of a solar thermal heat source. For the SFH the capacity of the PV is 2.4 kWp (15.6 m²) and the collector area is 9.2 m² and they are used both at the same time. The hydraulic scheme is shown in Figure 50.

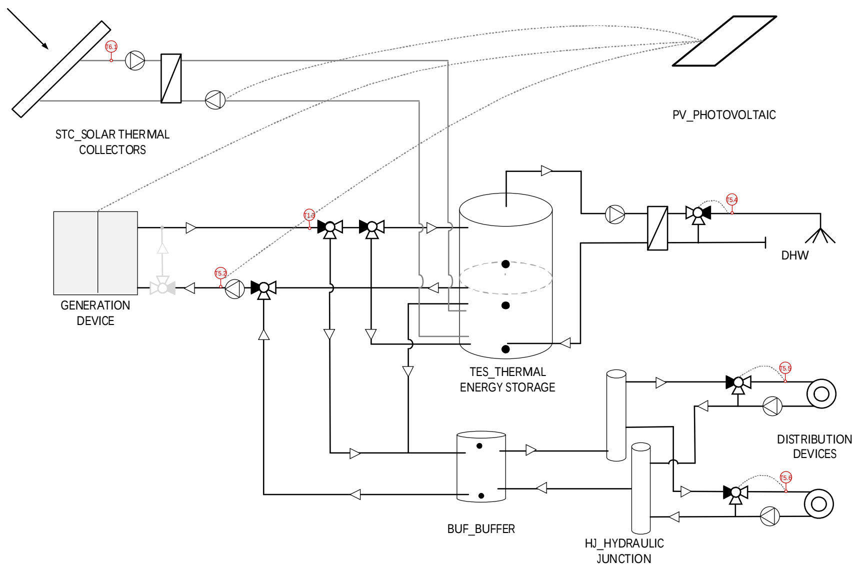

Figure 50: Hydraulic scheme of the centralized reversible heat pump system of the project iNSPiRe

Further details can be found in Dipasquale et al. (2011), Dipasquale et al. (2013) and Dipasquale et al. (2016).

Table 7: boundary conditions / systems for the 6 analysed plants

	2a	2b	2c	2d	2e	2f
Location	Madrid	Madrid	Stuttgart	Stuttgart	Madrid	Stuttgart
Load profile	MFH	MFH	MFH	MFH	SFH	SFH
Solar system	PV	ST+HP	PV	ST+HP	ST+PV	ST+PV

The non-renewable primary energy savings are calculated against the pre-defined Task 53 standard reference system. In the following, results referred to MFHs are reported, then results for SFHs are also presented. First plants #2a (PV) and #2b (ST+HP) are compared, as they are located at the same place (Madrid) and have the same load profile (MFH). Accordingly, the loads are the same, whereas the space heating demand is dominate (47%), followed by the space cooling demand (35%) and the domestic hot water demand (18%). The relatively high heat demand of 57 kWh/m².a is caused by a combination of insulation thickness of the external surfaces that causes a higher building demand compared to the building in Stuttgart. A 1 cm-step of additional insulation would have led much lower heating demand. Both systems, the PV driven, and the solar thermal can reach almost the same savings of 47% and thus ending up with the same equivalent SPF of 3.8.

From cost point of view, both systems achieve lower annualized cost as the reference system and thus presenting a CR lower 1. The PV driven system sums up to 10% lower costs than the ST system, mainly driven by lower investment costs. Finally, the PV driven systems reach a CR of 0.79 and the ST system of 0.90.

Table 8: Energy balance and cost comparison of the Inspire system for Madrid, MFH

ENERGY		**2a**		**2b**	
		kWh			
EC.Sys		0		0	
SC.sys		0		17'128	
PV.sys		6'676		0	
GD.sys		15'868		15'999	
EL.sys		2'444		0	
WD.sys		11'042	0.18	11'137	0.18
SH.sys		28'418	0.47	28'423	0.47
CD.sys		21'332	0.35	21'329	0.35
$f_{sav.NRE}$		0.47		0.46	
SPFequ		3.8		3.8	
COST		**SHC**	**REF**	**SHC**	**REF**
Annualized cost	€	5'629	7'153	6'496	7'181
LCOE	€/kWh	0.093	0.118	0.107	0.118
CR	-	0.79		0.90	

In the following 2 figures the breakdown to the entire subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($f_{sav.NRE}$) and SPFequ is presented as added annual figures but also the annual course. The overall system performance sums up to the same values for both PV and ST system, whereas the subsystems present very different efficiencies and savings respectively.

The key figures for subsystem cooling (C) already take PV electricity into account, thus the PV driven system reaches a higher PER_{NRE}, $fsav_{NRE}$ and SPFequ than the solar thermal supported system. The solar thermal preliminary supports the domestic hot water and secondly space heating preparation. This is especially reflected in the key figures of DHW where ST reaches 2.3 times higher efficiencies. Nevertheless, due to the low fraction of DHW it is not evident for overall performance. The PV support for space heating is more effective than the ST support, because of adopted control strategies and thus PV subsystem ends up with a higher PER_{NRE} etc.

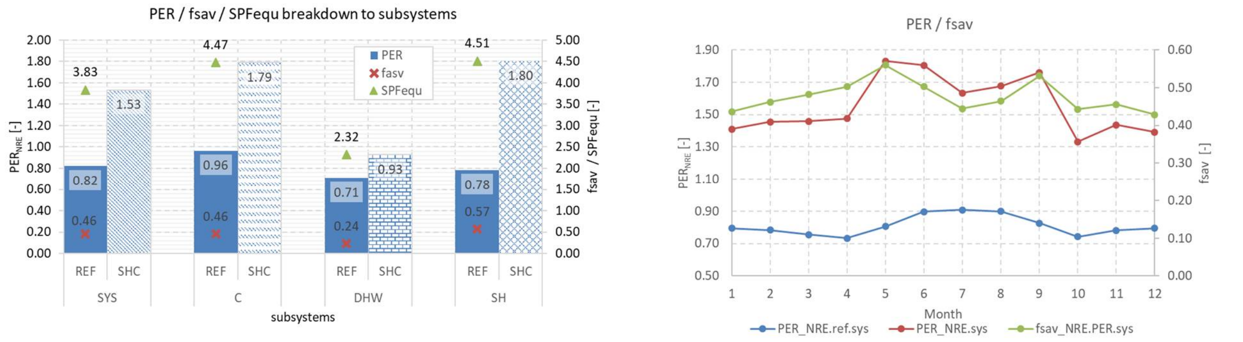

Figure 51:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the INSPiRe SHC system with PV for MFH in Madrid

The annual course reflects the annual (seasonal) values. In those months where DHW is dominate (e.g April / May) ST shows higher efficiencies, where cooling or heating is dominate PV driven systems shows their potential.

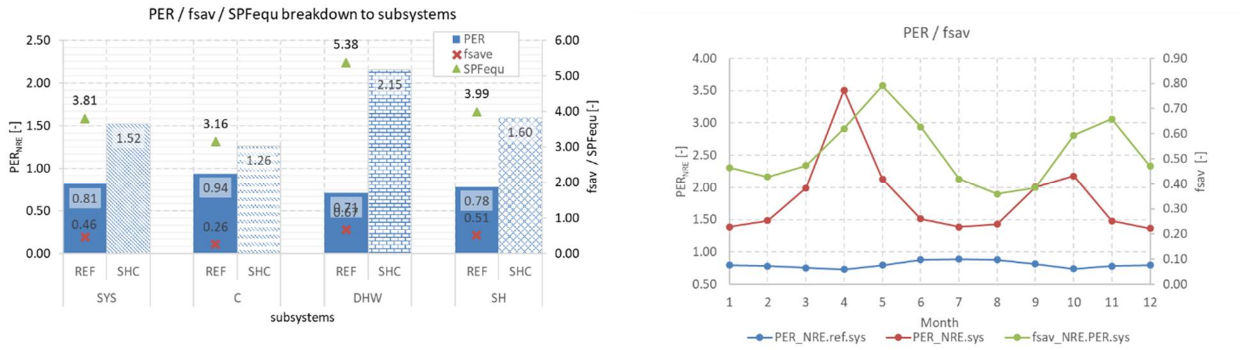

Figure 52:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the Inspire SHC system with ST for MFH in Madrid

The following two figures below present the annualized cost of the entire systems. The SHC systems are dominated by the electricity costs (heat pump) and investment. The comparison shows that the electricity cost of the PV and ST system are almost the same (reflecting the electricity demand of table above) but the investment cost of the ST are roughly 25% higher. The reference system shows the typical mix of investment, electricity (air cooled vapour compression chiller) and energy carrier cost (natural gas) for a system providing space heating, domestic hot water and cooling demands.

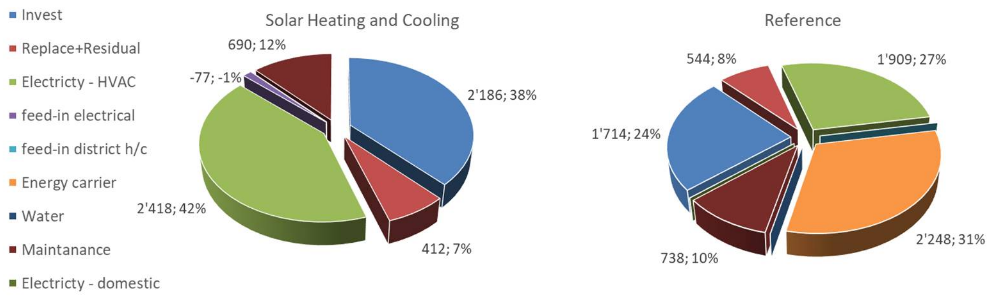

Figure 53: Annualized cost distribution of the Inspire SHC system with PV for MFH in Madrid

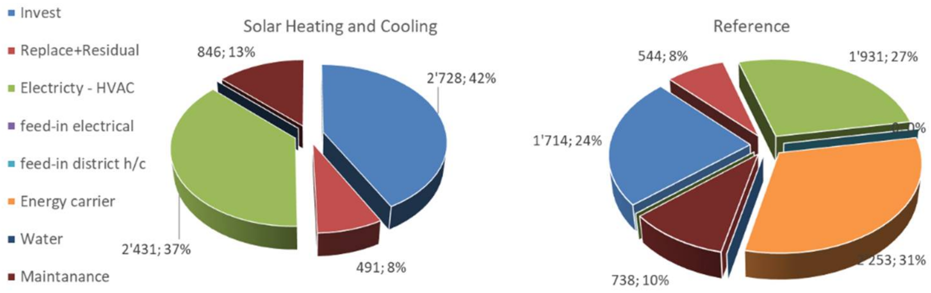

Figure 54: Annualized cost distribution of the Inspire SHC system with ST for MFH in Madrid

The comparison of plants #2c and #2d shows the difference of PV and ST supported system for the small multifamily house at the location in Germany (Stuttgart). The overall demand is dominated by space heating (56%). Followed by domestic hot water demand (26%) and cooling (18%). As the solar thermal system consumes less grid electricity than the PV driven the non-renewable primary energy savings and the equivalent SPF are slightly higher.

From cost point of view, the PV system sums up to lower total annualized costs than the ST supported system. The difference is roughly 10%, mainly forced by the higher investments. Nevertheless, both systems present CostRatios lower than 1 and thus are less expensive than the reference systems.

Table 9: Energy balance and cost comparison of the Inspire system for Stuttgart, MFH

ENERGY		**2c**		**2d**	
		kWh			
EC.Sys		0		0	
SC.sys		0		12'725	
PV.sys		4‘582		0	
GD.sys		12'305		12'060	
EL.sys		2'042		0	
WD.sys		10'982	0.26	11'116	0.25
SH.sys		23'835	0.56	25'155	0.57
CD.sys		7'703	0.18	7'706	0.18
$f_{sav.NRE}$		0.43		0.46	
SPFequ		3.5		3.6	
COST		**SHC**	**REF**	**SHC**	**REF**
Annualized cost	€	5'257	6'345	6'113	6'435
LCOE	€/kWh	0.124	0.149	0.139	0.146
CR	-	0.83		0.95	

The annual key performance figures show similar behavior as the system located in Madrid. Based on the grid electricity the subsystems cooling and space heating are more efficient in the PV supported than in the ST driven system. Due to the different distribution (DHW more dominate than cooling) the ST thermal driven system end up with a more efficient system, based on non-renewable primary energy demand.

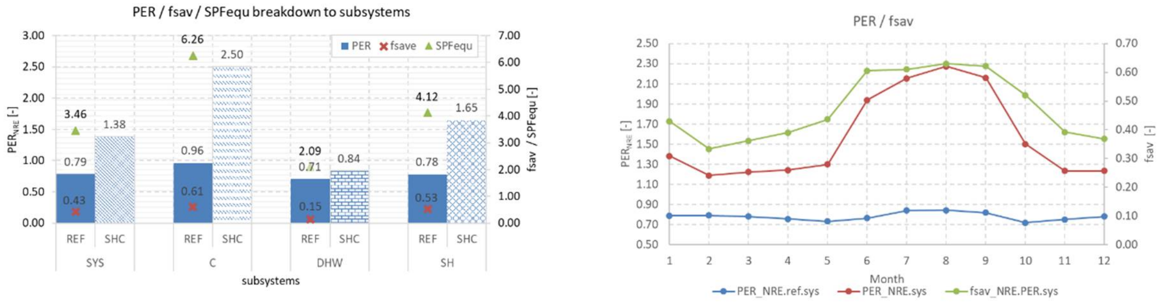

Figure 55:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the Inspire SHC system with PV for MFH in Stuttgart

The annual course of $PER_{NRE.SYS}$ and $PER_{NRE.ref}$ reflect the annual values. Highest savings of the PV supported system can be achieved in summer where cooling is dominate The ST system reaches its maximum savings in month with DHW dominance. (April, May, Sept.).

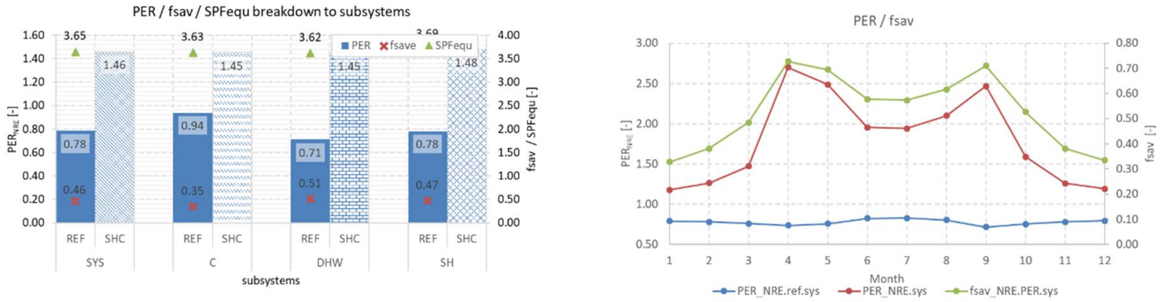

Figure 56:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the Inspire SHC system with ST for MFH in Stuttgart

The breakdown of the annualized costs does not change dramatically when the location is changed. The main difference is reflected in the electricity costs (less demands) for the SHC systems and the energy carrier for the reference system accordingly. The system is designed in the same size; thus, the investment costs are the same for both locations.

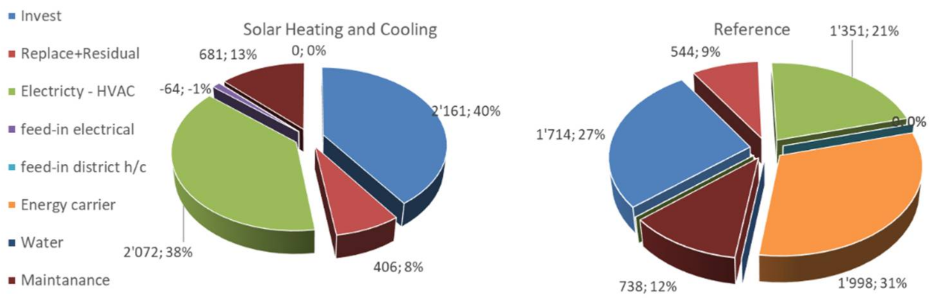

Figure 57: Annualized cost distribution of the Inspire SHC system with PV for MFH in Stuttgart

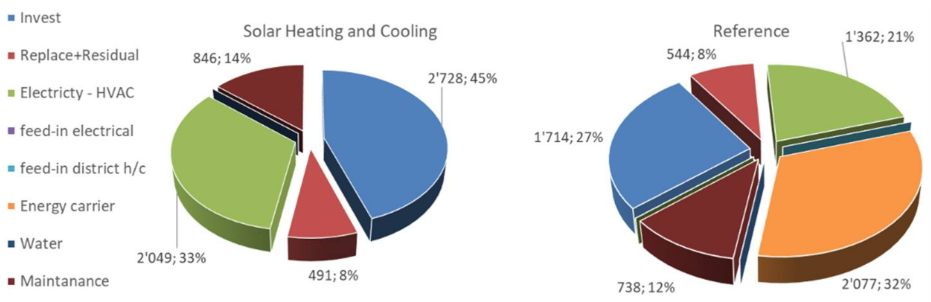

Figure 58: Annualized cost distribution of the Inspire 2d SHC system with ST for MFH in Stuttgart

Plants #2e and #2f are presenting the case study for the combined ST+PV system for a single-family house at different locations. Nevertheless, the absolute demand for Madrid and Stuttgart are almost the same for space heating and domestic hot water but the cooling demand is roughly 3 times higher in Madrid than in Stuttgart. The energy demand ratios account accordingly to 20 and 25% for DHW, 53 and 64% for SH as well as 26 and 11% for cooling.

The systems equal in design of collector and PV area but also for max. heat / cold capacities as the minimum most common on the market available devices are chosen. Due to the larger irradiation and thus higher solar yields the system in Madrid can achieve higher non-renewable primary energy savings and a higher equivalent SPF respectively. The system in Madrid reaches an SPFequ of 6.4, the system in Stuttgart roughly 4.4.

From cost point of view the differences occur because of the difference in energy demands. Both locations reach clearly higher costs than the reference system. The system in Madrid end up at 30% higher costs than the reference system, the system in Stuttgart at 40%.

Table 10: Energy balance and cost comparison of the Inspire system for ST+PV, SFH

ENERGY		**2e**		**2f**	
		kWh			
EC.Sys		0		0	
SC.sys		5'406		3'515	
PV.sys		3'380		2'319	
GD.sys		1'622		1'939	
EL.sys		2'622		1'892	
WD.sys		2'127	0.20	2'124	0.25
SH.sys		5'552	0.53	5'437	0.64
CD.sys		2'736	0.26	945	0.11
$f_{sav.NRE}$		0.71		0.58	
SPFequ		6.4		4.4	
COST		**SHC**	**REF**	**SHC**	**REF**
Annualized cost	€	2'643	2'041	2'696	1'942
LCOE	€/kWh	0.254	0.196	0.317	0.228
CR	-	1.29		1.39	

The annual figures reflect the high solar fractions of the subsystem cooling. In Madrid a SPFequ of 13.3 and in Stuttgart an SPFequ of 20.4 can be achieved. The high efficiency of the subsystem in Stuttgart is not reflected in the overall systems (especially not in Stuttgart) as the proportion of cooling is only small. The efficiency of DHW is smaller than for space heating for both locations.

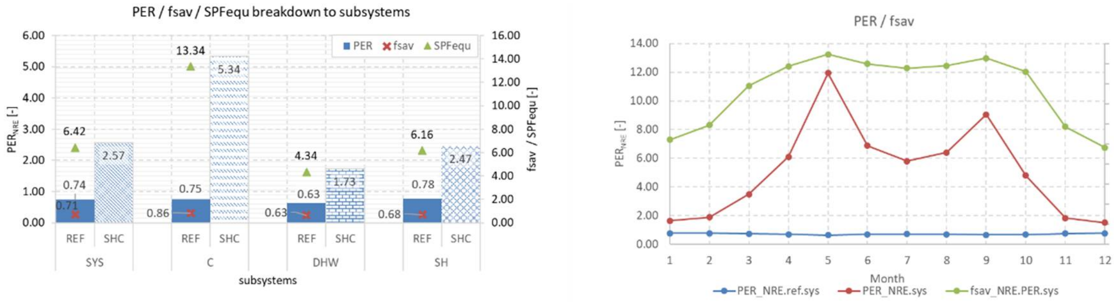

Figure 59:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the Inspire hybrid SHC system for SFH in Madrid

The annual course is reflecting the overall high solar fraction. In Madrid savings > 80% can be reached from March to October, in Stuttgart from April to September.

