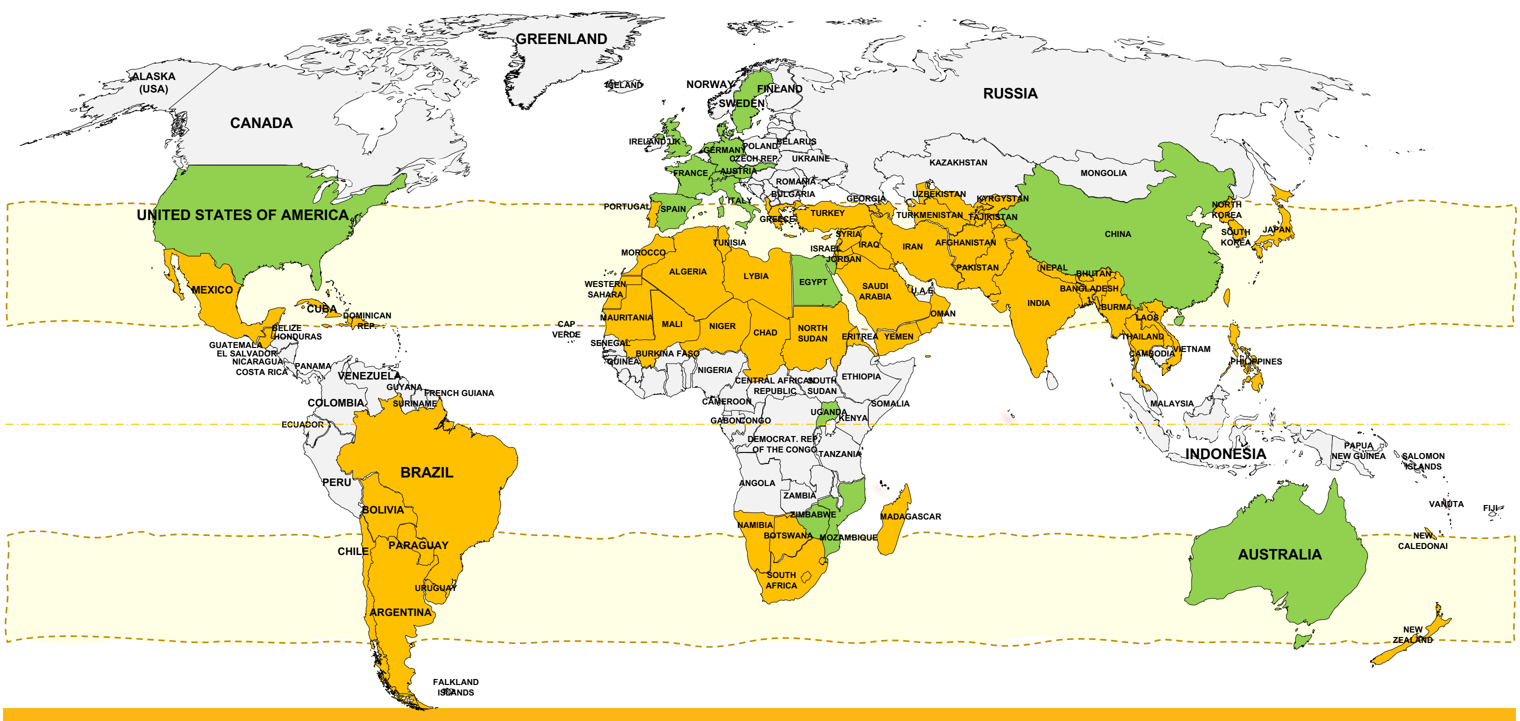
SHC
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Technical and Economic Benchmarking for Solar Cooling Plants



IEA SHC TASK 65 | SOLAR COOLING FOR THE SUNBELT REGIONS

Technology Collaboration Programme
by iea

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Technical and Economic Benchmarking for Solar Cooling Plants

This is a report from SHC Task 65: Solar Cooling for the Sunbelt Regions and work performed in Subtask C: Assessment and Tools

Authors: Daniel Neyer, Manuel Ostheimer (Neyer Brainworks / UIBK), Jan W. Bleyl (Energetic Solutions), Richard Gurtner, Tobias Schmetzer (ZAE Bayern), Lars Munkoe (PURIX) & Uli Jakob (UIBK / JER)

Date 9 September 2024

Report D-C4, DOI: 10.18777/ieashc-task65-2024-0010

Cover photo credit: World map with Sunbelt regions (marked yellow) and the 18 countries of the participating Task 65 experts (marked green), source: Neyer Brainworks & JER

Solar Heating & Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

Our mission is *To bring the latest solar heating and cooling research and information to the forefront of the global energy transition.*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:
- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54, 69)
- Solar Cooling (Tasks 25, 38, 48, 53, 65)
- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64, 72)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61, 70)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46, 71)
- Storage of Solar Heat (Tasks 7, 32, 42, 58, 67)

In addition to our Task work, other activities of the IEA SHC include our:
- ➢ SHC Solar Academy
- ➢ *Solar Heat Worldwide*, annual statistics report
- ➢ SHC International Conference

Our members

Australia	France	SICREEE
Austria	Germany	Slovakia
Belgium	International Solar Energy Society	South Africa
Canada	Italy	Spain
CCREEE	Netherlands	Sweden
China	Norway	Switzerland
Denmark	Poland	Türkiye
EACREEE	Portugal	United Kingdom
ECREEE	RCREEE	
European Commission	SACREEE	

For more information on the IEA SHC work, including many free publications, please visit www.iea-shc.org

Contents

1 Executive Summary

The goal of the IEA SHC Task 65 “Solar Cooling for the Sunbelt regions” is to focus on innovations for affordable, safe, and reliable Solar Cooling systems for the Sunbelt regions worldwide. Countries located between the 20th and 40th degree latitudes in the Northern and Southern Hemispheres, placed in the Sunbelt, face increasing cooling needs on the one hand and higher solar irradiation on the other a compelling solution.

Subtask C emphasizes the critical need for concurrent technical, economic, and financial assessments throughout all phases of solar cooling projects, highlighting the importance of robust tools and Key Performance Indicators (KPIs) that consider economic, financial, social, and environmental factors. It underscores the challenges in assessing solar cooling technologies across Sunbelt countries due to varying local conditions, necessitating a comprehensive database of technical and economic parameters to facilitate accurate comparisons and trend analyses across different solar cooling concepts.

Activity C4 within Task 65 focuses on transferring solar cooling knowhow from OECD countries to Sunbelt regions like Africa, MENA, and Asia through innovative adaptations. It involves rigorous evaluations of simulated/measured results under specific local conditions, benchmarking against conventional and renewable cooling solutions, and conducting Life-Cycle Cost-Benefit Analyses (LCCBA) across different project phases to provide insights into economic, financial, and environmental performance. Comprehensive sensitivity analyses on technical and economic parameters further inform future perspectives and developmental targets for solar cooling technologies in Sunbelt countries, supporting dissemination and communication activities.

Three cases where analysed in more detail in Activity C4.

- The SunBeltChiller (SBC), developed as part of the “Solar Thermal Energy System for Cooling and Process Heating in the Sunbelt Region” project, is a modified Double-Effect absorption chiller capable of re-cooling at high temperatures up to 90°C during the day, using waste heat stored in a hot water energy storage for night-time operation, achieving an overall coefficient of performance (COP) of up to 1.35, providing reliable, efficient cooling without requiring a wet cooling tower, and demonstrating significant CO_2 emissions savings and economic viability over a 20-year lifecycle, particularly enhanced by carbon pricing incentives.
- PURIX specializes in sustainable cooling technology using natural refrigerant R718 (water), focusing on high-volume markets with user-friendly, Plug & Play configurations powered by solar, waste heat, or district heating, aimed at reducing greenhouse gas emissions and promoting fluorinated greenhouse gases (F-gas) phase-out. Case studies illustrate diverse applications like integrating solar thermal in residential settings for energy efficiency, implementing 70 kW solar systems in Mexican hotels to enhance sustainability, and adopting 15 kW solar cooling systems in Latin American retail chains to cut emissions. Additionally, innovative solutions in EU retail and agribusiness sectors demonstrate PURIX's commitment to mitigating climate challenges through scalable, community-focused approaches.
- The SolarHybrid concept investigates the combination of an ammonia/water absorption and a vapour compression chiller in various operating modes to optimize energy efficiency and cost-effectiveness, demonstrating high potential for primary energy savings despite initial higher costs. Case studies like sol.e.h² illustrate significant reductions in building cooling loads through optimized building envelopes and solar cooling integration, leading to substantial economic savings and environmental benefits in varying climate conditions.

Hybrid system solutions are a key trend, offering high CO_2 savings and economic efficiency for small to medium cooling capacities. Medium-temperature systems and two-stage absorption chillers also promise better efficiency and cost-effectiveness. Despite its niche status today, solar cooling will expand globally by 2030, with compact, cost-effective small systems (<20 kW) targeting mass markets. Europe leads in installations for small and medium systems (<350 kW), but growth potential lies in the Global South. Efforts should focus on transferring expertise from OECD countries to emerging markets in Africa, MENA, and Asia, targeting commercial and industrial applications, particularly in agriculture, food, manufacturing, and tourism.