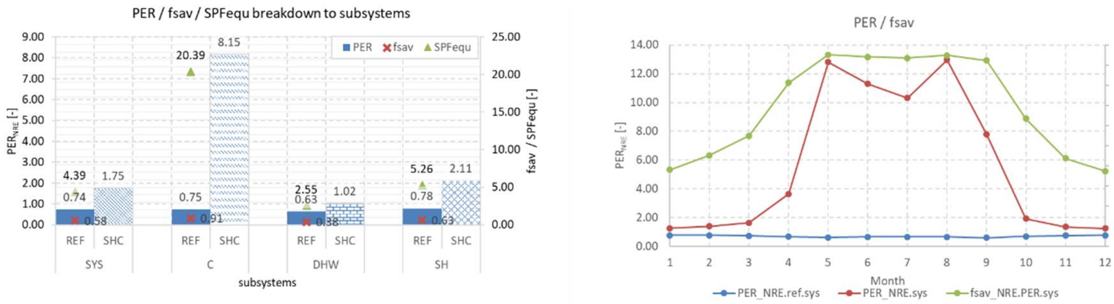

Figure 60:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the Inspire hybrid SHC system for SFH in Stuttgart

The breakdown of the annualized costs reflects the size and design of the system. The system is designed for a single-family house and provide both, ST and PV support, thus the investment is very dominant for both SHC and reference system. The ratio and absolute annualized costs of electricity and energy carrier of the reference system is reflecting the energy demand at the different locations.

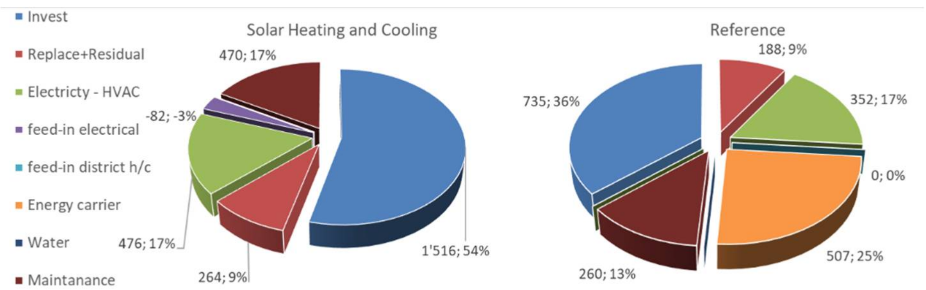

Figure 61: Annualized cost distribution of the Inspire 2e system – SFH in Madrid with PV+ST

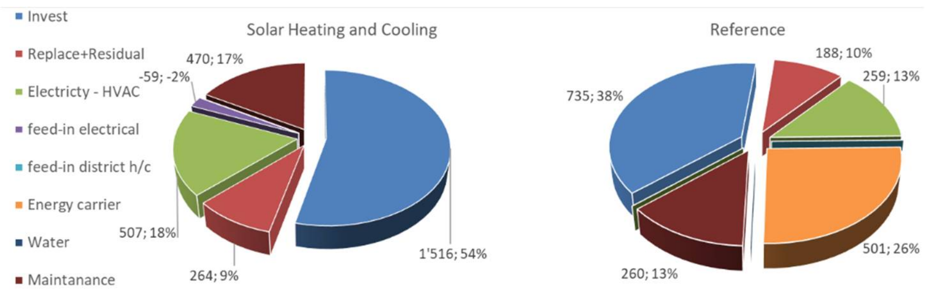

Figure 62: Annualized cost distribution of the Inspire 2f system – SFH in Stuttgart with ST+PV

8.3.FinGerS (by: ZAE; ST; SH+C)

Within the Finnish-German joint research project “Solar Heating and Cooling for Central and Northern Europe” (Reda et al., 2016; Sipilä et al., 2017) a small scale solar thermal cooling (10 kW) and heating (24 kW) plant was installed at Savo-Solar Ltd headquarter in 2016. A collector field of 18 MPE flat plate collectors with 2 m² aperture area each feeds a 2000-liter buffer tank. The storage is located in the factory hall. It is equipped with a density-controlled stratification device and sufficiently insulated. The absorption machine (lithium-bromide/water) transforms heat and cold at the required temperature level in order to fulfill the office building energy demand. It is driven by solar and/or district heat. In absorption chiller mode a dry air cooler on the rooftop with a capacity of 24.7 kW dissipates the waste heat to the ambient.

The Savo-Solar office building was built in 2012 as an extension on the side of the existing factory hall. It is located in Mikkeli Finland (N 61° 42'. E 27° 16'). The building has 170 m² temperature-controlled floor area consisting of an entrance hall, meeting rooms, single offices and an open space office.

Cooling is provided via activated ceilings at nominal supply temperature of 15°C. The air-handling unit requires constantly 10°C of chilled water and supplies 16°C tempered air to the offices during occupancy.

In heating season, the supply air temperature is increased to about 21°C, ceilings are disabled. In heating operation, the ground floor heating covers the main heating requirement with an ambient temperature dependant heating curve. During weekends, off time hours and festive seasons the air handling unit is not in operation.

During summertime the SHC system is expected to operate in solar cooling mode #C1 primarily shown in Figure 63. In that case. the absorption chiller provides chilled water at about 10°C to the office cooling system. To maintain the thermal absorption process pumps RP3.1. RP2.1 and RP1.1 transfer driving heat from the solar thermal collectors to the desorber of the machine. Thereby, the supply temperature level TIC302 is defined and set via MMV3.1 by the lift vs. thrust correlation and the requested cooling capacity. The buffer tank compensates temporal mismatch of heat supply and demand. At insufficient solar yield district heat is used in the Backup Cooling mode #C2.

COOLING

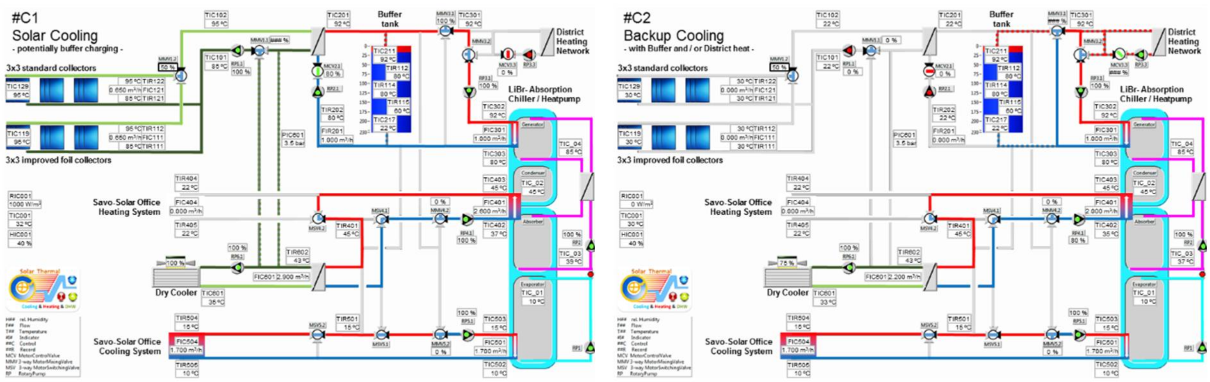

Figure 63: Nominal conditions of solar cooling mode #C1 (left) and district heat driven backup cooling mode #C2 (right).

In wintertime solar heating mode (#H1) is activated if the upper buffer tank temperature is high enough to satisfy the demand. Available solar yield from the collector system is stored at heating system supply temperature in the buffer tank. Subsequently. the absorption heat pump starts when the upper storage temperature drops below the required supply temperature. Then low temperature heat from the buffer tank is transferred to the evaporator. In that case the heat pump amplifies the temperature level to the required value by means of district heat via RP3.1 and 3.3. Thus, the heat content of the buffer tank can be used within the temperature range of 100 to 4 °C. That leads to a high heat storage density and an increased solar yield. According to the heat ratio between low temperature heat and driving heat of approximately 0.7 the heat delivered to the building still contains about 40% of solar heat. Finally, when upper buffer tank temperature falls below 5°C and no solar yield is available the building is heated by district heat solely.

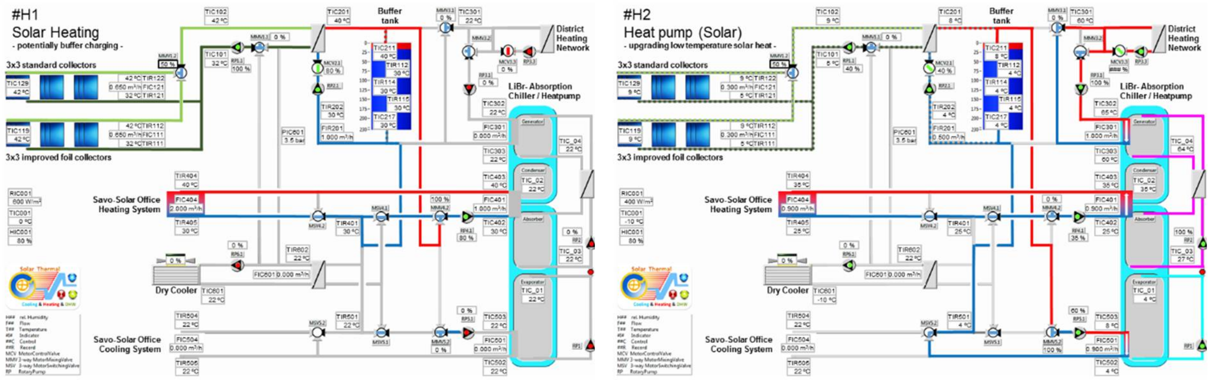

Figure 64: Standard solar heating mode #H1 (left) and low temperature solar heating with heat pump mode #H2 (right).

The non-renewable primary energy savings are calculated against the pre-defined Task 53 standard reference system. The lower the energy carrier (here biomass district heating) input the higher the savings. The solar fraction reaches roughly 35 %. In the analyzed year 85 % savings were achieved, dominated by the space heating, that accounts for 91 % of the demand. This leads to an electrical equivalent SPF of 13.2.

The total annualized cost of the SHC system sum up to 50% additional costs compared to the standard reference. The levelized cost of energy are rather high, as the demands are low over the entire year. Thus, the CostRatio is from higher interest still reflecting the investment dominant cost composition.

Table 11: Energy balance and cost comparison of the ZAE system

ENERGY		**3**	
		kWh	
EC.Sys		14'803	0.66
SC.sys		7'543	0.34
GD.sys		850	
WD.sys		0	0.00
SH.sys		17'216	0.91
CD.sys		1'761	0.09
$f_{sav.NRE}$		0.85	
SPFequ		13.16	
COST		**SHC**	**REF**
Annualized cost	€	6'606	4'414
LCOE	€/kWh	0.348	0.233
CR	-	1.50	

In the following figure presents the breakdown to the entire subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($f_{sav.NRE}$) and SPFequ as added annual figures and as annual course.

The difference in heating and cooling mode is respected by the PERs leading to a SPFequ of 4.9 for cooling and 16.3 for heating respectively. The total system performance sums up according to the ratio of heating and cooling. The annual course is showing an increasing PERNRE.sys due to rising solar fractions from Jan to April, while it drops down to cooling dominated month in June to August and increasing again as the heating demand gets larger.

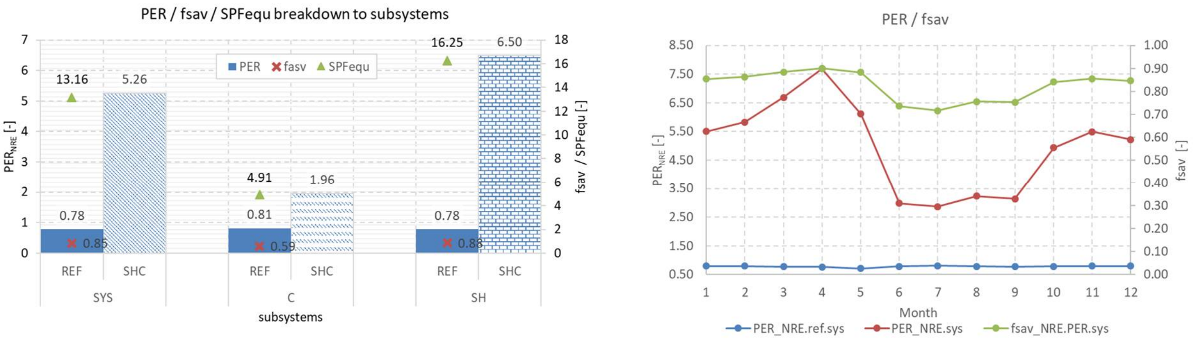

Figure 65:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the ZAE system

The following figures below present the total annualized cost of the entire systems. The SHC costs are dominated by investment, maintenance but also energy carrier cost as the solar fraction is rather low. The reference system presents a smaller ratio of investment but increased costs for electricity (for cooling).

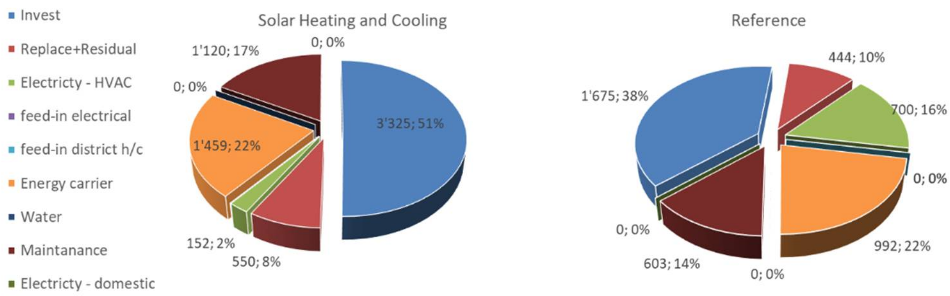

Figure 66: Annualized cost distribution of the ZAE system

8.4. UMH - DHW (by: UMH; PV; DHW)

The heat pump analysed is an ON/OFF equipment with a nominal heating capacity of 1.5 kW and a nominal electrical consumption of 470 W (nominal COP=3.19). Two photovoltaic panels with a total peak power of 470 Wp are connected to a micro-converter which is connected to the equipment at 230 Vac. The experimental setup was installed on the roof of the University's research laboratory located in Elche, Spain (Aguilar et al., 2016).

Tests were carried out under real climatic conditions while a recirculation circuit is used to simulate water consumptions. The facility simulates 6 domestic-hot-water consumptions a day of 20–23 liters each. The heat pump equipment heats the water to 55°C and it keeps the water temperature higher than 50°C. The water inlet temperature is between 12 and 15°C.

The average energy needed to heat the domestic hot water consumption of 129.5 liters with a mean water temperature increase of 41.0°C is Q_{DHW}=6.26 kWh a day. The average tank energy loses are estimated to be Q_{LOSS}=1.63 kWh therefore the average total energy needed is $Q_{U.TOT}$ = 7.78 kWh a day.

The experimental study was carried out during one year in order to establish seasonal results. Results are available in two levels: Detail level: data were taken every 2 minutes (720 data of every variable measured a day) and seasonal level: 248 days were analysed (at least 15 days every month). These results were used to obtain conclusions about the system seasonal behaviour.

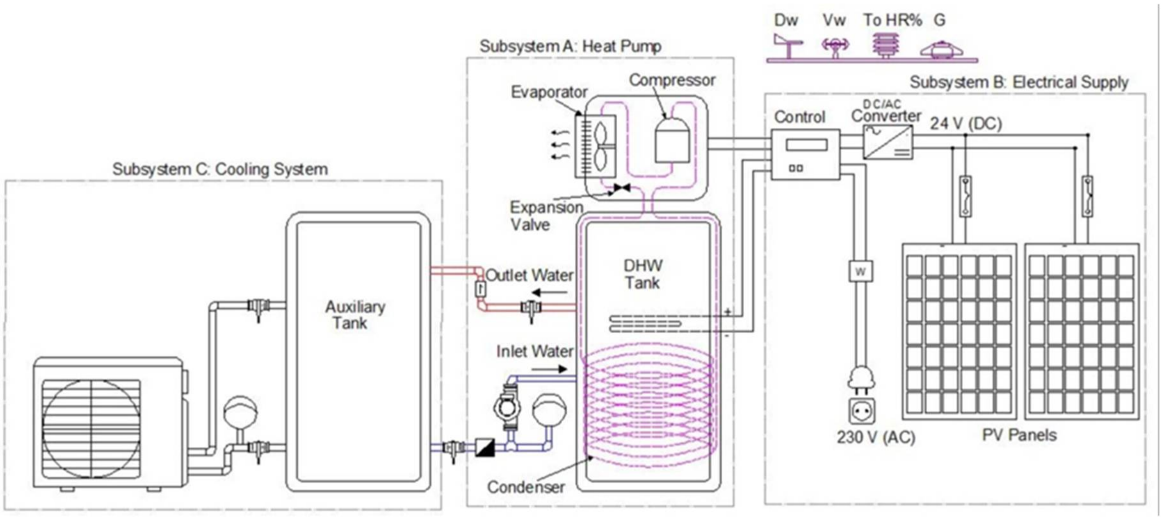

Figure 67: Hydraulic scheme of the PV-driven SHC system in Spain

The system is providing 100% domestic hot water and is running at roughly 1/3 grid electricity (318 kWh) and 2/3 PV electricity (783 kWh). The annual thermal DHW consumption of its experimental setting is summing up to 2248 kWh (thermal losses not included). If only grid electricity is considered, 64% of non-renewable primary energy savings can be achieved. This is corresponding to an equivalent seasonal performance ratio of 7.1.

From cost point of view the total annualized cost and the levelized cost of energy are almost the same, thus the CostRatio equals 1.

Table 12: Energy balance and cost comparison of the UMH DHW system

ENERGY		kWh	%
EC.Sys		0	
SC.sys		0	
PV.sys		783	
GD.sys		318	
WD.sys		2'248	1.00
SH.sys		0	0.00

CD.sys		0	0.00
fsav.NRE		0.64	
SPFequ		7.08	
COST		SHC	REF
Annualized cost	€	349	344
LCOE	€/kWh	0.155	0.153
CR	-	1.01	

In T53E4 Tool analysis the subsystem assessment is calculated with the overall electricity input (PV+grid), whereas the total system only considers grid electricity and therefore has higher values. In this case for the subsystem DHW the total electricity consumption sums up to roughly 1100 kWh and the $PER_{NRE.DHW}$, $SPF_{equ.DHW}$ and the $fsav_{NRE.DHW}$ drop accordingly. The reference system keeps constant at a level of PER equals 0.64. The annual course of the $PER_{NRE.sys}$ and $fsav_{NRE}$ is reflecting the mean ambient conditions during the test days: temperature and solar radiation.

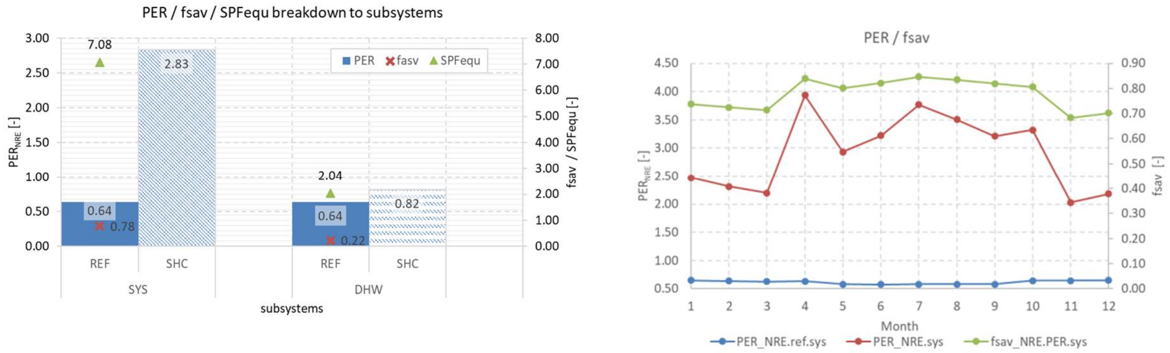

Figure 68: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the UMH HVAC system

The comparison of the annualized cost points out the difference in the PV driven system and the reference system. The SHC system is 50% driven by its investment (HP + PV + auxiliaries) and 26% by the electricity cost (only grid electricity). The reference system (natural gas boiler) is counting for 32% of the total costs while the natural gas costs sum up to 43%. Nevertheless, the sum of all annualized costs equals, and the CR becomes 1, which means cost-parity over the period under consideration (25 a). If more energy would be provided by the system at the same ratio of PV to Grid electricity the SHC system would get cheaper than the reference system.

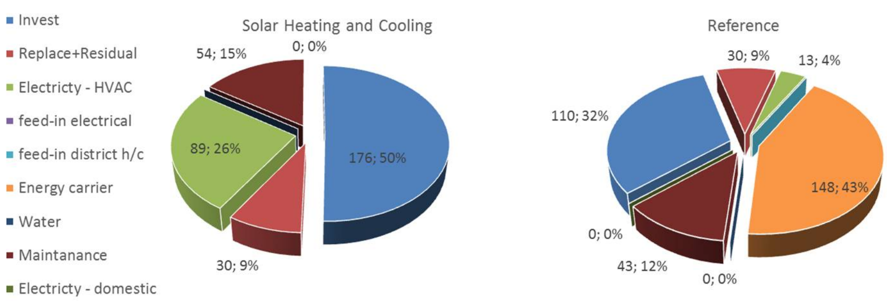

Figure 69: Annualized cost distribution of the UMH DHW system

8.5. UMH HVAC (by: UMH; PV; SH+C)

The used Air-Conditioner unit has a nominal cooling capacity of 3.52 kW (EER=4.09) and a nominal heating capacity of 3.81kW (COP=3.8). Three 235Wp photovoltaic panels were connected directly to the machine at 24Vcc. The PV panels have been directly connected to the 24 V connection of the air conditioning unit. There is a solar converter inside the unit that changes the DC voltage from 24 V to 200-300 V. This high voltage direct current is internally connected to the DC point in the frequency converter. Here, the electricity from the grid and from the PV panels is summed.