2 Methodology

The concurrent technical, economic and financial assessment of solar cooling options is of high importance in each stage of the life cycle of a project, starting with a comparison of different technology options and pre-design, detailed planning, optimizing of operation but also for policy design with proven concepts. In all life cycle phases, it is crucial to have corresponding tools that deliver the necessary information and key performance indicators for the various stakeholders. The Key Performance Indicators (KPIs) need to take into consideration economic, financial, social, and environmental issues as well as other 'Multiple co-benefits. Tools and their specific outputs permit to provide guidance on optimized system design and implementation and show the level of quality of both the most critical components and systems.

Assessing solar cooling along the Sunbelt countries is further challenging due to different local conditions such as energy prices, the investment cost of components, energy conversion factors, greenhouse gas (GHG) emission factors, conventional technical reference systems. A comprehensive database of these technical and economic parameters is crucial to deliver prompt and accurate KPIs. However, besides detailed local results, a set of generalized KPIs should be provided under standardized technical and economic boundaries to allow comparison, general conclusions, and trend analysis across different solar cooling concepts (e.g., photovoltaic (PV) vs. solar thermal (ST), single vs double effect chillers, etc.).

A thorough technic-economic-financial analysis based on a Life-Cycle Cost-Benefit (LCCBA) assessment allows answering questions like: (i) Which technical solutions to implement (e.g. higher CAPEX investment in exchange for lower OPEX)? (ii) Influence on cash flows? (iii) Calculation of bids to clients. (iv) Effects of equity and debt financing shares? (v) Needs for subsidies/grants? (vi) Which are parameters to monitor? Target-performance comparison? (vii) Project reporting and decision making (e.g. to management boards, project stakeholders). (viii) Financial engineering for reporting, negotiations & due diligence with financiers. (ix) Subsidy or funding demand calculations (amount and timing) for policymakers … and many more (Bleyl et al., 2018).

Several tools, models, and methods are available, which need to be screened, evaluated, and adapted for solar cooling in Sunbelt countries. A great number of these tools and methods are well known or even developed by previous IEA Task participants. However, taking the targeted countries and the number of new interested participants an iteration for reviewing should be set before getting into the act of adaptation.

Finally, when all questions can be answered satisfactorily with the corresponding tools and KPIs there is a need to show the future perspective of solar cooling. Thus, sensitivity analysis on most critical parameters is of great interest. It is to analyse the potential of future developments of conventional technology, energy prices, and optimization potentials of components/systems of solar cooling. These parameters are e.g. investment costs (solar/conventional), electricity price (energy/capacity), electrical efficiency (solar/conventional), etc.

3 Scope of Activity C4

The knowhow capitalized in OECD countries (Europe, US, Australia, etc.) on solar cooling technology (both thermal and PV) is already very relevant, but very few efforts have been made to adapt and transfer this knowhow to Sunbelt countries such as countries in Africa, MENA, and Asia which are all dynamic emerging economies. Therefore, the present project is aimed at the development of innovations for affordable, safe, and reliable cooling systems for the Sunbelt regions worldwide by using solar energy either solar thermal or solar PV.

The innovation driver and the keyword is adaptation of existing concepts to the Sunbelt regions, which is investigated within Task 65, Subtask C under Activity C4 – Benchmarking and sensitivity analysis.

The focus is on technical, economic and financial assessment of received simulated/measured results and specific local boundary conditions of the demonstration plants of Subtask B. The results are compared and benchmarked against conventional and other renewables cooling solutions.

The Life-Cycle Cost-Benefit Analyses of different solar cooling solutions for different project phases which are i.a. (a.) Pre-feasibility (b.) Detailed planning/design (c.) Proposals comparison (d.) Financing (e.) Operation phase (f.) Controlling (g.) Cash flow + profit & loss calculations (h.) Cash flow analyses and (i.) Support policy design of subsidies, provide a comprehensive overview on their performance. The evaluation values the conceptual and technical systems in aspects, such as economic, financial and environmental LCCBA as well as performance of energy and resource efficiency.

A comprehensive sensitivity analyses on technical and economic boundary conditions (e.g. reference system, energy (electricity) mix, energy prices, investment costs, etc.) provides the base for estimation of future perspective and possible targets for developments of solar cooling in the Sunbelt countries.

Following chapters show three projects which are analyzed with different methods/tools (see activity reports C2/C3).