Tests were carried out under "real" conditions in a 35 m^2 office located in Alicante (Spain). This office is on the second floor, in this case top floor of an offices building. It has only one external facade which is north facing and has a length of 4.5m. It has a window of 3 x 1.5m^2 with double glazing and sunscreen slats for sun protection. The ceiling height is 2.8 m. The indoor unit is working inside the office, while the outdoor unit has been installed on the building's roof, just above the office (Aguilar et al., 2014; Aguilar et al., 2017).

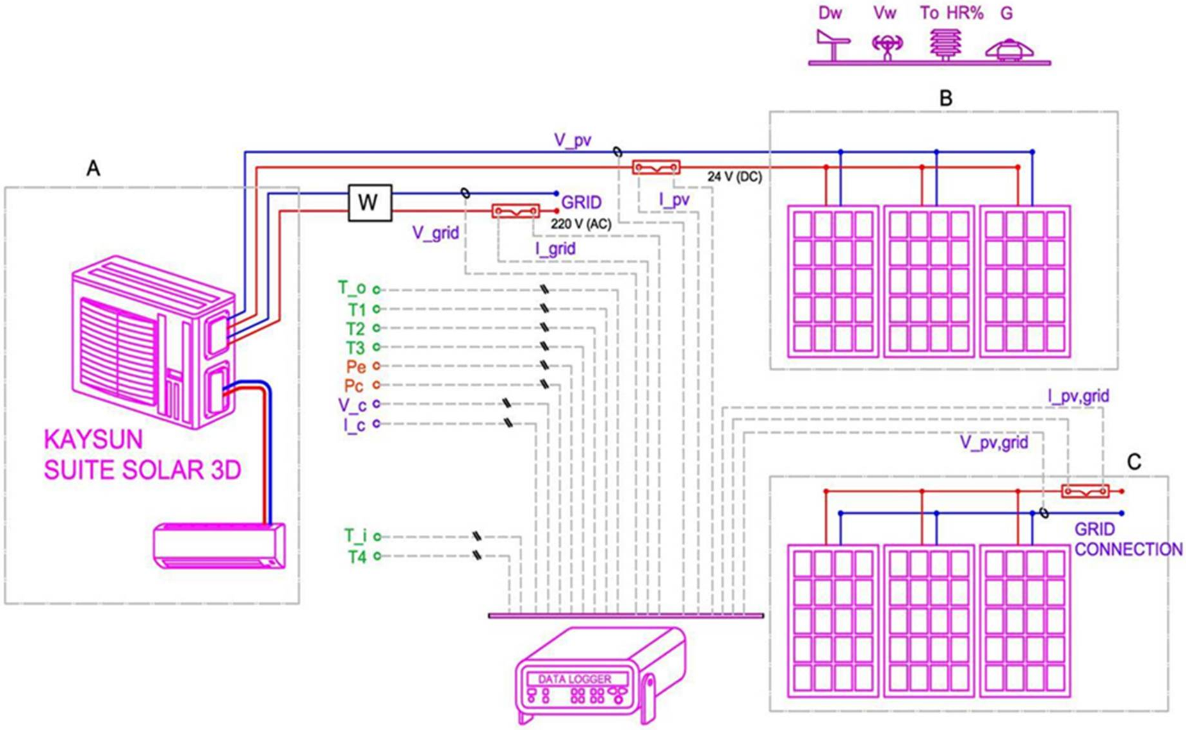

Figure 70: Scheme of the HVAC system in Spain

The established performance profile is focused on typical office hours from 8 to 20 h. The indoor temperature was set to 23ºC in cooling mode and to 21ºC in heating mode. The relative humidity was not controlled. The office is 7 km away from the sea, thus the humidity is frequently high.

The experimental study was focused in summer and winter months to establish seasonal results in cooling and heating conditions. Data from more than two hundred days of the study were analysed (at least 20 days every month). These results were used to obtain conclusions about the seasonal behaviour of the solar air-conditioner.

The following table shows the energy balance and annualized cost comparison of the system. The air-conditioning unit is used to cover the yearly space heating and cooling demand of about 3 to 3.5 MWh each. The annualized costs of the HVAC system are lower compared to the reference system and a hence a cost reduction of 21 % (CR = 0.79) can be achieved.

Table 13: Energy balance and cost comparison of the UMH DHW system

ENERGY		kWh	%
EC.Sys		0	
SC.sys		0	

PV.sys		791	
GD.sys		679	
WD.sys		0	0.00
SH.sys		3'044	0.47
CD.sys		3'478	0.53
fsav		0.78	
SPFequ		9.61	
COST		**SHC**	**REF**
Annualized cost	€	856	1.084
LCOE	€/kWh	0.131	0.166
CR	-	0.79	

The technical analysis can be seen in Figure 71. It shows the yearly breakdown to the subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($f_{sav.NRE}$) and SPF_{equ} as added annual figures but also the annual course. The subsystems analysis considers the total electricity (PV + grid), thus the referred values are smaller than the corresponding overall figures where only grid electricity is considered. The subsystem of cooling shows a higher PER_{NRE} (2.1) than for SH (1.5), same accounts for the savings and SPF_{equ} respectively. If only grid electricity is taken into account, the $PER_{NRE.C}$ ends up at 5.82 and for SH the $PER_{NRE.SH}$ equals 2.77. The course during the entire year of monitoring shows heating in January to April as wells as November and December, from May to October cooling mode is active. The lower PER's in July and August are due to a high cooling demand during those days, where the air-conditioner worked many hours at 100% capacity and PV contribution was low.

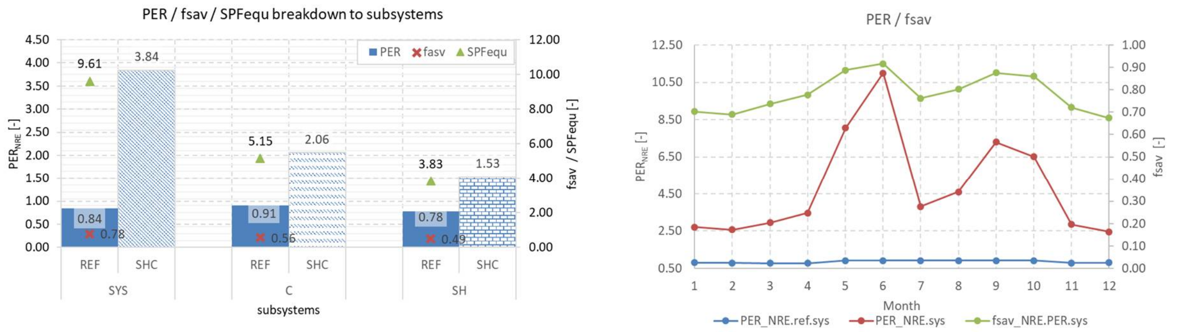

Figure 71: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the UMH HVAC system

The cost distribution shows the investment dominated SHC system. 50% are due to investments, and roughly 35% due to grid electricity costs. The reference system consists of a natural gas boiler and an air-cooled vapour compression chiller. These investments sum up to roughly 30% of the total annualized cost. Another 25% account for electricity costs and 15% for the natural gas (energy carrier). The overall sum of the SHC system is smaller than that of the reference system and thus the CR is smaller 1 (c.f. table above)

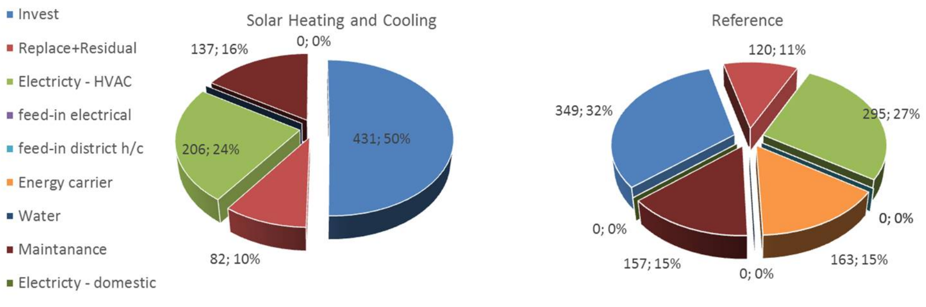

Figure 72: Annualized cost distribution of the UMH HVAC system

8.6.SERC (by: Dalarna University; PV; SH+DHW)

House model and boundary conditions

The modeled house is a typical Swedish single floor, single family house (SFH) with a gabled roof and an overall mean U-value of 0.2 W m^2 K^{-1} and 143 m^2 heated floor area. A detailed model of the house with six zones using space heating, developed in the simulation software TRNSYS, is described in detail and validated by Persson. T. and Heier. J. (2010) TRNSYS' type 56 is used for the house model.

The location of the house is Norrköping, Sweden (58.6°N, 16°2E). Measured meteorological data from the year 2007 in Norrköping is used in the simulations. The weather data is used both for calculation of the PV electricity production and for calculations of energy gains and losses in the house. Two adults and two children are living in the house and the DHW demand is based on the MacSheep project and adjusted for this study (Bales. C. et al., 2015).

SHC System

The house is equipped with a PV system, a heat pump for DHW storage and SH, a thermal storage and a battery. The PV system has a capacity of 5.7 kW and a Lithium-ion battery storage sizes of 7.2 kWh is used to study the impact on the performance in terms of self-consumption, solar fraction and final energy. The tilt angle is defined by the roof of the building whereas the azimuth angle is chosen to optimize the yearly PV electricity production. A control algorithm for increased self-consumption was aimed.

A variable speed, exhaust air HP delivers heat both for SH and DHW but cannot supply them both at the same time. A hot water storage tank of 180 litres is used for DHW. The HP is activated according to a heating curve and compensatory control algorithm dependent on the SH supply temperature. An electric auxiliary heater is activated when the thermal power provided by the heat pump is insufficient to meet thermal power need.

Control

The HP is controlled primarily by the need of SH and the temperature in the DHW storage tank. Excess PV power production is first used to charge the batteries, thereafter the HP is switched on if possible for overheating either the zones or the domestic hot water tank or is directly fed into the grid. The electricity for the end-user consumption can be received directly from the battery. A small 25 l buffer is included in the heating circuit but only serves as an expansion vessel. In case the heat pump's thermal capacity is not sufficient to cover the thermal loads, the auxiliary heater with a capacity of 6.5 kW can supply additional heat. A block diagram of the HP system is shown in Figure 73.

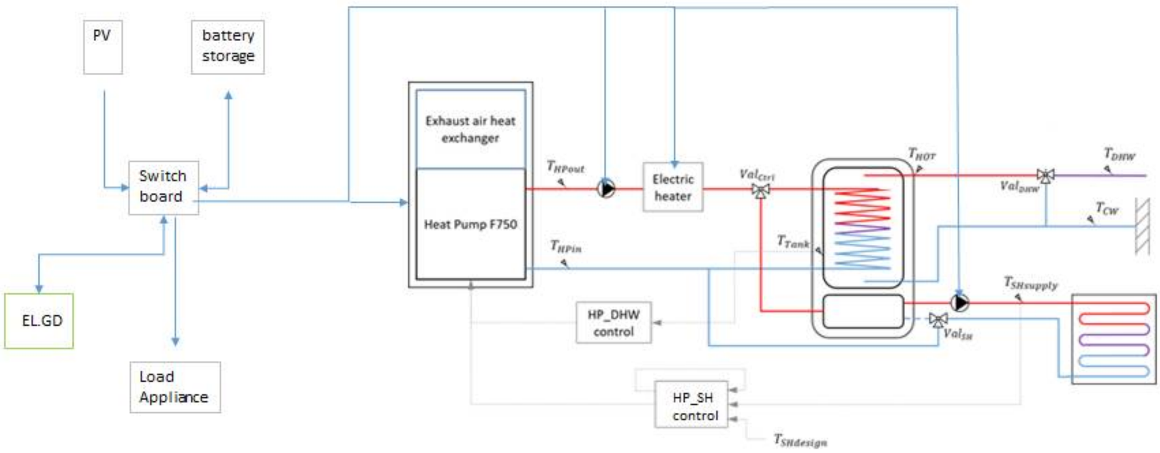

Figure 73: Hydraulic scheme of the compact exhaust air HP system simulated by the University Dalarna (Psimopoulos et al., 2016)

The following table shows the energy balance and annualized cost comparison of the system. The PV is providing roughly 6 MWh electricity another 7.6 MWh are purchased by the grid whereas 2.3 MWh is feed into the grid. Main energy demand is space heating with 14 MWh compared to 3 MWh of DHW demand. The overall energy balance includes house hold electricity (3.4 MWh) as well and leads to non-renewable primary energy savings of 40% and a SPFequ of 2.8 respectively.

The annualized costs of the heat pump system are 79 % higher than the annualized costs for the reference system, the CostRatio equals 1.79 accordingly.

Table 14: Energy balance and cost comparison of the SERC system

ENERGY		kWh	%
EC.Sys		0	
SC.sys		0	
PV.sys		5'994	
GD.sys		7'560	
EL.sys		2'292	
WD.sys		2'994	0.17
SH.sys		14'335	0.83
CD.sys		0	0.00
fsav		0.40	
SPFequ		2.75	
COST		**SHC**	**REF**
Annualized cost	€	3.717	1.785
LCOE	€/kWh	0.182	0.102
CR	-	1.79	

The technical analysis can be seen in below. It shows the yearly breakdown to the subsystems and its key figures. The subsystems analysis considers the total electricity (PV + grid), thus the referred values are smaller than the corresponding overall figures where only grid electricity is considered. The subsystem of domestic hot water shows a lower PER_{NRE} (0.6) than for space heating (1.0), same accounts for the savings and SPFequ respectively. The PER for DHW is even lower than for the reference system, thus the savings get negative. The course during the entire year of monitoring shows heating and DHW demand over the entire year. In June to August the demands can be satisfied by PV by a large ratio, thus the PERs are very high and the savings of 90% can be reached.

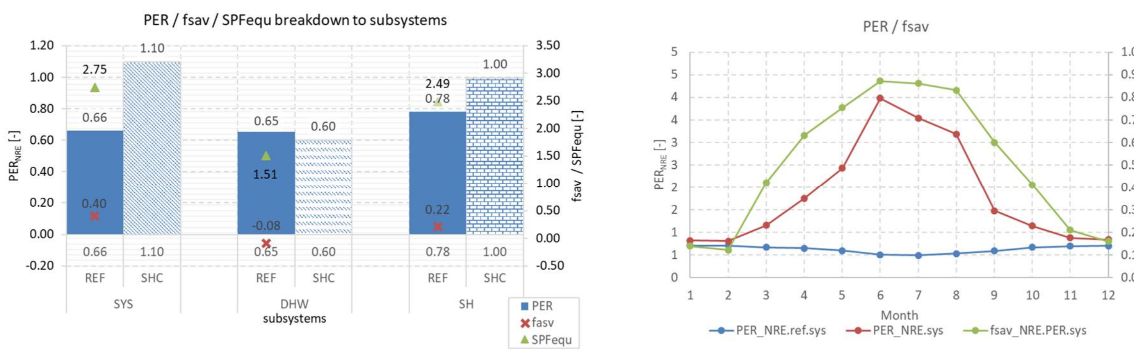

Figure 74: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the SERC system

The main cost driver of the heat pump system is the higher investment costs for heat pump, PV modules, buffer storage and battery compared to the investment costs of a natural gas boiler of the reference system. Also, the electricity and maintenance costs are higher for the SHC system. The PV is not only driving the heat pump, it is also used for domestic electricity. Therefore, the costs for domestic electricity can be reduced significantly by the HVAC system compared to the reference system. The surplus PV feed into the grid gives a small gain (-4%).

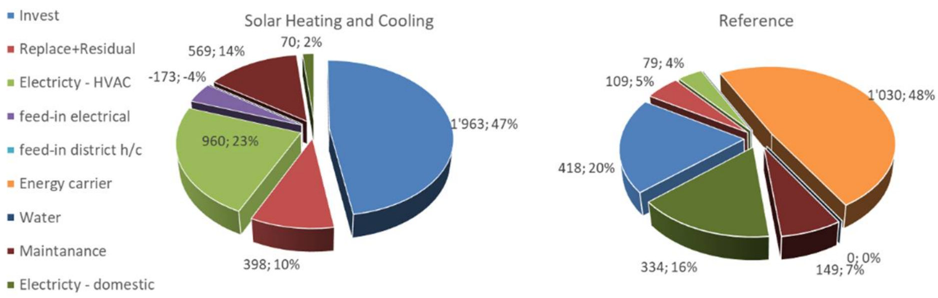

Figure 75: Annualized cost distribution of the SERC system

8.7.Juice farmer (by: AEE Intec; ST; SH +C + process heat/cold)

The SHC system was built in 2012, by a farmer for juice production in Austria. They have a production of around 250.000 l apple juice and 100.000 l cider per year. In addition to the process heat and cold the SHC system is applied to cover also the heating and domestic hot water demand of the residential building.

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 process heat is used for the juice production and bottle washer process, whereas the cold is used for the refrigeration of the produced juice. The heat is stored in a 20 m³ buffer storage with a stratified lance and connected to a single-stage absorption chiller (ammonia/water) with a capacity of 19 kW. The flow temperature for the process heat is between 83 and 84 °C and for driving the absorption chiller a temperature of 80 °C is necessary. The access heat is transferred to the ambient via 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. (Fink et al., 2011; Fink and Knabl, 2014)

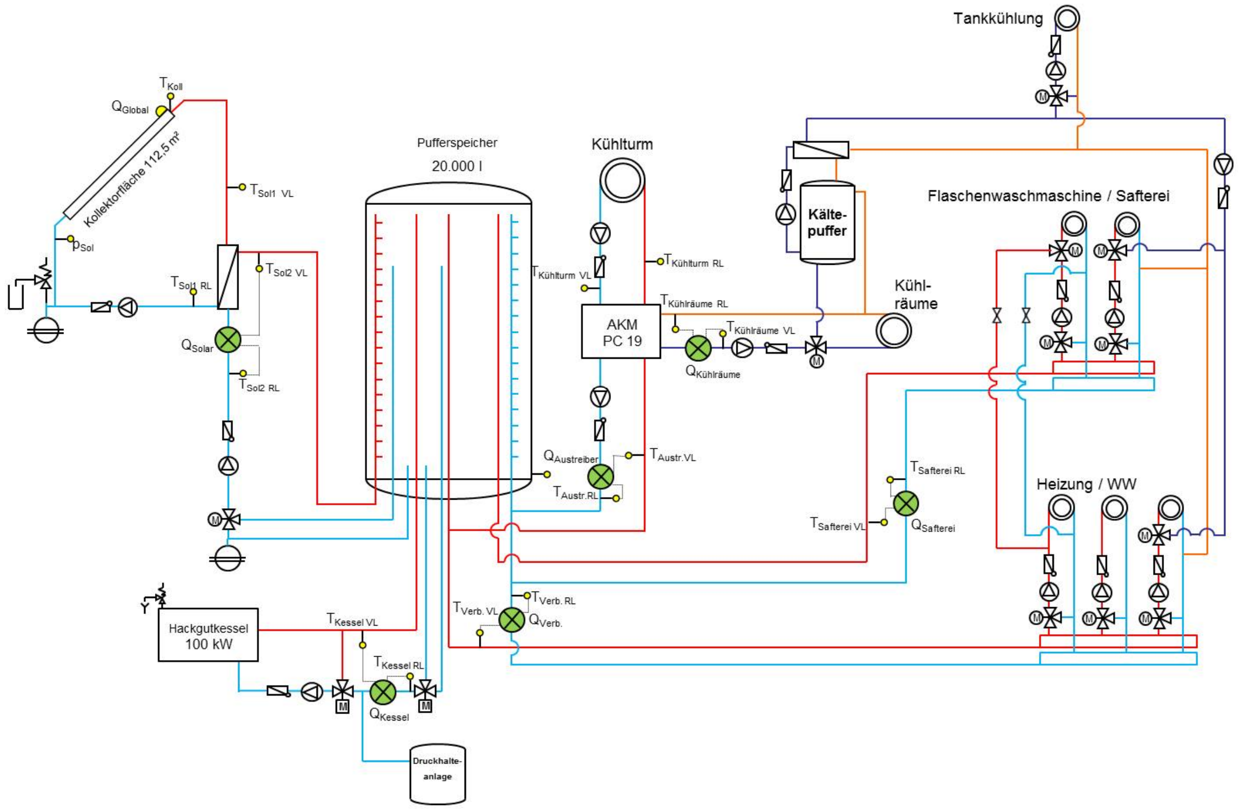

Figure 76:Hydraulic scheme of the SHC system in Austria

The following table shows the energy balance and annualized cost comparison of the system. The main part of the energy is provided by the wood-chip boiler and about 20 % can be covered by the solar collector. Regarding the demand, 57 % of the energy was used for heating and domestic hot water preparation of the residential house (both are summarized in SH). In addition, around 42 MWh (39 %) are supplied for process heat for juice production and the bottle washer. The smallest part is the cooling demand with only 4.5 MWh (4%) of the total energy demand. The annualized costs of the SHC system are 53 % higher compared to the reference system.

Table 15: Energy balance and cost comparison of the SERC system

ENERGY		**kWh**	**%**
EC.Sys		130.070	
SC.sys		38.759	

GD.sys		2.706	
PH.sys		42.026	0.39
SH.sys		62.240	0.57
CD.sys		4.528	0.04
fsav		0.78	
SPFequ		13.76	
COST		**SHC**	**REF**
Annualized cost	€	16.423	10.717
LCOE	€/kWh	0.151	0.099
CR	-	1.53	

The SHC system shows high efficiencies for the heating applications (PER = 7.7, SPF = 19.2) and therefore also high non-renewable primary energy savings of 90 % can be achieved compared to the reference system. The cooling subsystem on the other hand shows a lower primary energy ratio compared to the reference system and therefore no primary energy savings can be achieved. Since the cooling demand only has a small ratio compared to the space heating and process heat demand, the overall savings sums up to 86 %. The low performance of the cooling system and good performance of the heating system is also reflected in the yearly profile.

Different issues cause the low performance of the cooling system. Firstly, the power of the ventilation of the cooling tower was not controlled, instead it was running on full power when turned on. In addition, the necessary flow temperature for the juice refrigeration was lower than expected during the system design, which caused low efficiencies of the ACM. The performance of the cooling system could also be improved by a better control strategy of the wood chip boiler. The boiler had a high amount of running hours to achieve the necessary temperature level for regeneration of ACM. This induced stagnation of solar collector, since the buffer was always on high temperature and could not be charged by the solar collector.

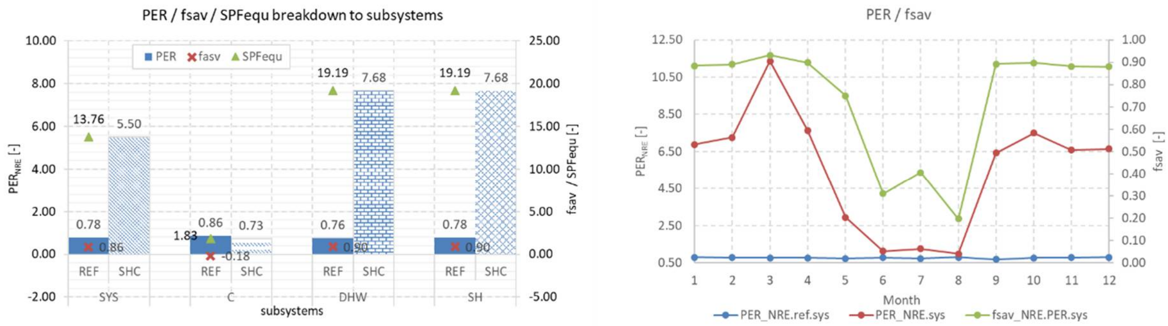

Figure 77: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the juice farmer system in Austria

In Figure 78 the annualized cost distribution of the SHC system with solar thermal collectors and wood chip boiler is compared to the cost distribution of the reference system. The annualized costs for the SHC system are driven in equal shares by investment costs and costs for the energy carrier (wood chips), whereas the maintenance costs sum up to 15 % of the total annualized costs. On the other hand, the reference system is mainly driven by the costs for the energy carrier (53 %), followed by the investment costs (22 %) and electricity and maintenance costs.

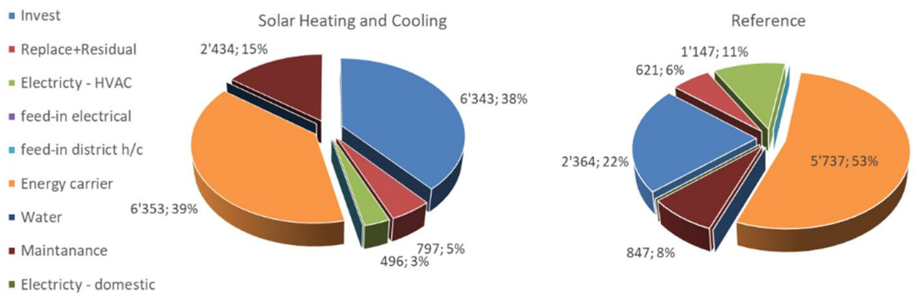

Figure 78: Annualized cost distribution of the juice farmer system in Austria

8.8.SolPol (by: UIBK; ST; SH+DHW)

The SolPol system simulation study is based on the simulation studies of system 12 (TheBat, Thür et al., 2017a), where electrical driven heat pumps in combination with thermally activated building systems (TABS, here a standard floor heating system is used) and conventional hot water storages (TES) are used as thermal battery for electricity produced by photovoltaic systems.

In this SolPol study (Thür and Maslikova, 2016; Thür et al., 2017b) a solar thermal system is considered instead of a PV-system, which also can use either the TES or the building (TABS) as heat storage. The heat pump is used as a standard auxiliary heater if solar thermal energy is not sufficient.

Simulations within the project SolPol are done for a single-family house (based on the IEA SHC Task44 reference building; (Dott et al., 2013)) designed as low energy standard (RES45: 45 kWh/m^2a space heating consumption, SH) at Innsbruck climate with thermal active mass by floor heating. The reference floor area is 140 m^2, the standard reference room temperature is 21°C ± 0.5K and the domestic hot water (DHW) consumption at 45°C tap temperature is 2’175 kWh per year.

A solar thermal system (ST) with 20 m^2 collector area with flat plate collectors (η_0 = 0.80; a_1 = 3.0 W/m^2K; a_2 = 0.010 W/m^2K^2), mounted south oriented and 45° tilted is considered in the system. The heat pump is equipped with a desuperheater with variable volume flow to reach 50°C set temperature. The ground source brine heat pump (HP) is connected to a water storage (TES) directly via the desuperheater. The condenser of the HP can charge the TES or bypass the TES for direct heating of the building. Domestic hot water preparation is done with an external plate heat exchanger with controlled primary mass flow.

The heat pump is designed for thermal capacity of about 10 kW_{th} at B0W35. The brine source temperature is modelled with average temperature of 5°C ± 6 K varying over the year. The heat pump is operated power controlled depending on the ambient temperature for direct space heating and in parallel using a desuperheater for heating the top 300 liter of the TES for domestic hot water preparation. If necessary, the heat pump can heat only the TES to cover the DHW demand.

The control concepts are named “REF”, “TES”, “BUI” and “BUI+TES”. The “REF” has no solar thermal system and is using only electricity from the grid to run the heat pump. For DHW preparation as standard control, only the top volume of 300 liter of the TES is heated up to 50°C.

If solar thermal power is available, the ST can store heat in the TES or the TABS. In the “TES” control strategy the TES is completely heated up to 90°C. In the “BUI” control strategy (in winter season) the building with the TABS is heated until a maximum room temperature is reached (variations from 22°C up to 26°C). In “BUI+TES” first the “BUI” algorithm is used and second, if still ST power is available, the “TES” algorithm is used.

The following results are based on the following two system control configurations:

- 8a: TES1000: in case of available ST power, ONLY the TES with a volume of 1000 liter is used for overheating up to 90°C; the room temperature is controlled to 21°C ± 0.5K.
- 8b: TES500-BUI23: in case of available ST power, FIRST the building mass is used for overheating up to 23°C room temperature (in winter heating season) and SECOND the TES with a volume of 500 liter is used for overheating up to 90°C.

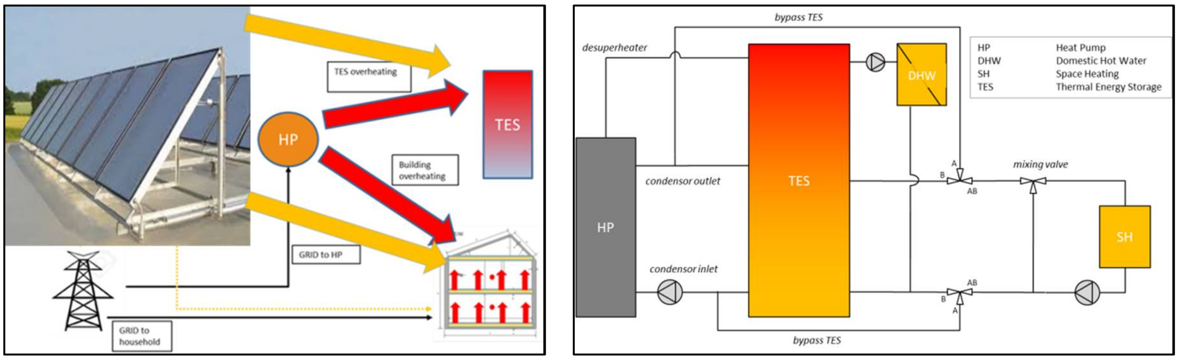

Figure 79: Hydraulic scheme of the SHC system “SolPol” by UIBK

The system is located in Austria; thus, the energy demand is dominated by space heating. The difference in the control strategy and design can be seen in the energy delivered for space heating, 8b with the thermal activated floor can store and use slightly more space heating energy, but contrary the solar yield is slightly smaller and the electricity demand higher. In 8b due to the overheating of the building higher heat losses occur resulting in more space heating than in 8a where the larger 1000 liter storage has lower overheat losses due to good insulation. From primary energy point of view the system 8a performs better than 8b. Savings of both reach roughly 80% whereas system 8a achieves an SPFequ of 9.5 and 8b an SPFequ of 9.2.

From cost point of view the performance is vice versa. System 8a results with higher total annualized cost than the system 8b, whereas both systems are more expensive than the reference system. Both systems use the floor heating system, only the control strategy is different, thus these costs are not included in the analysis. 54% and 47% additional cost will be reached in this small-scale system.

Table 16: Energy balance and cost comparison of the SolPol 8a and 8b systems

ENERGY		8a		8b	
EC.Sys		0		0	
SC.sys		7'057		6'934	
GD.sys		955		1'024	
WD.sys		2'173	0.24	2'173	0.23
SH.sys		6'892	0.76	7'193	0.77
CD.sys		0	0	0	0
$f_{sav.NRE}$		0.8		0.8	
SPFequ		9.49		9.15	
COST		**SHC**	**REF**	**SHC**	**REF**
Annualized cost	€	2'415	1'566	2'329	1'583
LCOE	€/kWh	0.266	0.173	0.249	0.169
CR	-	1.54		1.47	

In the following 2 figures the breakdown to the entire subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($fsav_{NRE}$) and SPFequ is presented as added annual figures but also the annual course. The performance of DHW is much higher than for space heating, the solar fraction in summer for DHW reaches almost 100% with the 20 m² of collector. Due to the larger hot water tank the system 8a can reach slightly higher DHW subsystem efficiencies than system 8b. The system 8a can achieve a non-renewable primary energy saving of 97% and 8b of 91% respectively. The performance of space heating is slightly higher for the system with activated floor. The SPFequ equals 7.5 for 8a and 8.1 for 8b. Nevertheless, system 8a ends up with a higher fsav of 78% and system 8b with a fsav of 76%. This is due to the slight change of efficiency of the natural gas reference boiler where the efficiency is depending on the demand / degree of capacity utilization.

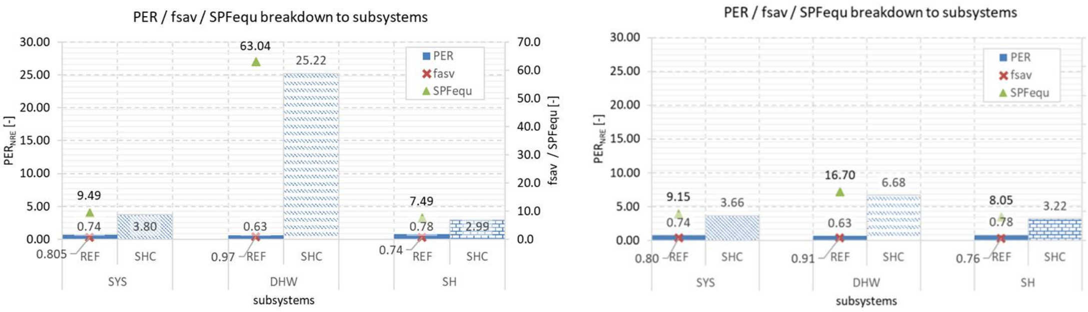

Figure 80:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the SolPol 8a and 8b

The annual course is not shown because the energy balances are only available as annual values. Thus, the $PER_{NRE.sys}$ is constant over the year. Nevertheless, the savings are higher in summer due to higher solar fractions and the method of calculation of the efficiency of the reference boiler.

The total annualized costs are reflecting that the system is designed for a single-family house with small energy demands, thus the investment is clearly dominating the cost, followed by the maintenance cost. The difference in cost of storage are evident as system 8a is more expensive than system 8b. The reference system is also dominated by the investment costs, but energy carrier costs are almost as high. System 8b is showing slightly higher energy costs as the energy consumption is slightly higher due to the building overheating.

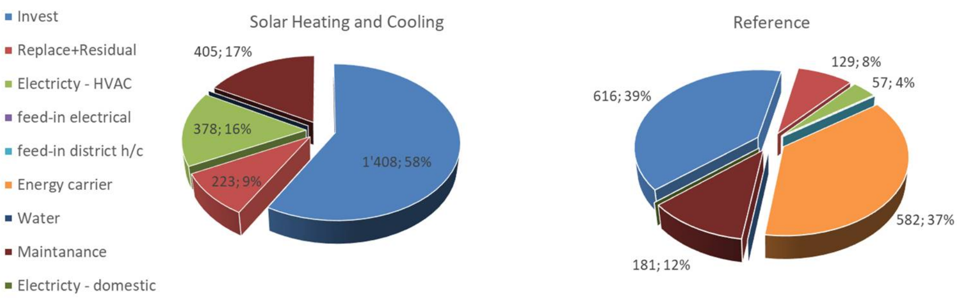

Figure 81: Annualized cost distribution of the SolPol system 8a

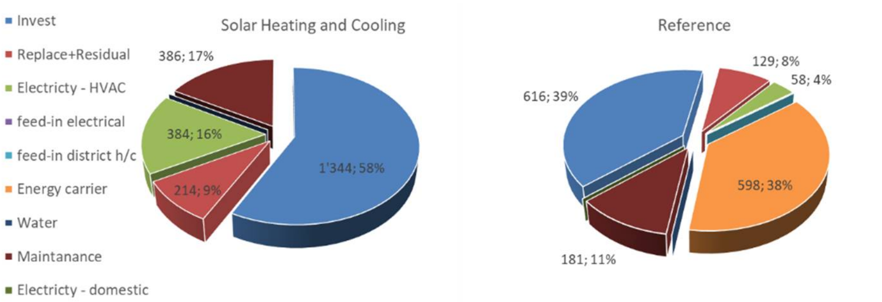

Figure 82: Annualized cost distribution of the SolPol system 8b

8.9.SolarHybrid (by: UIBK; ST vs. PV; SH+C+DHW)

SolarHybrid (Neyer and Thür, 2014) is an Austrian research project dealing with solar thermal and PV supported HVAC systems, the development and optimization of an absorption- & a compression-chiller as well as the theoretical investigation of hybrid system by means of simulations and hardware-in-the-Loop measurements. The major target of SolarHybrid was to develop and evaluate the economics. efficiency and reliability of solar hybrid systems. Results shown here focus on one of the simulation studies and its assessment for comparison of ST and PV for a Hotel profile in Innsbruck, Austria and Sevilla, Spain.

The profile used is a 240-bed hotel with spa area and a floor area of 10’080m². Results for other load profiles can be found in the SolarHybrid (Neyer, 2017a) final report. The hotel was designed according to standard designs with internal loads and air exchange rates according to SIA 2024. The hotel. located in Innsbruck (and Sevilla) has a total heat requirement of 160 (120) kWh/m².a and cooling demand of 8 (31) kWh/m².a. The space heating sums up to 17 (1) % of the heating demand, but the majority is needed for the energy supply for pool heating (35 (53)%) and domestic hot water demand (DHW 48(46)%).

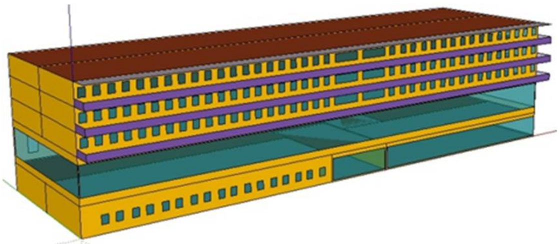

Figure 83: Reference building of the hotel (Gritzer, 2017)

Two HVAC systems are compared here, the system layouts are described and shown in Fig. 9. The collector area for ST and PV is the same.

(I) ST: solar thermal + absorption- and compression chiller + natural gas Boiler

The ST (720m²) feeds a hot water storage tank (30 l/m²ST), which ensures the heat supply for domestic hot water (DHW), pool and space heating with a natural gas boiler as backup, as well as the operation of the absorption chiller (ACM - without hot backup). The absorption chiller, a single-/half-effect (SE/HE) ammonia water chiller developed to operate with dry coolers at high ambient temperatures, serves the base load cover (20 kW); the remaining requirement is covered by a conventional compression chiller (70 kW). Both chillers operate in parallel with a dry cooling tower. Heat rejected towards the cooling tower is partly used for pre-heating the DHW.

(II) PV: heat pump + photovoltaic

The heat pump (HP) operates reversible and feeds the hot- and cold-water storage tank. Groundwater is used as heat-source/sink the effects on the COP / EER are modelled simplified by means of a Carnot model. The HP is not controlled specifically to reach high self-consumptions. The concurrency of PV production (84.5 kWp) and electricity demand is resulting according to load and irradiation, the grid cover and the excess of PV result correspondingly. The additional demand for house hold electricity for the hotel or a shift in the load (as. for example. in TheBat (Thür et al., 2017a)) are not considered here.

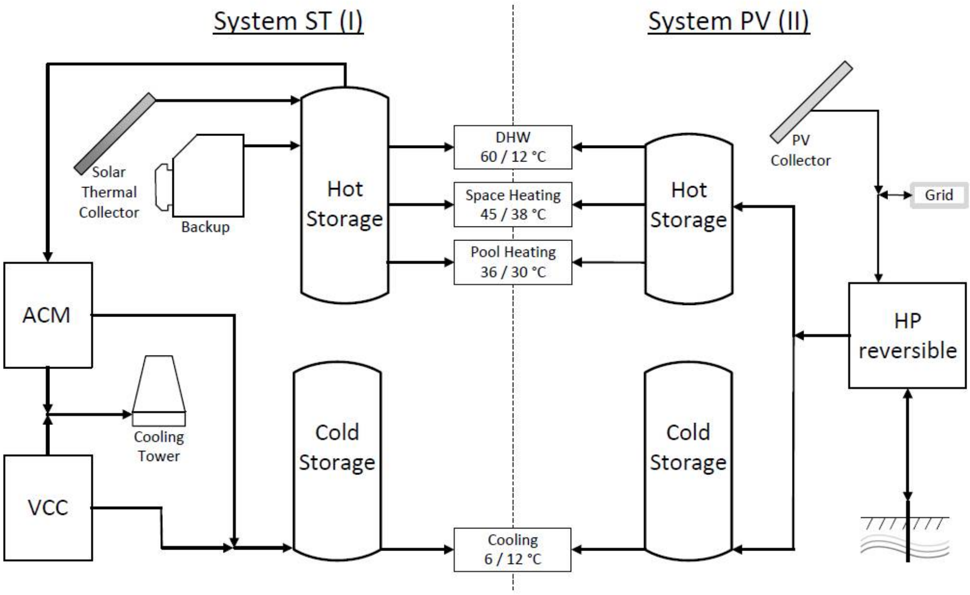

Figure 84: Schematic system configuration for solar thermal (ST: left) and photovoltaic (PV: right)

Tabelle 1: boundary conditions / systems for the 4 analysed plants

	9a	9b	9c	9d
Location	Innsbruck	Innsbruck	Sevilla	Sevilla
Solar system	ST	PV	ST	PV

The non-renewable primary energy savings are calculated against the pre-defined Task 53 standard reference system. Plants #9a and #9b represent the results for location Innsbruck. The demand for heating and domestic hot water are almost equal, space cooling is of minor priority. The solar fraction of #9a is roughly 40%, complemented by natural gas for heating and electricity for cooling. Accordingly, a non-renewable primary energy savings of 35% or an equivalent SPF of 3.1 can be reached. The PV supported, and electricity-based system reaches almost the same savings.

Both system achieve roughly the same annualized cost, whereas the solar thermal is slightly cheaper on life cycle base than the PV driven system. The ST reaches a CR of 0.98 and the PV driven of 1.03.