4 SunBeltChiller (SBC) Life-Cycle Cost-Benefit Analyses and Influence of Carbon Pricing

4.1 Introduction to SBC

Solar thermal driven cooling systems can play an important role for decarbonization of the worldwide cooling demand. Especially if beside cooling demand there is a demand for heating. One of the most widely used solar thermal cooling systems are two-stage absorption chillers (Double-Effect) powered by concentrating solar collectors. However, in regions, e.g. the SunBelt, with high ambient temperatures regularly above 30°C, these systems absolutely require a wet cooling tower. Often in these regions the availability of water is limited and therefore wet re-cooling systems cannot be used (for regulatory or economic reasons).

To solve this problem the SunBeltChiller (SBC) was developed within the research project "Solar thermal energy system for cooling and process heating in the Sunbelt region – SunBeltChiller (SBC)" (for more details, please refer to SHC Task 65 A1 report). The SBC is a modified Double-Effect (DE) absorption chiller. During daytime, it can be re-cooled in the first stage at high temperatures of up to 90°C with a COP of 0.35, when ambient temperatures are high. The waste heat produced is stored in a hot water energy storage. In the second step this heat is reused to run the SBC with a COP of 0,75 when ambient temperatures are lower (especially during night-time) so that a dry cooling tower can be used.

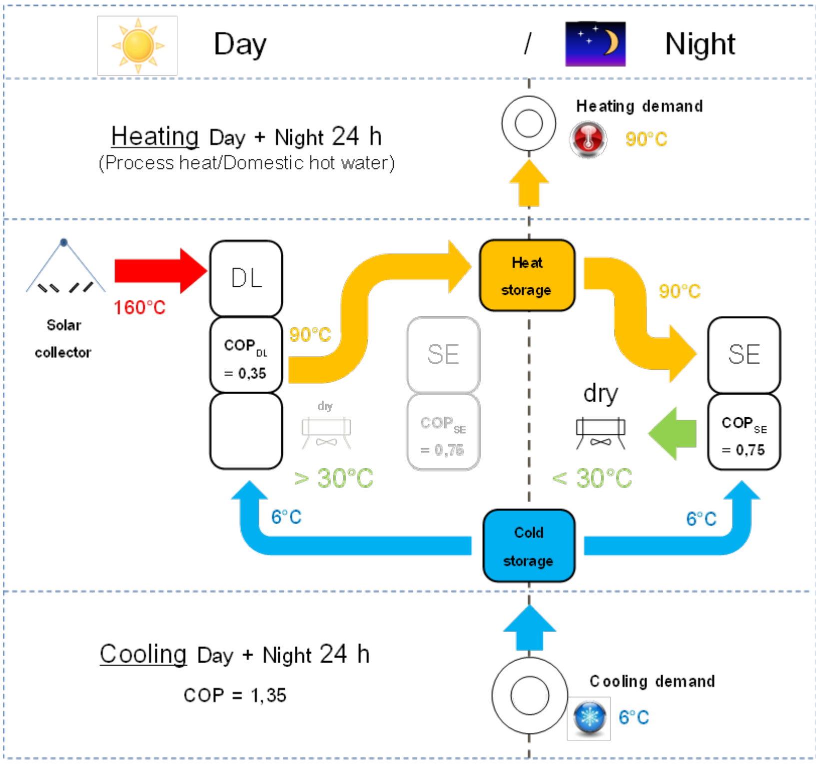


Figure 1: SunBeltChiller concept (Source: ZAE Bayern)

Depending on the application, the use of a cold storage is suitable to cover the cooling demand as required. In summary, this results in the following advantages of the SBC:

- No wet cooling tower needed.
- Reliable operation even at high ambient temperatures.
- High efficiency with an overall COP of up to 1.35.
- High solar cooling coverage reachable.
- Highly efficient heat supply at up to 90°C.
- Components are available on the market.

4.2 Industrial Use Case for Comparative Analyses of 4 Cooling and Heating Supply System Options

For the comparative economic and ecological assessment of the SunBeltChiller, an industrial, heat- and cold-intensive production process (representative e.g. for food industry) located at Windhoek, Namibia was designed. This use case serves as an application example for the comparative analyses of four different fossil and decarbonized cooling and heating supply system options, described below.

Its energy demand properties are summarized in Table 1, followed by a description of climate conditions and weekly load curves.

Table 1: Summary of energy demands of the industrial use case in Namibia for the comparative analyses of the 4 fossil and renewable supply options.