Table 17: Energy balance and cost comparison of the SolarHybrid system for Innsbruck

ENERGY		**9a**		**9b**	
		kWh			
EC.Sys		794'932		0	
SC.sys		423'400		0	
PV.sys		0		111‘960	
GD.sys		32'065		408'339	
EL.sys		0		1'397	
WD.sys		562'002	0.47	562'079	0.47
SH.sys		545'934	0.46	545'848	0.46
CD.sys		82'110	0.07	82'105	0.07
$f_{sav.NRE}$		0.35		0.32	

SPFequ		3.1		2.9	
COST		**SHC**	**REF**	**SHC**	**REF**
Annualized cost	€	80'904	82'835	85'140	82'835
LCOE	€/kWh	0.068	0.070	0.072	0.070
CR	-	0.98		1.03	

In the following 2 figures the breakdown to the entire subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($f_{sav.NRE}$) and SPFequ is presented as added annual figures but also the annual course. The overall system performance sums up to the same values for both PV and ST system, whereas the subsystems present very different efficiencies and savings respectively.

The efficiency of subsystem cooling is very high for the solar thermal cooling system including the electrical backup, an equivalent SPF of 6.9 and savings of 55% can be reached. The PV driven system consist of a standard chiller and reaches including PV production an SPFequ of 3.1 and no savings. The heating system is supported 35% by solar (for both PV and ST) and thus summing up to the respective savings of 33-35%. The system performance accounts accordingly to the demand mixture, the good performance of solar thermal cooling is evened.

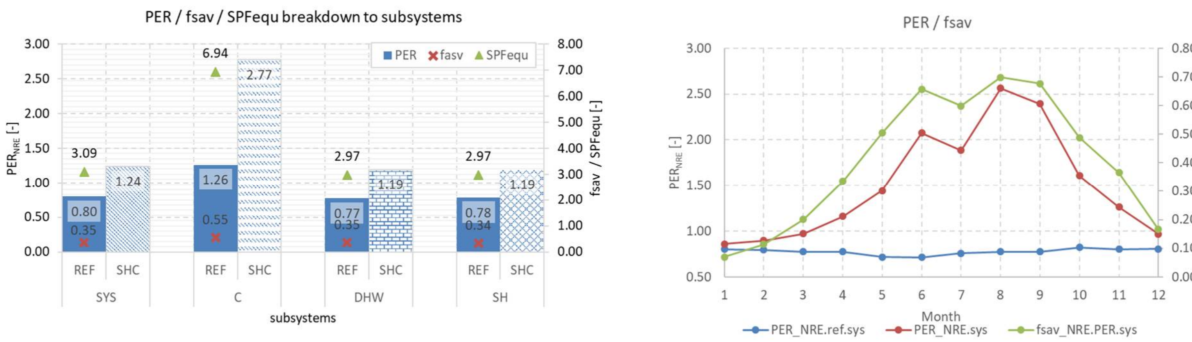

Figure 85:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the SolarHybrid solar thermal system in Innsbruck

The annual course reflects the annual (seasonal) values. The ST supported system reaches its maximum savings in summer when a high solar fraction is evident and cooling and domestic hot water production are dominant. Same occurs for the PV supported system, in summer the highest savings can be achieved, whereas the course is more constant over the entire year.

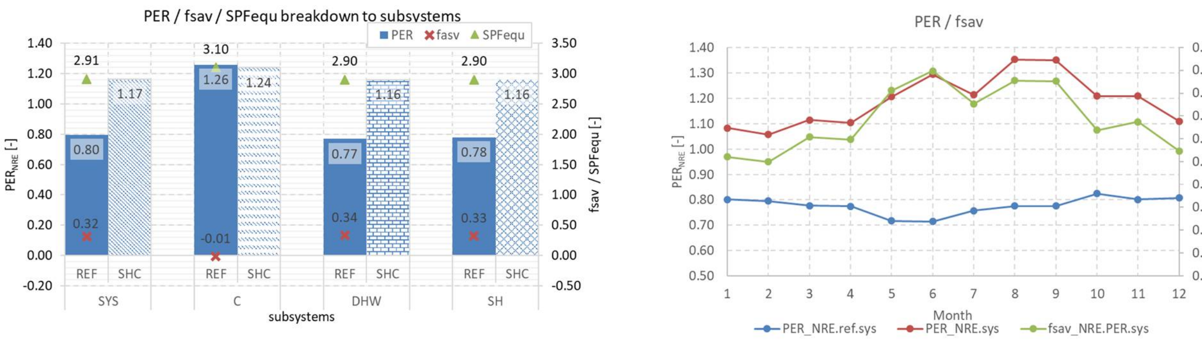

Figure 86:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the SolarHybrid PV-driven system in Innsbruck

The following two figures below present the annualized cost of the entire systems. As the profile has a large energy demand the costs are dominated by the energy carrier (backup for ST) and electricity (PV-driven) cost. The electricity cost for the heat pumps account more than the natural gas backup for the ST system. From investment point of view the PV-HP system slightly cheaper than the ST system. The reference costs are as well dominated by the energy carrier cost.

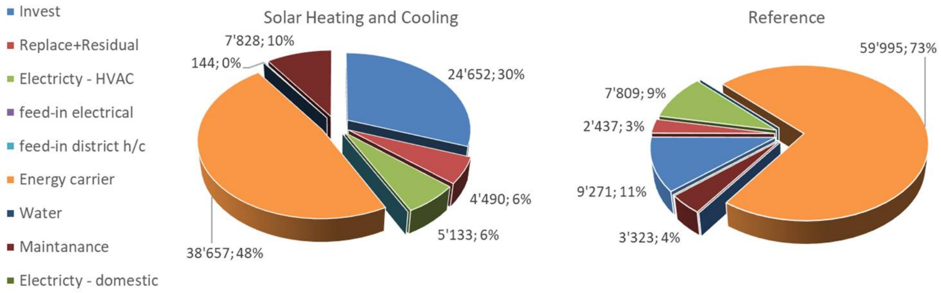

Figure 87: Annualized cost distribution of the SolarHybrid solar thermal system in Innsbruck

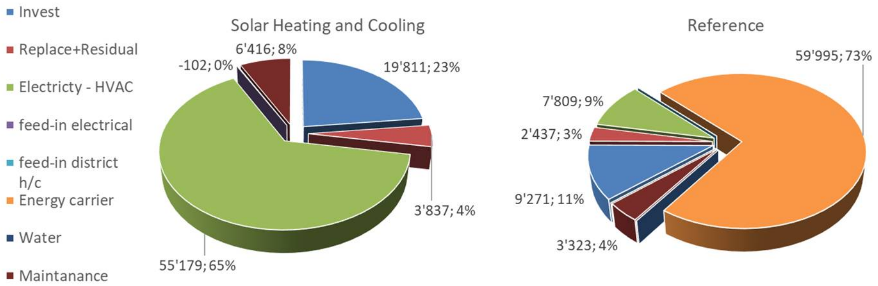

Figure 88: Annualized cost distribution of the SolarHybrid PV-driven system in Innsbruck

The comparison of plants #9c and #9d shows the difference of PV and ST supported system for the location Sevilla. The overall energy demand is lower than in Innsbruck, the domestic hot water is dominant, and cooling is slightly more in demand than space heating.

The solar yield and thus the solar fraction for heating are higher compared to Innsbruck, the solar thermal system ends up with non-renewable primary energy savings of 65% and a SPFequ of 6.2. The PV system can also increase its performance but needs to feed-in more electricity at the same time. Thus, the PV supported system reaches 56% savings and an SPFequ of 5.

From cost point of view both systems sum up to total annualized cost below that of the reference system and thus reaching CR <1. Solar thermal system can reach a CR of 0.8 and the PV system of 0.85.

Table 18: Energy balance and cost comparison of the SolarHybrid system for Sevilla

ENERGY		2c		2d	
		kWh			
EC.Sys		177'842		0	
SC.sys		755'994		0	
PV.sys		0		186‘809	
GD.sys		94'454		217'200	
EL.sys		0		71'154	
WD.sys		541'782	0.50	541'803	0.50
SH.sys		234'728	0.22	234'747	0.22
CD.sys		299'006	0.28	299'016	0.28
$f_{sav.NRE}$		0.65		0.56	
SPFequ		6.2		5.0	

COST		SHC	REF	SHC	REF
Annualized cost	€	61'222	75'206	64'115	75'208
LCOE	€/kWh	0.057	0.070	0.060	0.070
CR	-	0.81		0.85	

The breakdown to subsystems shows that the solar fraction for cooling is lower compared to Innsbruck case for the ST supported system. The highest efficiencies can be reached by the ST system and domestic hot water production. As DHW is the dominant demand the annual key figures increase accordingly.

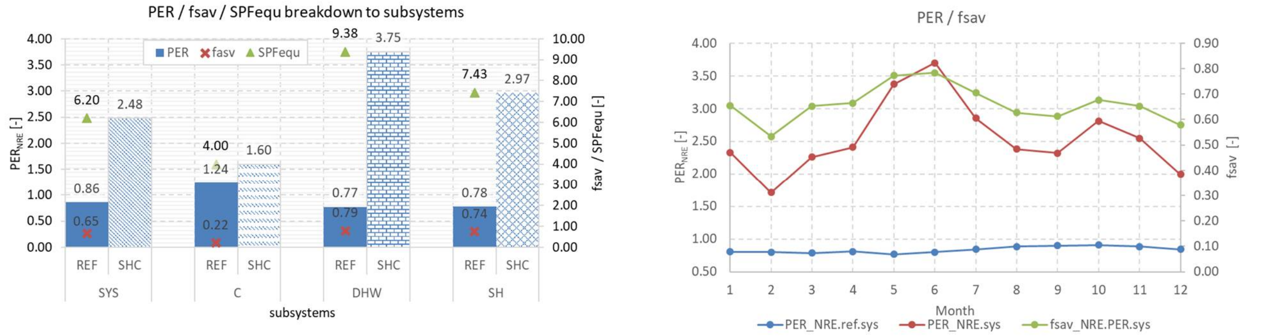

Figure 89:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the SolarHybrid solar thermal system in Sevilla

The annual course of $PER_{NRE.SYS}$ and $PER_{NRE.ref}$ reflect the annual values. Savings occur between 50 and 70% for the ST system and 50-60% for the PV supported system. The course of the PV driven systems reflects the simplified calculation method but does not effect the annual performance calculation.

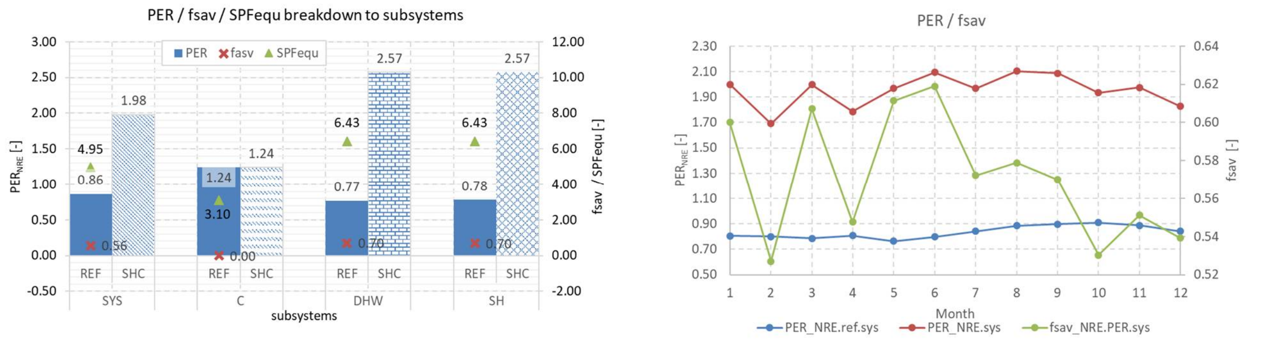

Figure 90:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the SolarHybird PV-driven system in Sevilla

The total annualized costs reflect the demands, as they are smaller compared to Innsbruck the relative share of investment is increased. The higher cooling demand leads to a higher electricity demand and thus higher electricity costs.

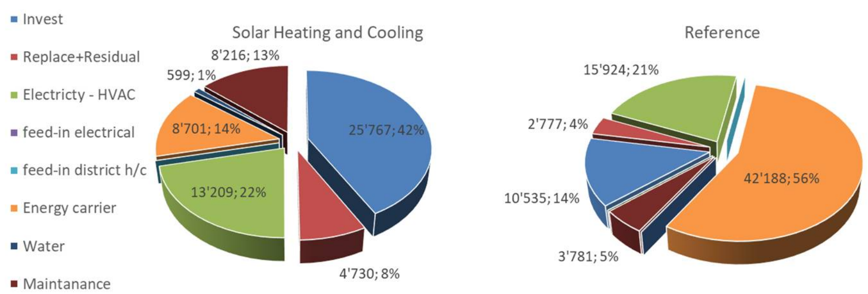

Figure 91: Annualized cost distribution of the SolarHybrid solar thermal system in Sevilla

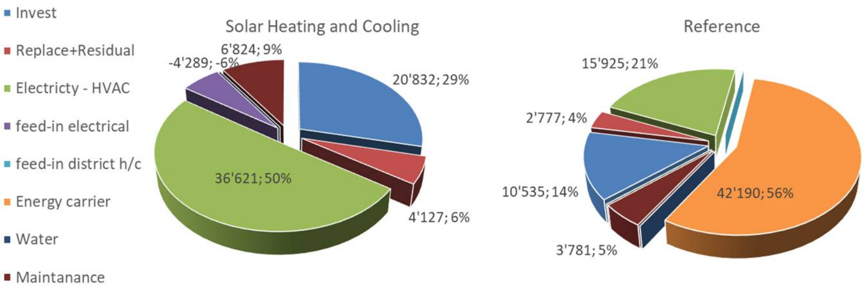

Figure 92: Annualized cost distribution of the SolarHybrid PV-driven system in Sevilla

8.10. Jinan (by: YAZAKI; ST; SH+C+DHW)

The project location is Jinan in P.R. China with a humid continental climate (longitude 116.98. latitude 36.67). The monthly average ambient temperature is varying from minimal -10°C in Jan to min. 15°C in July, while the maximum is varying from 13°C in January to 38 in June/July. The total annual irradiation sums up to 1338 kWh/m².a. The climatic conditions influence the implementation of the passive house building and the solar yield of the SHC system accordingly.

The Jinan Disaster Prevention Center is designed as passive house. The building has a gross area of roughly 1300 m² and is used as office with working time: 07:00-19:00, 5 days/week; there is no domestic hot water demand in the office. The annual space heating demand is summing up to 6.95 kWh/m².a while the annual cooling demand equals 24.30 kWh/m².a with approximately 55% sensible and 45% latent (dehumidification) shares.

The SHC system in Jinan served as base for a detailed simulation study by Yazaki and University of Innsbruck (Neyer, 2017b; Zheng et al., 2017). On the one hand the design and control strategies were optimized and on the other hand the effect of different energy consumption (SH, C, DHW) was analysed. The results shown here include hot water consumption, which is not present in the actual project.

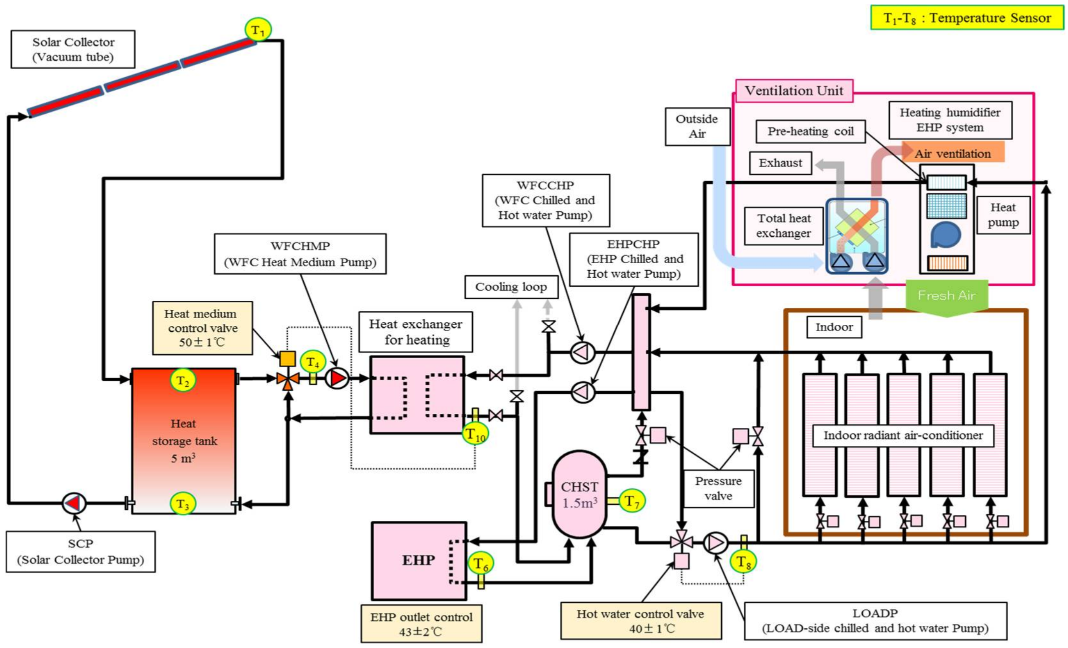

Figure 93: Hydraulic scheme of the YAZAKI System in Jinan (heating mode)

The HVAC was planned and designed by Chinese Partner the layout and details about solar thermal cooling were detailed in cooperation with YAZAKI. The solar energy, collected via two solar collector fields with evacuated tube collectors with an overall area of approx. 110 m², is stored in a 5 m³ hot water tank (HST). No other heat sources are fed into the hot water storage. In summer case the heat is used to run the absorption chiller (WFC) with 35 kW nominal capacity and the heat is rejected via a wet cooling tower. The chilled water is stored again in a 1.5 m³ tank (CHST) and complemented by a reversible air-water electrical heat pump. In winter case the heat from HST is fed into CHST via a heat exchanger and complemented by the heating mode of the 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 reheating coil. The control strategy includes the solar controller, realizing the highest priority of solar thermal driven system and thus higher solar fraction.

The non-renewable primary energy savings are calculated against the pre-defined Task 53 standard reference system. In the analyzed year 94% savings were achieved, dominated by the space cooling (50%) and domestic hot water (36%), space heating is from minor priority. This leads to an electrical equivalent SPF of 8.9.

The total annualized cost of the SHC system sum up to 16% additional costs compared to the standard reference. The levelized cost of energy are on an acceptable but higher level, as the demands are low because of passive house serving as load profile. Thus, the CostRatio is from higher interest still reflecting the investment dominant cost composition.

Table 19: Energy balance and cost comparison of the YAZAKI system

ENERGY		**10**	
		kWh	
EC.Sys		0	
SC.sys		50'164	
GD.sys		7'122	
WD.sys		22'500	0.36
SH.sys		9'121	0.14
CD.sys		31'681	0.50
$f_{sav.NRE}$		0.94	
SPFequ		8.89	
COST		**SHC**	**REF**
Annualized cost	€	13'762	11'843
LCOE	€/kWh	0.217	0.187
CR	-	1.16	

In the following figure presents the breakdown to the entire subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($f_{sav.NRE}$) and SPFequ as added annual figures and as annual course.

The difference in heating and cooling and DHW mode is respected by the PERs leading to a SPFequ of 4.6 for cooling and > 100 for heating and cooling respectively. The total system performance sums up according to the ratio of cooling, DHW and heating. The annual course is showing the fictive DHW demands in those month where no heating or cooling demand is occurring. A decreasing $PER_{NRE.sys}$ due to very low demand can be observed from Jan to march, while it increases to the DHW only operation in month of April/May and September to November and decreasing in the cooling only period from June to August. Main reason for the low performance in summer is the heat pump backup and its low performance. With increasing solar fraction or increased back up efficiency the cooling but also overall performance could be increased significantly.

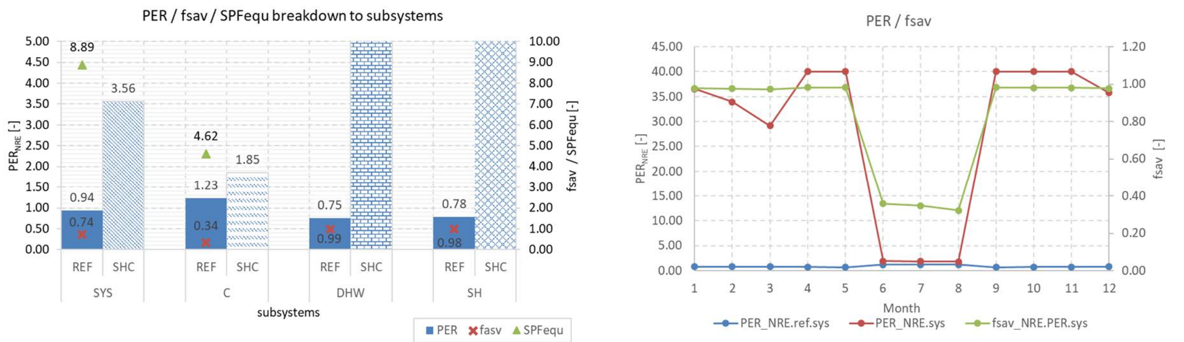

Figure 94:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the ZAE system

The following figures below present the total annualized cost of the entire systems. The SHC costs are dominated by investment and maintenance. The reference system presents a smaller ratio of investment but increased costs for electricity (for cooling) and energy carrier (for heating and DHW).

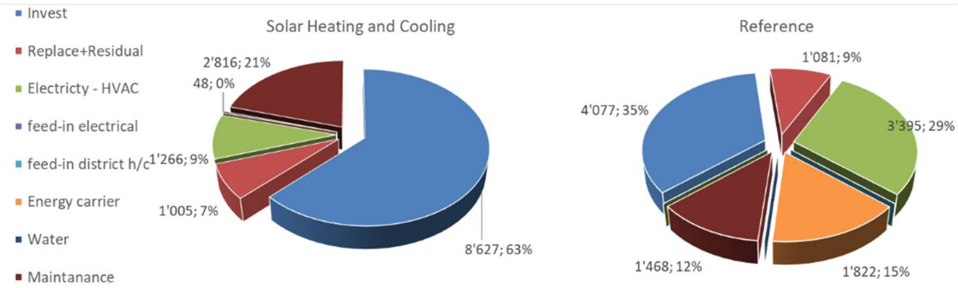

Figure 95: Annualized cost distribution of the ZAE system

8.11. Mono-split (by: ILK Dresden, PV; C)

A single-family house according to EnEV2016 building standards including PV-modules and a mono-split-unit for cooling is considered. This system is compared to a building including an additional ice storage for decoupling of cooling generation and cooling supply. Main objective is to increase PV self-consumption.

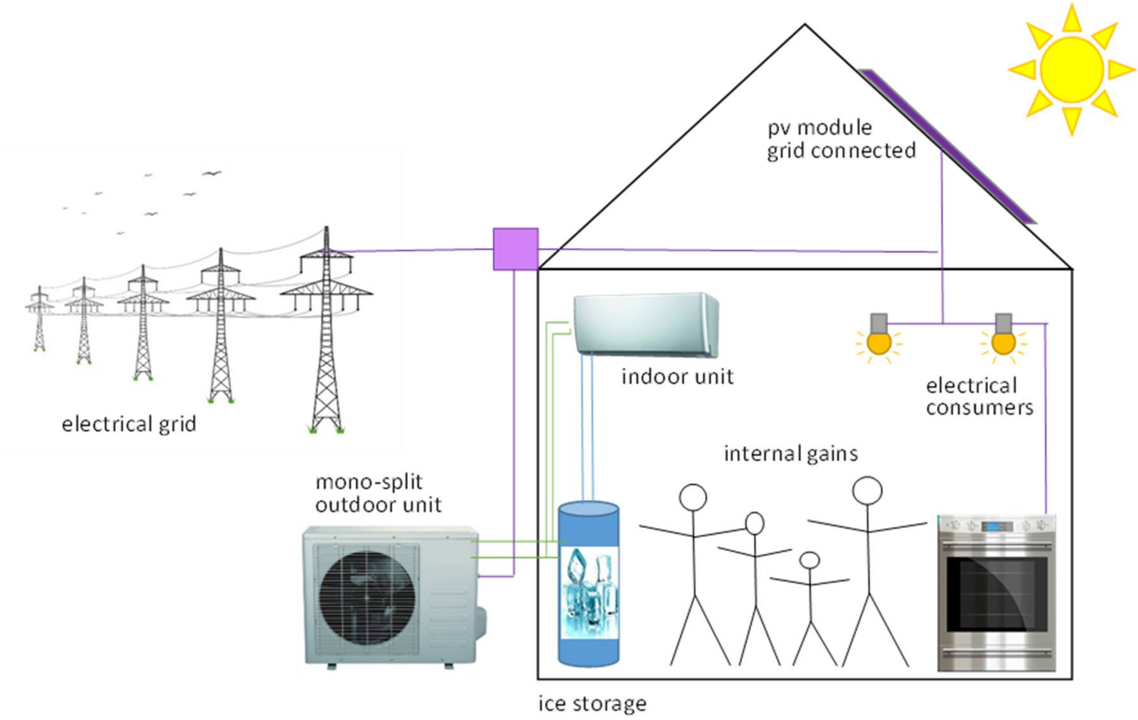

Figure 96: Basic schema of application and system

Important boundary conditions of the building are:

total living area of 100 m², distributed on two floors; thermal building standard according to German Building Regulation EnEV2016; infiltration and ventilation are combined to 0.5 h^{-1}, heat recovery is only active in heating period; shading is automatically controlled based on surface insulation level; internal gains resulting from a family of four and electrical loads; basic electricity consumption is modelled according to German h0-Profil multiplied by a factor of 5 for a four persons household (Hayn et al., 2014) → 5'000 kWh/a; required room temperature of 23°C in case of occupant's present; 16 PV modules à 230 W → 3.68 kWp

The cooling system consists of (*Figure 96*):

- mono-split outdoor unit Fujitsu AOYG 14 LMCA, designed cooling capacity acc. to Ecodesign: 4.0 kW, EER 3.52, SEER 6.90
- ice storage with a water volume of 60 l
- combined indoor unit including evaporator for direct cooling and water-based heat exchanger for storage discharge mode
- system is always grid connected

The split-system including ice storage allows three operation modes:

- direct cooling: magnetic valves to evaporator in storage are closed, operation is like split-unit without ice storage
- charge mode: magnetic valves to evaporator in storage are open, valves to indoor unit are closed, outdoor unit operates to charge ice storage only
- discharge mode: water cycle between ice storage and indoor unit is active, storage is discharged, cooling power is supplied to the room
- direct cooling and discharge mode can be work simultaneously

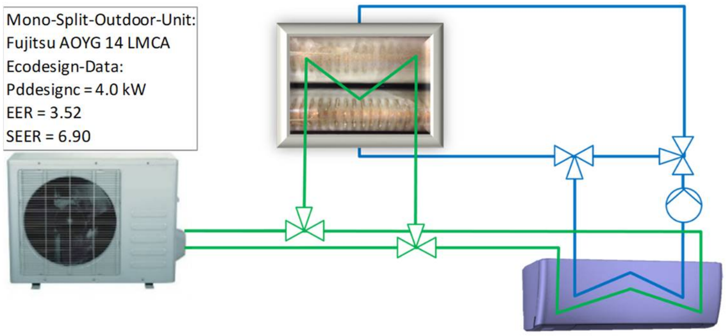

Figure 97: Description of the cooling system

Controller principles:

- household electricity consumption is always prioritized
- in case of no present cooling demand but forecast cooling demand, remaining PV-power is used to charge ice storage
- in case of cooling demand
  - first: remaining PV-power output is used in direct cooling mode
  - second: cooling power is increased by discharging the ice storage
  - third: direct cooling mode is controlled on demand using additional electricity from the grid

The evaluation is based on a combination of experimental investigations of the cooling system and a building and system simulation model in Modelica / Dymola. The ice storage in combination with the split unit was experimentally investigated with varying outdoor unit part load factor from 20 to 100%, ice fractions between 0 and 80 % and ambient temperatures between 20 and 25 °C. A simulation model was developed based on measurement results. PV-module and building model are based on the BuildingSystems-library. The system is simulated for German site Berlin.

System cost remarks:

Main objective is the comparison of systems with and without thermal storage for demand side shifting and increasing of PV self-consumption. The PV system is designed to provide roughly 50% electricity for the household over an entire year, thus the PV is oversized for the split unit and the electricity obtained from grid is almost negligible (56 kWh (11a) / 22 kWh (11b).

The PV production provides 3.6 MWh and 3.1 MWh are drawn from the grid whereas 1.6MWh are feed back into the grid. The demand is dominated by house hold electricity, only cooling is analyzed on the site of Berlin. The results of this small-scale system result in LCOE of 0.12 €/kWh for the reference system and 0.15-0.16 for the PV driven system respectively. This numbers are that low because the majority of the demand is the electricity for household. If only energy for heating and cooling would be counted the LCOE would end up > 1€/kWh because of the climatic conditions of Stuttgart (only 1'000 kWh/a demand and 5-month load). The system could run reversible and provide heating in winter as well, but this was not analyzed here.

More relevant are the total annualized costs and the CR for the mono-split unit. The annualized costs are 24 % higher compared to the reference system (CR = 1.24), but the additional costs are increasing to 32 % (CR = 1.32) when a cold storage is included.

Table 20: Energy balance and cost comparison of the ILK PV cooling system 11a without storage and 11b with storage

		11a		11b	
ENERGY		**kWh**	**%**	**kWh**	**%**
EC.Sys		0		0	
SC.sys		0		0	

PV.sys		3'619		3'619	
GD.sys		3'124		3'090	
EL.sys		1'676		1'546	
WD.sys		0	0.00	0	0.00
SH.sys		0	0.00	0	0.00
CD.sys		1'004	1.00	935	1.00
EL.DE		4’963		4’963	
fsav		0.41		0.42	
SPFequ		1.91		1.91	
COST		**SHC**	**REF**	**SHC**	**REF**
Annualized cost	€	579	224	630	222
LCOE	€/kWh	0.146	0.118	0.16	0.12
CR	-	1.24		1.32	

In this case, to show the effects about PV-self consumption targeted in the project, T53E4 Tool subsystem assessment is calculated with the grid electricity only. The subsystem cooling can achieve a SPFequ of 17.6 (11a) and 41.76 (11b) leading to 84% and 93% savings respectively. Including the household electrify leads to a drop of the SPFequ down to 1.91 for both systems. The difference in cooling get even due to the dominance of household electricity.

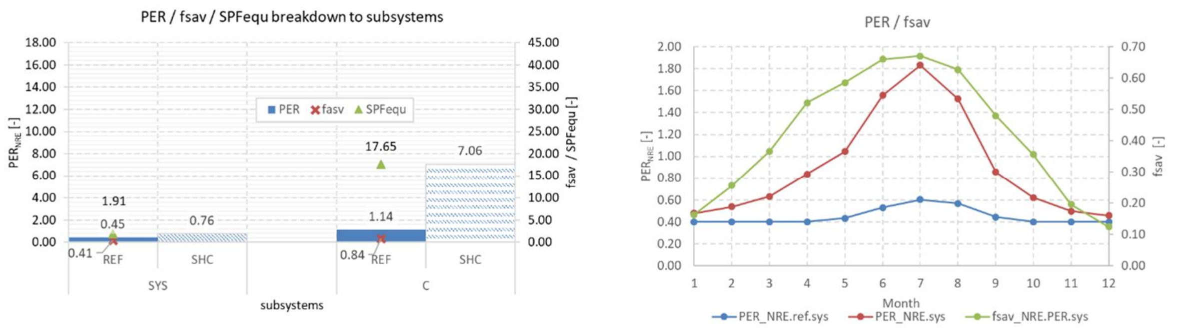

Figure 98: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the 11a Mono-split System in Berlin.

The annual profile of case 11a shows that the cooling demand was in the months May till September. The savings increase and decrease with the solar yield and reach its highest value of 67% in July. The annual course of the second case 11b looks quite similar but reaching higher PER_{NREsys} and thus higher savings due to the higher share of PV for the cold production (see Figure 99).

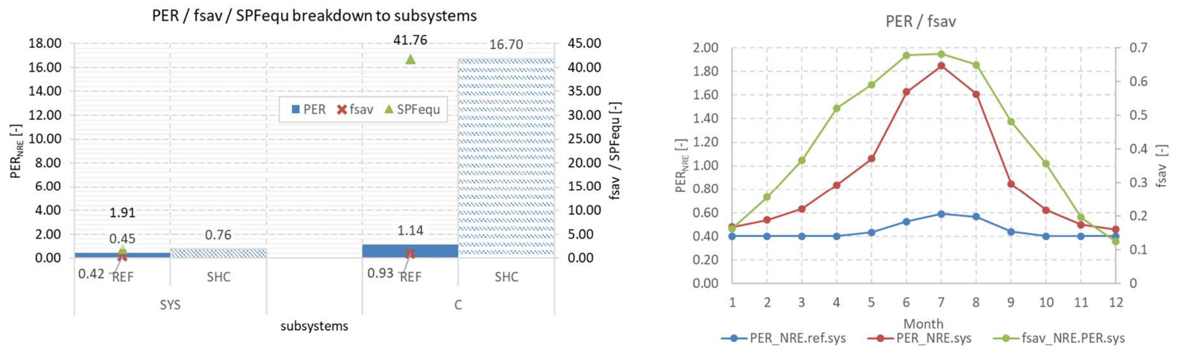

Figure 99: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the 11b Mono-split System in Berlin.

The following figures show the annualized cost distribution of the PV-cooling system. The cost distribution of the system in case 11a and 11b is similar, but the absolute values are higher for the 11b system with an additional storage. The cost for the SHC system are dominated by investment followed by domestic electricity costs. For the reference system the household electricity is clearly dominating.

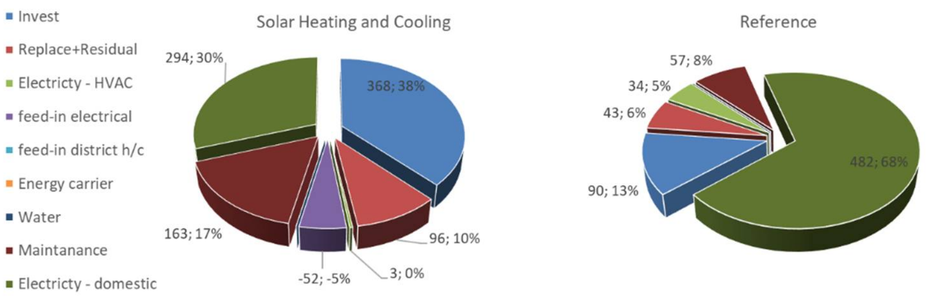

Figure 100: Annualized cost distribution of the #11a Mono-split System in Berlin.

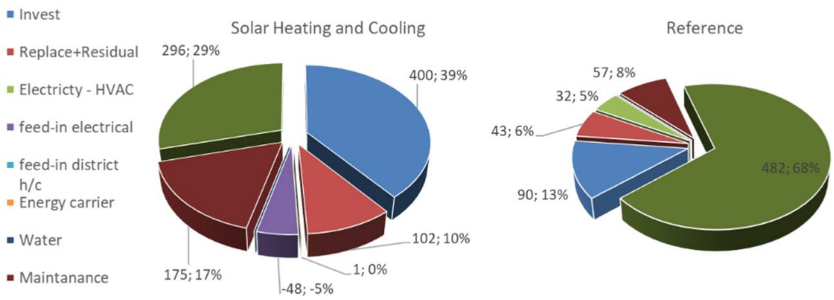

Figure 101: Annualized cost distribution of the #11b Mono-split System in Berlin.

8.12. TheBat (by: UIBK; PV; SH+DHW)

Electrical driven heat pumps in combination with thermally activated building systems (TABS) and conventional hot water storages (TES) can be used as thermal battery for electricity produced based on renewable energy sources. This electricity might be produced locally with photovoltaic systems on the building with the goal to realize a maximum of self-consumption. Based on a set of theoretical simulations it was investigated how a heat pump system in combination with a building with different designed TABS can act as a thermal battery when supplying space heating and domestic hot water to the building with different control strategies.

Simulations within the project TheBat (Thür et al., 2016, 2017a) are done for a single family house (based on the IEA SHC Task44 reference building; (Dott et al., 2012; Dott et al., 2013)) designed as low energy standard (RES45: 45 kWh/m²a space heating consumption, SH) at Innsbruck climate with thermal active mass by floor heating. The reference floor area is 140 m², the room temperature is controlled to 21°C ± 0.5K and the domestic hot water (DHW) consumption at 45°C tap temperature is 2,175 kWh per year.

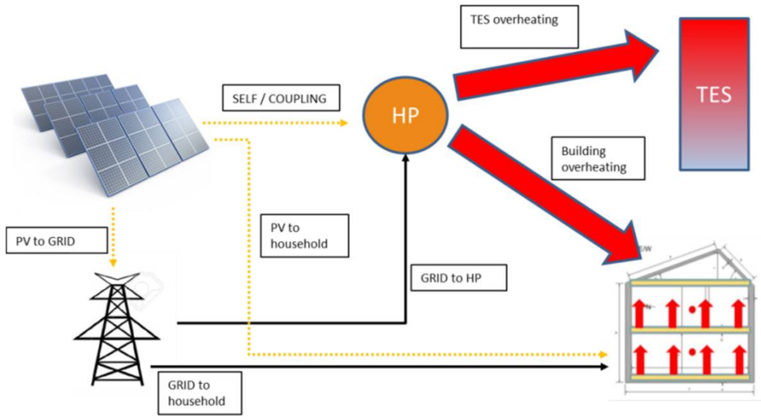

Figure 102: Energy flow of a PV+HP system to the TES or the TABS of the RES45 single family house.

The heat pump is equipped with a desuperheater with variable volume flow to reach 50°C set temperature. The ground source brine heat pump (HP) is connected to a water storage (TES) directly via the desuperheater. The condenser of the HP can charge the TES or bypass the TES for direct heating of the building. Domestic hot water preparation is done with an external plate heat exchanger with controlled primary mass flow.

The heat pump is designed for thermal power output of about 10 kW_{th} at B0W35. The brine source temperature is modelled with average temperature of 5°C ± 6K varying over the year. The heat pump can be operated in different ways like: a) power controlled depending on the ambient temperature, b) power controlled depending on availability of photovoltaic electricity, c) with or without using a desuperheater for domestic hot water preparation, d) charging a water storage tank at different temperature levels or e) heating the building to room temperatures with more or less hysteresis.

Five different control concepts where simulated (Thür, 2017), just the concept TES1000 with TES overheating in combination with a 1000 liter storage is presented here: For DHW preparation as standard control, only the top volume of 300 liter of the TES is heated up to 50°C.

As PV system a 2.5 kW_{peak} system (20 m²) mounted south oriented and 45°C tilted is assumed. If the PV power is higher than 1 kW and greater than the actual electricity demand of the compressor. According to the standard control strategy, the heat pump is in operation with compressor speed matching the PV electricity and therefor the system can store heat in the TES until it is completely heated up to 55°C.

No household electricity is taken into account in these simulations to avoid the influence of assumptions for the household consumption profile. Therefore, the PV electricity is first used by the heat pump and the remaining electricity is completely feed into the grid.

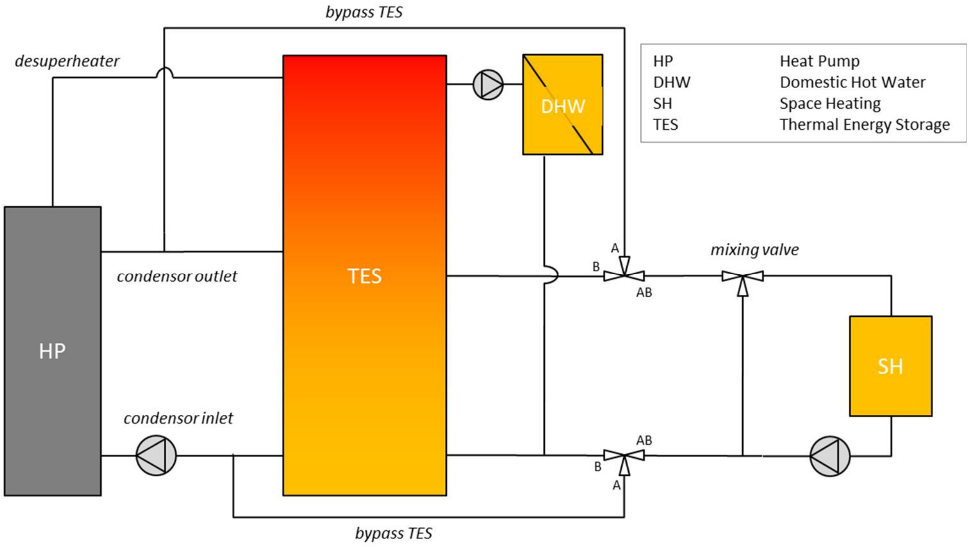

Figure 103: Hydraulic scheme of the SHC system "TheBat" by UIBK

The energy demand is reflecting the size, its location in Austria but also the energy standard. The demand is dominated by space heating, less than 1/3 is used for domestic hot water preparation (typical values for 45kWh/m².a energy standard). No cooling demand is present in single-family houses in Austria.

The coincidence of PV production and HVAC electric demand due to the control concept is comparable high, as 3.6MWh are provided by PV and 1.2MWh are directly used by the heat pump and only 2.4MWh are feed into the grid meanwhile 1.3MWh electricity are drawn from the grid. This result in a self-consumption ratio of 33% (compared to 7% of the standard system control without the TES overheating strategy). Therefor a high solar fraction and thus high non-renewable primary energy savings (73%) can be achieved leading to an SPFequ of 6.9. From cost point of view the total annualized cost end up 44% higher than the reference system.

Table 21: Energy balance and cost comparison of the TheBAT

ENERGY		12	
		kWh	
EC.Sys		0	
SC.sys		0	
PV.sys		3'637	
GD.sys		1'289	
EL.sys		2'390	
WD.sys		2'173	0.24
SH.sys		6'707	0.76
CD.sys		0	0.00
$f_{sav.NRE}$		0.73	
SPFequ		6.89	
COST		SHC	REF
Annualized cost	€	2'241	1'556
LCOE	€/kWh	0.252	0.175
CR	-	1.44	

The figure below shows the yearly breakdown to the subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($fsav_{NRE}$) and SPFequ as added annual figures. The subsystems analysis considers the total electricity (PV + grid), thus the referred values are smaller than the corresponding overall figures where only grid electricity is considered as energy input. As the energy balance is available only on annual base no automatic subdivision by the T53E4 Tool of SH and DHW can be performed. Thus, the same PER and SPFequ respectively occur but the savings are slightly different due the calculation method of the reference system.

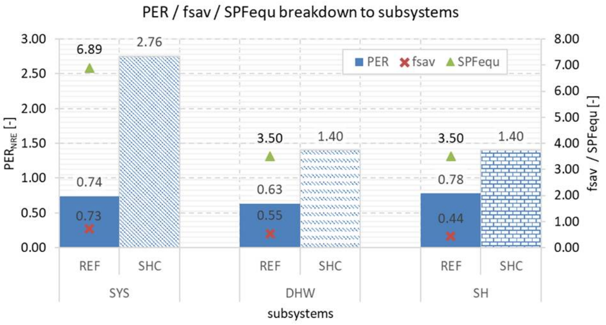

Figure 104:Yearly breakdown to subsystem and annual profile of PER, fsav and SPFequ for the TheBAT

The total annualized costs are reflecting the small scale of the system. For the SHC system investment costs are dominate followed by the electricity cost. The reference costs are dominated by investment and energy carrier cost equally.

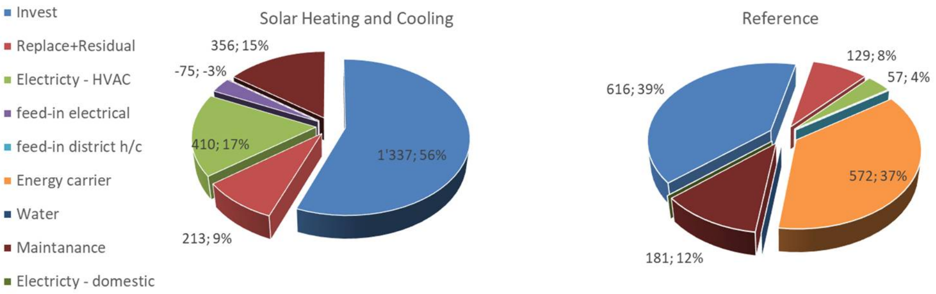

Figure 105: Annualized cost distribution of the TheBAT system

8.13. PVCOOLING (by: ATISYS, PV, C)

The PVCOOLING pilot project installed on the ATISYS head-office roof-top, is located in Toulon area (South East of France, lovely site in French Riviera). This French SME is coordinating the innovative project of a smart designed system named PV COOLING to produce solar cooling using a low GWP heat pump system (propane based) coupled with a standard photovoltaic plant. A maximum of self-consumption is promoted by means of a light bank of batteries and a chilled water tank.

In this pilot testing system, electricity is delivered by 18 mono-crystalline photovoltaic modules (280 Watts peak (Wp) for each module), which represents a total power of 5.0 kW_p. This power is sufficient for driving 2 chiller compressors and all ancillary equipment dimensioned for 10 kW_{th} chilling capacity (condenser fan and chilled water circulation pump). The photovoltaic panels are connected to a three-phase wired inverter along with batteries bank. The four 12-Volt batteries are connected in series to obtain a voltage of 48 V. Their 150 Ah capacity each with a 50% depth of discharge (DOD) allows obtaining a useful electrical storage of about 3.6 kWh. This is sufficient to drive the full load power installation for at least one hour. For a real operational system, battery capacity may be chosen according to actual need to limit the inrush current during compressor run-up.

A variable-frequency drive has been installed downstream from the inverter which divides the inrush current by 6. Two parallel-mounted semi-hermetic compressors were selected and adapted for propane. Each compressor can provide from 2.4 to 5.4 kW of cooling by varying its rotation frequency from 30 to 70 Hz. This allows a cooling capacity between 2.4 and 10.8 kW. For the future, commercial PV cooling systems will be able to reach high cooling power till 300 kW using larger compressors.

The condenser is an air/R290 type heat exchanger, also called air-cooled condenser. In order to reduce refrigerant load, a micro-channel type condenser has been chosen. The evaporator selected for the project is a brazed plate heat exchanger also suitable for propane. The major innovation regarding the heat pump system lies in the use of low Global Warming Potential (GWP) refrigerant. The choice fell on propane (R290) with GWP (<10), which is considerably low compared to a common refrigerant (e.g. GWP=1300 for R134a). The only drawback with using propane is the necessity of additional safety due to flammability. According to French safety regulation, positioning the chiller outdoor is considered as sufficient. Thus, no additional safety measures are necessary.

The fluid that transports the refrigerating capacity from the cold unit to the chilled water tank is water/methyl propylene glycol (MPG) mixture, to avoid any freezing risk. For this test bench, the chilled water tank is representative for a typical building which thermal load is simulated with an electrical resistor heating the 180 liter chilled water tank. That gives the advantage to fully control the building loads and consequently simulate several conditions which correspond to different building utilization/insulation and climate conditions in the large period of the year in this sunny part of France (far South). Solar production is not simulated therefore the essential period of cooling tests is located from mid-April to end of November.

A monitoring system has been set up to show performances of the system according to the needs throughout the year. The monitoring equipment is powered by PV-COOLING itself (Esparcieux P. and et al., 2017). The hydraulic setup is shown in Figure 106.

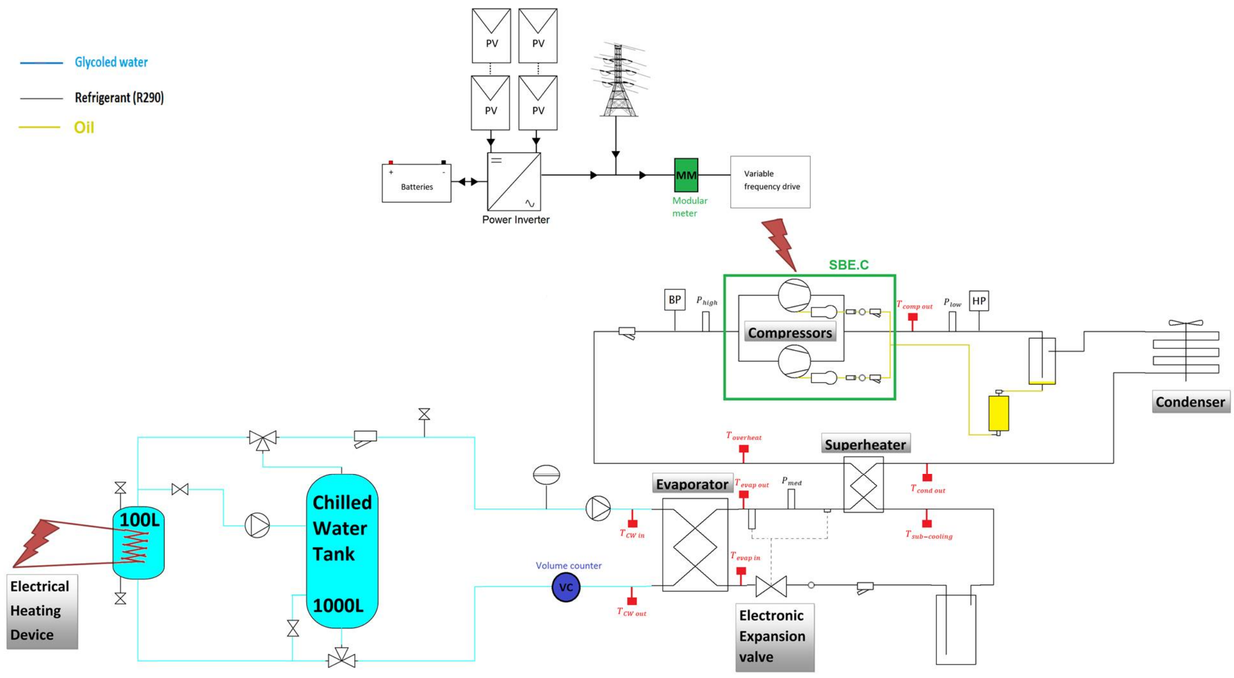

Figure 106: Hydraulic scheme of the PVCOOLING project in France (Esparcieux P. and et al., 2017)

Since the system was installed recently no annual data was available for the analysis. For the analysis data from the months July and August was available. The following table shows the energy balance and cost comparison based on the data available so far.

The system is designed to cover the cooling demand only. The main electricity consumption of the cooling system can be covered by the PV system (60 %), 40% of the electricity is drawn from the grid. The PV-electricity which cannot directly be used is fed into the grid which is 59 % of the total electricity produced by the PV modules. The savings of the system sum up to 66% and an electrical equivalent SPF of 5.6 respectively. An important penalty in term of grid energy consumption is based on the fact that the chilled water tank of the test facility had to be cooled down first every morning to create conditions compatible with the simulated building behaviour, thus leading to significant higher grid electricity consumption.

The annualized costs of the SHC system are 60 % higher compared to the reference system but is misleading with only two months of operation. If full data is available, the CostRatio will decrease accordingly and be lower than the reference from the designer prospective and assumptions.

Table 22: Energy balance and cost comparison of the PV-driven cooling system from TECSOL in France

ENERGY		kWh	%
EC.Sys		0	
SC.sys		0	
PV.sys		480	0.60
GD.sys		322	0.40
EL.GD		283	
WD.sys		0	0.00
SH.sys		0	0.00
CD.sys		1’793	1.00
fsav		0.66	

SPFequ		5.57	
COST		**SHC**	**REF**
Annualized cost	€	2’980	1’861
LCOE	€/kWh	1.662	1.038
CR	-	1.60	

In the following figure the breakdown to the entire subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($f_{sav.NRE}$) and SPFequ is presented as added annual figures but also the annual course. The subsystems analysis considers the total electricity (PV + grid), thus the referred values are smaller than the corresponding overall figures where only grid electricity is considered. The SHC system shows a PER_{NRE} = 2.23 and can achieve primary energy savings of 66 % compared to the reference cooling system.

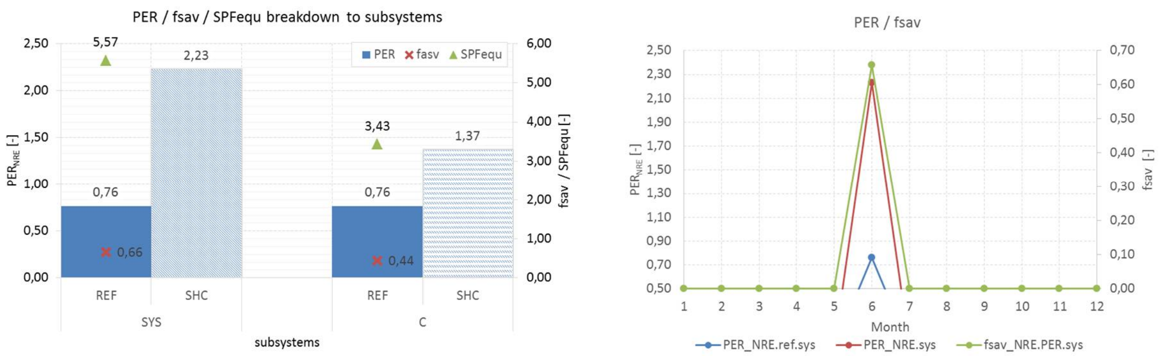

Figure 107: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the PV-driven cooling system from TECSOL in France

The main cost driver for the SHC system are the investment costs followed by the maintenance costs. Also, for the reference system the investment costs amount to the highest share, followed by costs for electricity. The share for electricity will increase significantly when considering the yearly data.

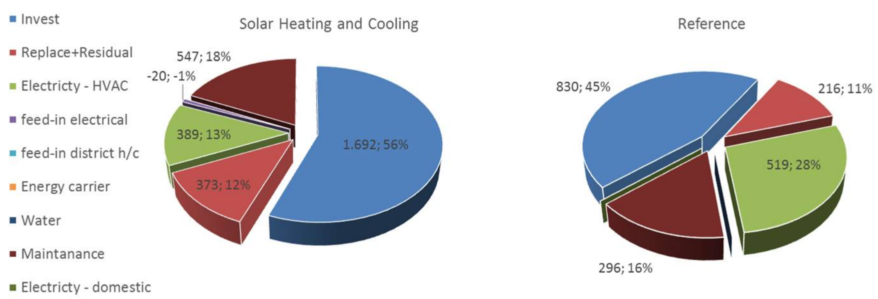

Figure 108: Annualized cost distribution for the PV-driven cooling system from ATISYS in France

8.14. Waldispühl (by: SPF Rapperswil, PV, SH+DHW+C)

In a single-family house, a solar driven heating, ventilation and air conditioning system (HVAC) is installed. The standard building is located in Arth (422 m a.s.l.), a pre-alpine region of moderate climate. A family of four people is living in the house. Beside of space heating and cooling the HVAC is also used for domestic hot water preparation. A grid connected 11.1 kWp photovoltaic (PV) panel field supplies all the electrical components of the building. With this PV field a net positive yearly energy balance result can be achieved and thus it is a Swiss Minergie (total yearly specific end energy use: 35 kWh/m^2*a).

The main component of the HVAC system is a compressor heat pump with ground water as low temperature heat source / heat sink (free cooling). An external plate heat exchanger separates the input loop of the heat pump and the ground water loop. The thermal energy distribution sub-system for room heating and cooling contains a thermo-active building component (TABS) which is implemented in the room floors. A 500-litre tank is installed to store the domestic hot water. This water tank is charged by the heat pump via a tank integrated heat exchanger and an electric heater for back up reasons.

The room cooling is done in the free cooling mode by direct cooling with the ground water as the heat sink. In the free cooling mode of the HVAC system the compressor unit is bypassed with an internal three-way valve (V1) and the cold can be distributed either to the TABS or also, with an additional heat exchanger, to the room ventilation. Figure 1 shows the schematic of the HVAC system.

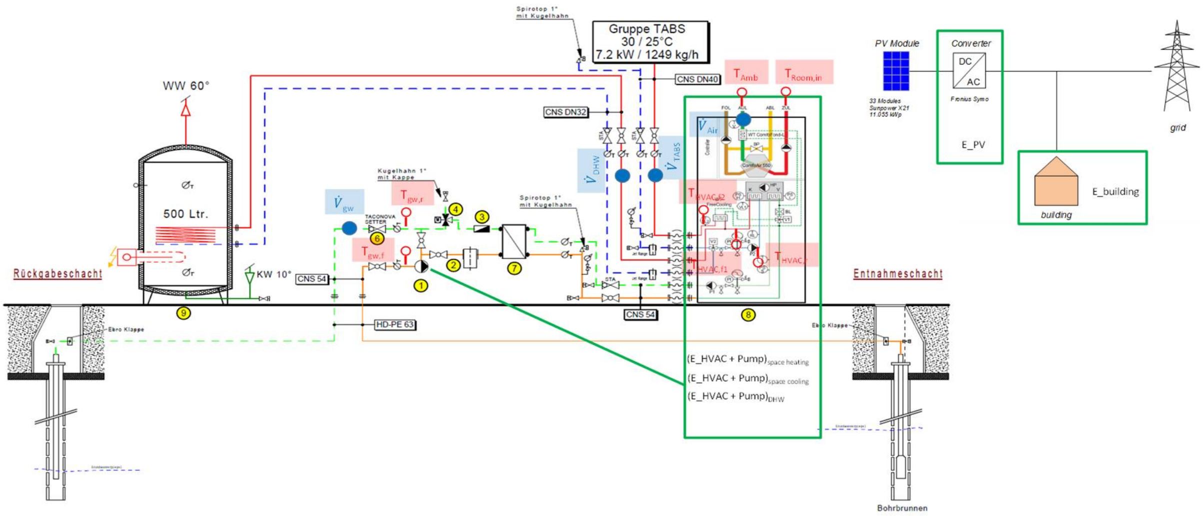

Figure 109: Hydraulic and electric scheme of the HVAC system with heat pump of Waldispühl in Arth (SPF Rapperswil). Additionally, inserted are the points of measurement for acquiring the thermal and electric energy flows.

Since the system was installed recently no complete annual data are available for the analysis and no heat demand was covered yet. For the analysis data from the months July and August was available.

The system is dominated by the cooling demand (78 %) and 22 % is used for the domestic hot water preparation. The electricity demand of the building in the measurement period is 1.3 MWh. This energy demand is covered by the 0.6 MWh (PV.sys minus El.sys) of the PV system and by 0.7 MWh (GD.sys) of the public grid. The total electricity conversion of PV is 2.8 MWh but 2.2 MWh of the energy is feed into the grid. The reason of this high feed-in rate is that the PV system is designed for the heating season in winter time where a lower solar irradiance is available but higher electrical energy demand is needed.

The annualized costs of the HVAC system are 33% above the costs of the reference system (CR = 1.33), Table 23. In this case, as only two months of demand are included in the calculation the Cost figures are misleading and not reflecting the real cost. The only values that can be analysed are the investment, replacement and maintenance cost.

Table 23: Energy balance and cost comparison of the PV-driven SHC system in Switzerland

ENERGY	kWh	%

EC.Sys		0	
SC.sys		0	
PV.sys		2'839	
GD.sys		725	
El.sys		2'151	
WD.sys		458	0.22
SH.sys		0	0.00
CD.sys		1'595	0.78
fsav		0.67	
SPFequ		4.33	
COST		**SHC**	**REF**
Annualized cost	€	3'373	2'472
LCOE	€/kWh	1.090	0.822
CR	-	1.33	

In the following Figure 110**Erreur ! Source du renvoi introuvable.** the breakdown to the entire subsystems and its non-renewable primary energy ratio (PER_{NRE}), savings ($f_{sav.NRE}$) and SPFequ is presented as added annual figures but also the annual course. The key figures for the total system are including the domestic electricity demand and thus reflecting the concurrency of PV production and demand.

The cooling is provided via free cooling and thus very efficient, an electrical equivalent seasonal performance factor of >10 was reached. This value is including the overall electricity demand (PV+grid). If only grid electricity would be considered, the SPFequ is much higher as almost 60% are covered by PV. The same occurs for domestic hot water preparation. For DHW the heat pump is working, thus more electricity is needed summing up to an equivalent SPF of 2.63 (including 30% PV coverage). In comparison in July the cooling demand is almost double as high than in August were as the DHW demand is 30% higher and domestic electricity demand is constant. Thus, the system Waldispühl is dominated by cooling and reflecting the high savings at roughly 70%, whereas the $fsav_{NRE.sys}$ in Aug sums up to 40%.

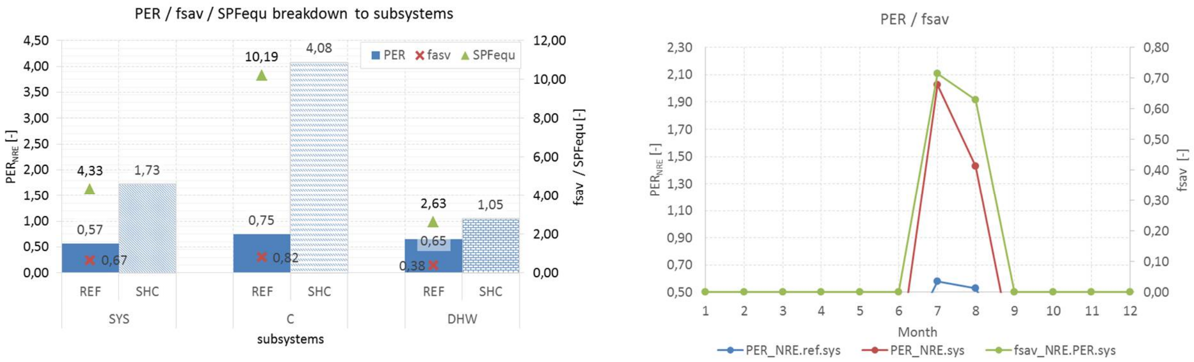

Figure 110: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ of the HVAC system in Arth

The total annualized costs are reflecting that only two months of operation was monitored. Thus, the investment and replacement costs are dominate. In this case the absolute values of investment plus replacement (SHC: 2.6k€; REF: 1.5k€) are compared, showing an investment ratio of roughly 1.7. Although this plant is only running for two months it ends up with an CR of 1.3, thus showing the potential to reach cost parity within an entire year of operation.

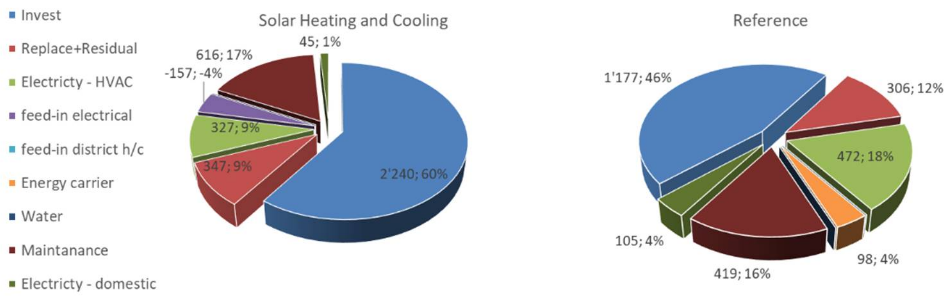

Figure 111: Annualized cost distribution for the PV-driven HVAC system in Switzerland

8.15. Freescoo AHU Morocco (by: FREESCOO, ST, C+SH)

The system has been installed at the library of AMEE in Marrakech within a research project between Politecnico di Milano and AMEE (Agence Marocaine pour l'Efficacité Energétique). The aim of the project was to develop, test and optimize a robust, low cost, low maintenance solar driven air-conditioning concept, suitable for Northern African climates.

The system is an all-in-one concept and integrates four evacuated tube solar collectors X RAY 10 by Pleion having a design solar heating power of 4.8 kW and a gross area of 8.8 m^2. It has a maximum total air flowrate up to 1000 m^3/h, a maximum cooling capacity of 5.8 kW and a global rated EER of 16.7. Since the system recirculates part of the return air, it takes about 50% of fresh air from the ambient and 50% from the building, providing at least 0,4 vol/h of air change in the room. The max power needed is about 360 W at the operative flow rate (1000 m^3/h). To drive the cooling process, about 2 litres of water per kWh of cooling energy are needed.

In the wintertime, when the sun shines the system can provide also heating to the room and ventilation in the middle seasons.

The building is a three-stage structure-oriented NE-SW and the last stage hosts the library. The library stage has a square shape. The roof is plane and presents a square-shaped skylight in the centre with a sloped roof. The skylight height is 1.30 m and his rooftop is 3.50 m above the plane level. The internal ambient is developed around the central space, corresponding to the square skylight. The ambient is composed of two different spaces. The first is assigned to the document shelves, while the other is designated to the hosts' seats. The net internal area is about 300 m^2. The internal ambient temperature is controlled by four existing electrical split systems, with a global cooling power of about 18 kW. It has to be noted that only some split units could operate properly, causing frequent overheating during the summertime and insufficient heating during the wintertime.

The monitoring campaign has been performed during the year 2017. For the heating mode data have been registered in January and February (59 days), whereas for cooling operation from May to September (159 days). During the wintertime daily operation hours varied according to the working hours of the solar collectors. In heating mode, the system runs solar autonomous, it is operated only when temperature at the solar collectors exceeded 25°C. In summertime the operation hours varied according to the will of the users and varied from 10 to 24 hours a day. During the monitoring period the building was occupied as normal. Global radiation on the horizontal on the site of Marrakech reaches 1100 W/m^2, whereas global solar irradiation in one year is about 1.9 MWh/m^2. Average temperatures vary from about 7°C to 35°C, peak temperature from 4°C to 43°C. Peak humidity ratio is about 16 g/kg in July but mean daily values normally don't exceed 12 g/kg (Beccali et al., 2017).

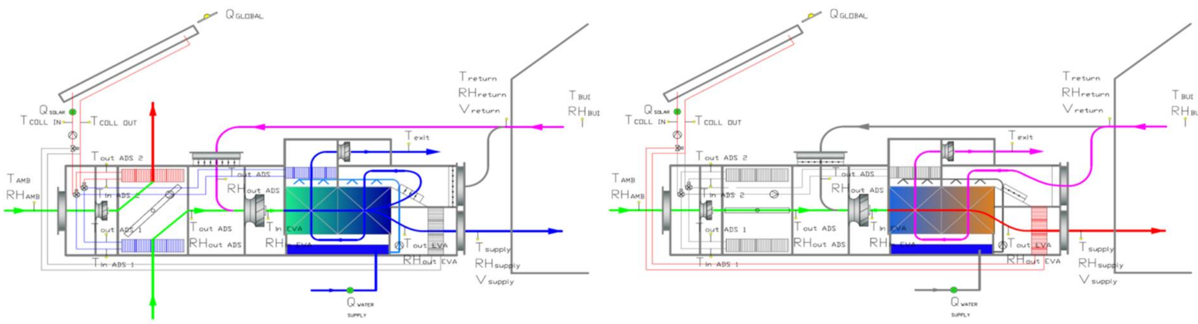

Figure 112: Hydraulic scheme of the Freescoo AHU System in Morocco in summer operation (left) and in winter operation (right)

The Freescoo system in Marocco is a solar autonomous system which is used to cover 100 % of the cooling demand due to the ventilation, without any backup. The measured data which is the basis for the analysis is not available for the complete year, but from May to September and January to February in 2017. During the mentioned months the system was in operation almost every day, in summer system the system was off for 14 days in total whereas it was not stop in the daily operation during the winter. The following table shows the energy balance and annualized cost comparison of the system.

Table 24: Energy balance and cost comparison of the Freescoo system in Morocco

ENERGY		kWh	%
EC.Sys		0	
SC.sys		4’925	
GD.sys		911	
WD.sys		0	0.00
DHW.sys		0	0.00
CD.sys		5’528	0.85
SH.sys		960	0.15
fsav		0.74	
SPFequ		7.12	
COST		SHC	REF
Annualized cost	€	1'033	1'061
LCOE	€/kWh	0.159	0.164
CR	-	0.97	

The system is designed to cover 100 % of the cooling demand by solar thermal heat. The only additional energy input is coming from the grid electricity to operate the solar pump and ventilators. The annualized costs for the Freescoo system are competitive to the costs of the reference system, showing a cost ratio of 0.97, although only 7 months of operation are considered.

In T53E4 Tool subsystem assessment is calculated with the non-renewable energy input. In this case only grid electricity is necessary to run the system and all the other energy is provided by heat from solar thermal collectors. The cooling system is very efficient (PER of 3.02) and achieves 75% non-renewable energy savings compared to the reference system. The overall primary energy savings for the system sums up to 75% compared to the reference system. The monthly profile of the $fsav_{NRE}$ shows a constant value above 70 % savings in summer. In September the value drops to 60 %, due to a problem in the system (that was detected and solved). In the winter months savings of above 80 % can be achieved with the Freescoo system. The subdivision if the heating and cooling mode in the yearly balance is misleading as the electricity is divided according to the demands (SH:20 / C:80) but the measured electricity shows a ratio of SH: 10 to C:90. Nevertheless, the monthly values of the system and the overall system key figures reflect the quality and the degree that can be reached with solar thermal autonomous operation.

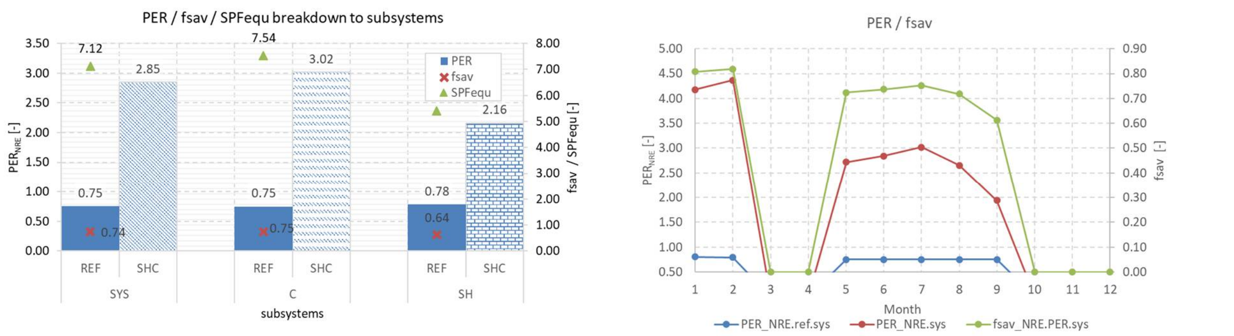

Figure 113: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the Freescoo system in Morocco.

The total annualized cost is showing the difference of SHC and reference system clearly. The main cost driver of the SHC system are the investment cost, followed by the maintenance. These two costs are already summing up to 93% of the total cost, thus other cost (e.g. electricity) can be neglected. The reference systems also relatively high cost for investment, as this system was only in operation for 2937 hours over the year. If the system would run more often, the cost for energy carrier and electricity respectively would get larger and the SHC system would result in a smaller CR.

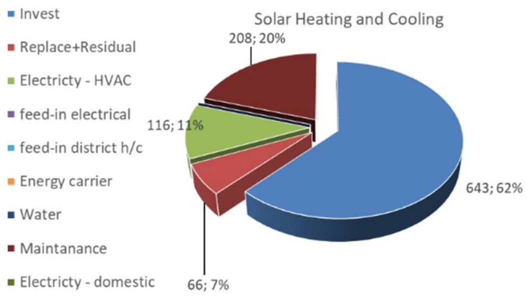

Figure 114: Annualized cost distribution for the PV-driven SHC system in Morocco

8.16. Freescoo Palermo (by: Freescoo, ST+PV, C+SH)

The unit has been installed in 2014 at the Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici (DEIM) of the University of Palermo in Italy. Data have been registered during July and August 2015 for summer operation and between January and February 2015 for winter operation. The room served by the system is an office with an area of about 46 m^2 and a volume of about 190 m^3. During the test, rooms were occupied as normally. Above a maximum room temperature of 26°C, an additional split system was operated to assist the freescoo unit in controlling the sensible load.

The system was properly designed for the air-conditioning of under-roof spaces. A casing contains the solar air collector, the adsorption beds, an integrated cooling tower, wet-plate heat exchangers, fans and all other auxiliaries needed to accomplish the air handling process. The solar photovoltaic and thermal air collector (total area 2.4 m^2) provide respectively electricity used for the machines and heat for the regeneration of the desiccant material. Peak power produced by the PV is about 170 W. A battery system is used to store electricity produced from PV (65 Ah). If the solar PV production is not sufficient to drive the system, systems commutates automatically to the grid.

The maximum total cooling power is 2.7 kW at design summer conditions (Toutside = 36°C, RHoutside = 50%, Tbui = 26°C, RHbui = 50%) with an air flow rate of 500 m^3/hr. A cooling tower, which is integrated in the system, is used to reject the adsorption heat generated by the desiccant bed during the dehumidification process. Regeneration is carried out using hot air directly warmed by the solar air collector. The air flow rate passing the adsorption bed is 200 m^3/hr, which is 40% of the air delivered to the conditioned space. Electricity is only consumed by the operation of three fans and two pumps. Cooling power is controlled by variable speed fans. (Finocchiaro et al., 2015; Finocchiaro et al., 2016)

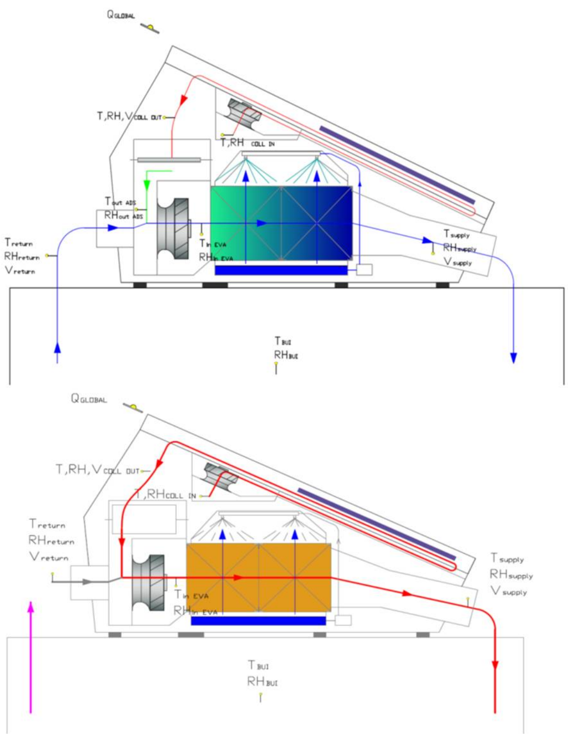

Figure 115: Hydraulic scheme of the Freescoo compact system in Palermo in summer mode (left) and in winter mode (right)

Only data from one winter month (January) and one summer months (August) was considered for the analysis as well as only grid electricity is measured and was analyzed. The following table shows the energy balance and annualized cost comparison of the system.

The electricity driving pumps and ventilator was only counted from grid, PV production is unknow. Nevertheless, the grid electricity demand and the provided heating / cooling reflects the almost 100% solar autonomous operation of the FREESCOO design. The overall savings sum up to 96%, reflected by an SPFequ of 61.6. Whereas the demand is dominated by the cooling (81 %) and 19 % was used for space heating. The system is not designed to provide domestic hot water.

Due to low operating hours and analysed data respectively, the cost analysis is misleading. The LCOE include the complete investment and replacement but only low running cost for electricity and energy carrier (for reference). In this case the ratio of investment is from higher interest than the total cost, LCOE or CostRatio.

Table 25: Energy balance and cost comparison of the Freescoo System in Palermo

ENERGY		kWh	%
EC.Sys		0	
SC.sys		609	
PV.sys		45	
GD.sys		11	
EL.sys		0	
WD.sys		0	
SH.sys		126	0,19
CD.sys		533	0,81
fsav		0.96	
SPFequ		61.55	
COST		SHC	REF
Annualized cost	€	347	372
LCOE	€/kWh	0.527	0.565
CR	-	0.93	

Figure 116´shows the yearly breakdown to the subsystems and its key figures. The T53E4 Tool subsystem assessment is calculated with the overall electricity input (PV+grid), whereas the total system only considers grid electricity for the calculation. The subsystems are reflecting the efficiency and degree of autonomy. The space heating can be provided with 7.2 kWh electricity (PV+grid), thus reaching 78% savings. Cooling auxiliaries sum up to 48.5 kWh, thus reaching savings of 77%. Excluding the PV and only considering the grid electricity leads to a overall saving of 97%.

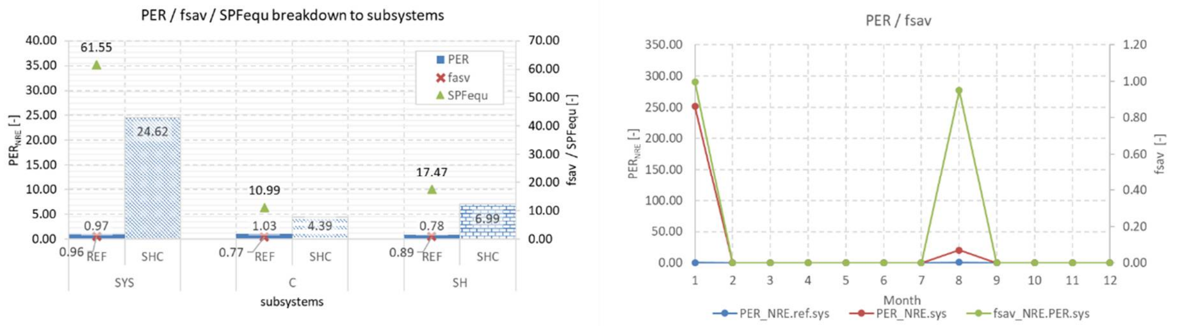

Figure 116: Yearly breakdown to subsystem and annual profile of PER, fsav, SPFequ for the Freescoo System in Palermo

The main cost drivers for both systems (SHC and Ref) are the investment costs followed by the maintenance costs. Due to the low running hours of the system the costs of energy carrier for the reference system are very low but will increase when considering the full annual data. This will result in a lower CostRatio of the

Freescoo system. Additionally, the electricity costs and replacement and residual costs are neglectable for the SHC system whereas those cost factors account for 32 % for the reference system.

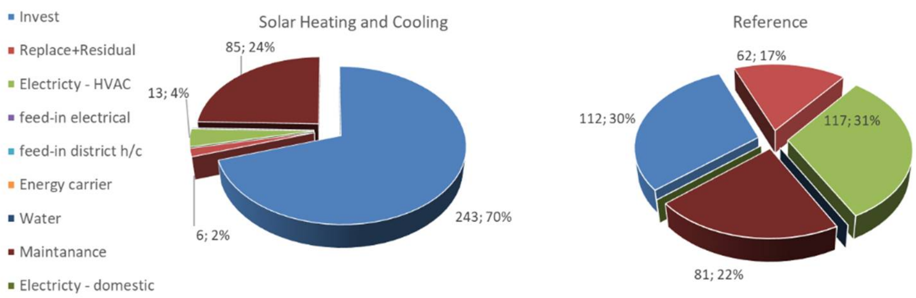

Figure 117: Annualized cost distribution for the Freescoo System in Palermo

8.17. Echuca (by: CSIRO, ST, SH+C)

Echuca Regional Health is a public hospital in Echuca, Northern Victoria, Australia (www.erh.org.au). Solar thermal heat delivery and cooling system was conceived to benefit the hospital: (i) avoid expensive electrical network upgrades, (ii) reduce hospital's energy consumption and hospital's carbon emissions and reliance on fossil fuels.

Phase I of solar cooling system in Echuca Regional Hospital was commissioned into service in 2011. This system consists of 406 m^2 of evacuated tube collectors delivering heat to the facility. The design uses a variable speed control pump in the solar loop to deliver 95ºC hot water to the chiller. A 500 kW (rated cooling capacity) single stage absorption chiller with gas backup is used to deliver cooling to the building. While heat is not being used for cooling the solar heat can be stored in two 5000 litre storage tanks for domestic hot water or space heating purposes.

Phase II of the solar cooling system was commissioned into service in 2017. It consists of 820 m^2 of single axis tracking Fresnel concentrating collectors delivering heat to the building. A 1500 kW (rated cooling) two stage thermal chiller is used for delivering cooling.

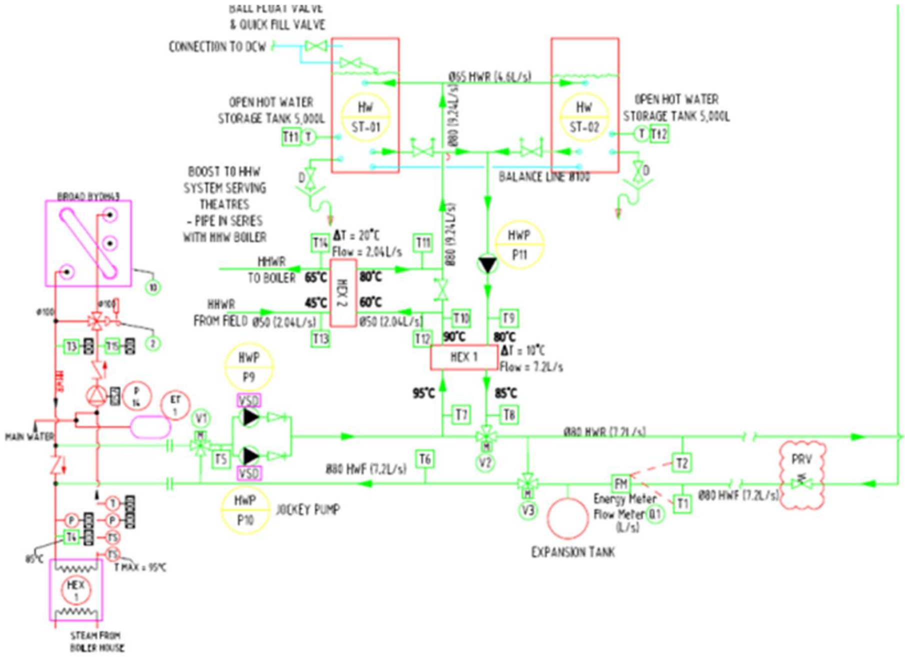

Figure 118: Hydraulic Scheme of the SHC system in Echuca

The following table shows the energy balance data for the system for one year of operation. The analysis is based on the data during the cooling and the shoulder seasons. Thermal energy utilized during the winter months is included in the analysis. Natural gas is used to backup the solar thermal plant. Due to instrumentation issues, solar thermal energy delivered to the storage tank has not been included in the analysis. As a result, the system operates with a solar fraction of (SC/SC+EC) of 51%. Since natural gas is the backup energy source, the PER of the SHC is lower than that of the entire reference system.

At the time of compiling the report, annualised cost information, fsav, CR etc. of the system is not yet available.

Table 26: Energy balance and cost comparison of the CSIRO System in Echuca

ENERGY		kWh	%
EC.Sys		131,229	0.49
SC.sys		136, 813	0.51
el.sys		32,500	
WD.sys		NA	
SH.sys		NA	

CD.sys		304,604	1.00
fsav			
SPFequ			
COST		**SHC**	**REF**
Annualized cost	€	NA	
LCOE	€/kWh	NA	
CR	-	NA	