	Energy demand
Cooling demand	10.955 MWh/year
Heating demand	16.433 MWh/year
Electrical demand	2.191 MWh/year

The electricity cost is calculate at 150 EUR/MWh and for natural gas 45 EUR/MWh serve as baseline/reference cost.

The climatic boundary conditions in Windhoek, Namibia can be summarized as follows:

- High ambient temperature during daytime almost all around the year.
- Frequently ambient temperature below 25°C during nighttime.
- High solar irradiation.
- High baseline water stress.

To map the energy requirements in more detail, load curves for process heating (at 160°C), process cooling (at 6°C) and electricity were assumed to reflect a typical production cycle (two shifts during the week, rest day on Sunday).

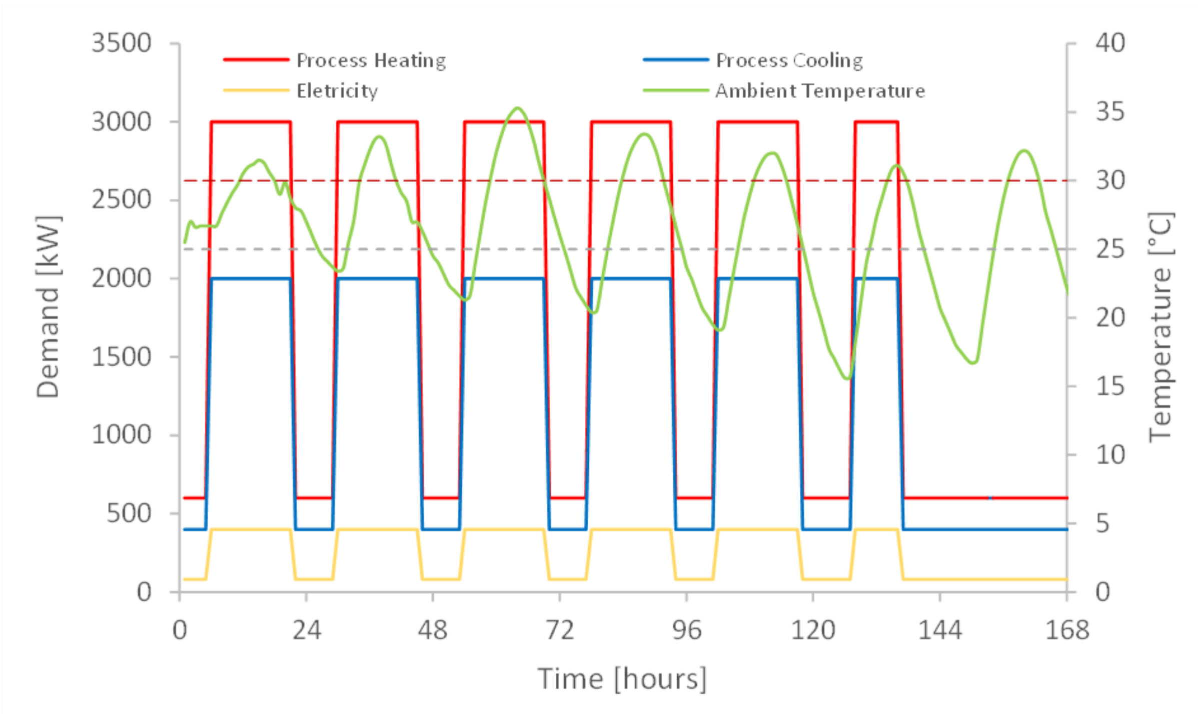


Figure 2: Plot of energy load curves of the industrial use case and ambient temperature located at Windhoek, Namibia for an exemplary week (Source: ZAE Bayern)

The above use case serves as a comparative bases for the following four fossil and decarbonized cooling and heating systems:

1. *ZAE Opt. 1:* Compression cooling with electricity from the grid + natural gas heating serves as reference system. (O1)
2. *ZAE Opt. 2:* Compression cooling with PV electricity + Power to Heat with backup from electric grid and natural gas heating. (O2)
3. *ZAE Opt. 3:* Concentrated solar collectors (Fresnel collectors) + SunBeltChiller with ZAE Opt. 1 as backup system. (O3)
4. *ZAE Opt. 4:* Concentrated solar collectors (Fresnel collectors) + standard double stage absorption chiller with ZAE Opt. 1 as backup system. (O4)

The main technical design parameters of the core components of the 4 systems are summarized below:

System	*ZAE Opt. 1*	*ZAE Opt. 2*	*ZAE Opt. 3*	*ZAE Opt. 4*
	CC + el. Grid + fossil heating	PV+CC+PTH	Fresnel+SBC	Fresnel+DE
Back-up	-	el. Grid+fossil heating	CC+el. Grid+fossil heating	CC+el. Grid+fossil heating
Technical parameter				
Nominal cooling power CC [kW]	3.000	3.000	3.000	3.000
Nominal cooling power AbCh [kW]	-	-	1.500	1.500
Gross collector land area [m²]	-	15.000	15.000	15.000
PV peak power [kW_{el}]	-	2.063	-	-
Fresnel peak power [kW_{th}]	-	-	6.000	6.000
PtH-System [kW]	-	927	-	-
Cold storage size [m³]	-	-	1.000	-
Hot storage size [m³]	-	-	1.800	-

Both solar absorption cooling systems are using concentrated solar collectors (Fresnel collectors) as heat source to cover the heat requirements of the process and the chillers. Both systems have identical sizes of installed collector peak power and nominal cooling capacity and are both equipped with dry re-cooling towers due to shortage of water availability. Additionally, the SBC has a hot water and cold water storage.

The investment cost (CAPEX) of the core components of the 4 energy supply systems are summarized in the table below:

System	*ZAE Opt. 1*	*ZAE Opt. 2*	*ZAE Opt. 3*	*ZAE Opt. 4*
	CC + el. Grid + fossil heating	PV+CC+PTH	Fresnel+SBC	Fresnel+DE
Back-up	-	el. Grid+fossil heating	CC+el. Grid+fossil heating	CC+el. Grid+fossil heating
Add. Investment costs (CapEx)		**2.104.578,23 €**	**6.756.968,73 €**	**5.755.582,62 €**
Compression chiller CC	€ 475.481,10	€ 475.481,10	€ 475.481,10	€ 475.481,10
Absorption chiller AbCh	-	-	€ 1.105.852,33	€ 1.105.852,33
PV collector	-	€ 1.823.135,36	-	-
Fresnel collector	-	-	€ 4.331.689,53	€ 4.331.689,53
PtH-System	-	€ 185.459,62	-	-
Cold storage	-	€ -	€ 328.369,31	€ -
Hot storage	-	-	€ 507.597,51	€ -
Periphery	€ 95.096,22	€ 95.983,25	€ 483.460,05	€ 318.040,75
Total investment costs	**570.577 €**	**2.580.059 €**	**7.232.450 €**	**6.231.064 €**

For CO_2-calculations, emission factors are calculated at 180 g/kWh_{gas} for natural gas and 420 g/kWh_{elt} for grid electricity.

Financing for all case studies is modelled with a 70% share of debt at 5% interest and weighted average cost of capital (WACC) of 6,5%.

The economic and financial analyses is done with the adapted LCCBA method (Subtask C, Delivery C3, chapter 6.2). Selected results of the study are described and analysed in the next sub-chapters.

4.3 SunBeltChiller vs. Fossil Fuel Cooling and Heating System including Carbon Pricing Scenario

Life-cycle costs and benefits of the SunBelt Chiller (SBC) business case (ZAE option 3) are modelled over a 20-year project cycle, taking the conventional fossil fuel cooling and heating system (ZAE option 1) as a reference case (baseline).[1] The net-CF accounts for revenues from electricity savings as well as all life-cycle cost (CAPEX, fix and variable OPEX). The LCCBA results are depicted below in Figure 3:

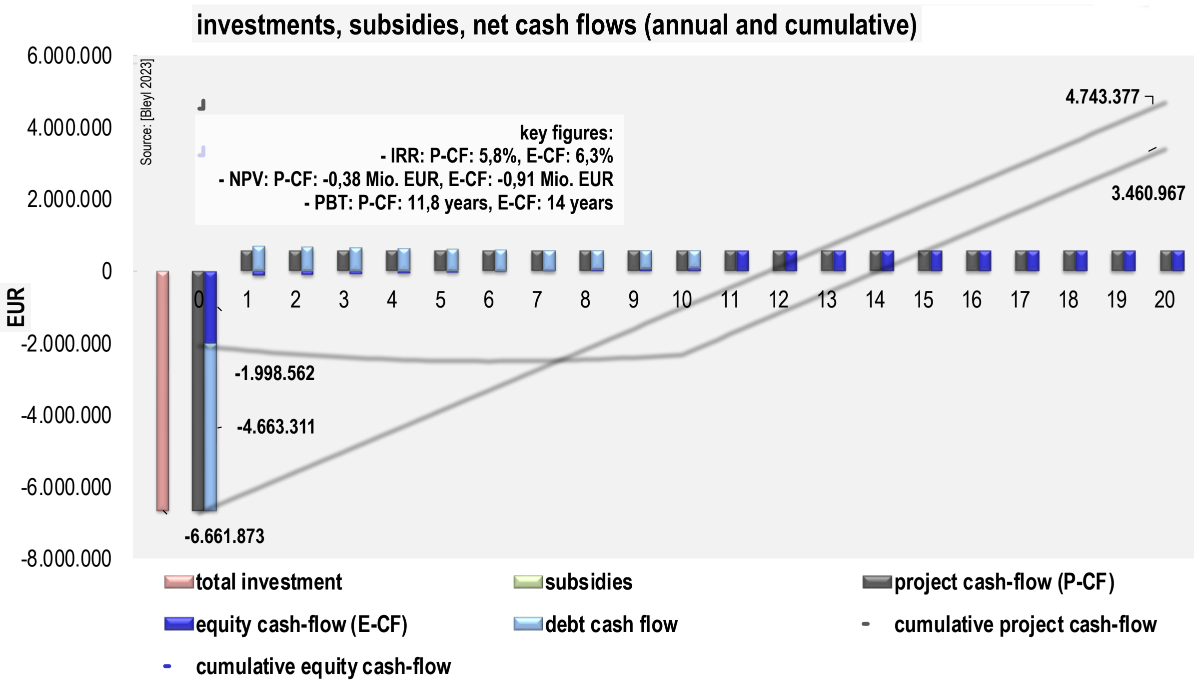


Figure 3: SBC vs. standard fossil heating and cooling system: Dynamic Cash Flow LCCBA model

Based on the initial SBC investment cost of 6.7 million EUR, the project-CF reveals a cumulative net surplus of 4.7 million EUR after 20 years. It's internal rate of return (IRR) stands at 5.8% and a dynamic payback period of 11.8 years.

Regarding financing, the annual debt service consisting of principal and interest payments (light blue bars) of about 600 T.EUR on average can mostly be covered from the net savings (grey bars). After the 10-year loan repayment, the net surpluses (dark blue bars) accrue to the equity investor and amount to a surplus of 3.5 million EUR with an IRR of the equity CF of 6.3%.

The key economic figures and KPIs are summarized below:

		project cash-flow	equity cash-flow
project duration	years	20	
total investment	EUR	6.661.873	
invested equity	EUR	-	1.998.562
invested debt capital	EUR	-	4.663.311
cumulative cash-flow	EUR	4.743.377	3.460.967
interest rate for discounting	%	6,5% (WACC)	10% (equity interest rate)
net present value	EUR	-378.431	-907.953
internal rate of return (IRR)	%	5,8%	6,3%
payback period (dynamic)	years	11,8	14,0
Loan Life Cover Ratio	-	-	1,4

[1] Results of a comparison of ZAE options 1 and 3 are summarized in section 4.7.

The case study reveals the following CO2-savings in comparison to the conventional fossil fuel system (ZAE option 1):

key figures environmental data		total over project duration	% savings
CO_2 savings electricity	t | t/a	7.309	18,3%
Electricity CO_2 saving revenues	EUR | EUR/a	0	
CO_2 savings heat	t | t/a	40.598	49,2%
Heat CO_2 saving revenues	EUR | EUR/a	0	
Total CO_2 savings	t | t/a	47.907	39,1%
Total CO_2 saving revenues	EUR | EUR/a	0	

By way of a scenario analyses, the business case assumes carbon pricing @90 EUR/t CO2. If included in the LCCBA model, results are improved as follows in Figure 4:

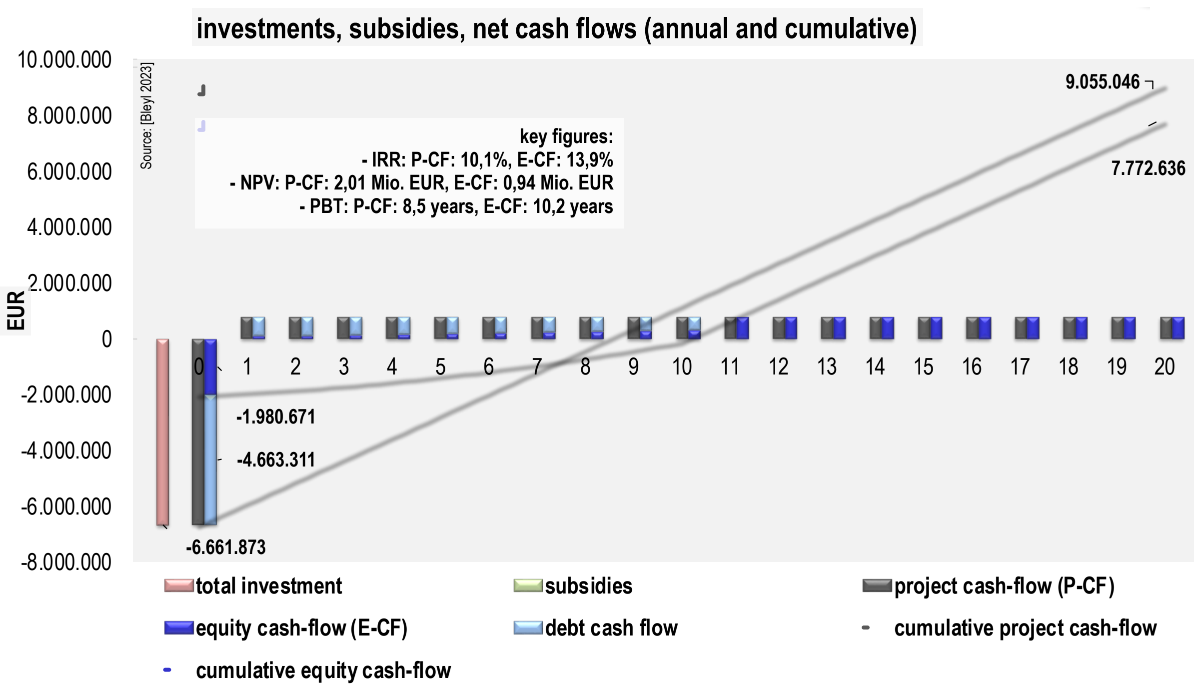


Figure 4: SBC vs. standard fossil heating and cooling system: Dynamic Cash Flow model including carbon pricing @90 EUR/t CO_2

key figures environmental data		total over project duration	% savings
CO_2 savings electricity	t | t/a	7.309	18,3%
Electricity CO_2 saving revenues	EUR | EUR/a	657.807	
CO_2 savings heat	t | t/a	40.598	49,2%
Heat CO_2 saving revenues	EUR | EUR/a	3.653.862	
Total CO_2 savings	t | t/a	47.907	39,1%
Total CO_2 saving revenues	EUR | EUR/a	4.311.669	

Including the carbon pricing, the cumulative net surplus increases to 9.1 million EUR with an IRR of 10.1% and the payback of the project cash flow is reduced to 8.5 years as depicted in the Figure above.

4.4 SunBelt vs. Double Effect Chiller Comparison Including Carbon Pricing Sensitivity

As an additional case study, both solar thermal absorption cooling options (O3, O4) are compared.

Results: From a technical point of view, both absorption cooling systems are reaching a high solar heating coverage of nearly 50%. However, the DE-Chiller can provide a solar cooling coverage of 16% only due to the limitation of dry cooling tower operating at high ambient temperature. The SBC on the other hand achieves a solar cooling coverage of 41% and thus enables a significant reduction in CO2 -emissions of 221 tons per year.

Table 2: DE vs. SBC: Key results of the comparative study (Source: ZAE Bayern)

	Fresnel Collector + DE Chiller	Fresnel Collector + SBC
Solar heating energy provided	8.098 MWh/year	
Solar heating coverage	49%	
Solar cooling energy provided	1.701 MWh/year	4.522 MWh/year
Electrical energy demand savings	338 MWh/year	864 MWh/year
Solar cooling coverage	16%	**41%**
Reduction CO_2 emissions for cooling	142 tons/year	363 tons/year
Reduction electrical energy demand for cooling / Reduction CO_2 emissions for cooling	13%	**34%**

Economic and financial LCCBA assessment:

Similar to the previous case studies, life-cycle costs and benefits of the SunBelt Chiller (SBC) business case are modelled over a 20-year project cycle, but in this case the standard Double-Effect (DE) solution is taken as a reference case (baseline). As before, the net-CF accounts for revenues from electricity savings as well as all life-cycle cost (CAPEX, fix and variable OPEX as well as 5% re-investment budgets in year 13).

Based on the additional SBC investment cost of 1 million EUR (compared to the DE), the project-CF reveals a cumulative net surplus of 325 T.EUR after 20 years. It's internal rate of return (IRR) stands at just 2.9% and a dynamic payback period of 15.4 years, which would require very low expectations on the investors side.

If carbon pricing @90 EUR/t CO_2 is included in the LCCBA model, the cumulative net surplus increases to 725 T.EUR with an IRR of 5.9% and a reduced payback of 11.4 years as depicted in the Figure 5 below.

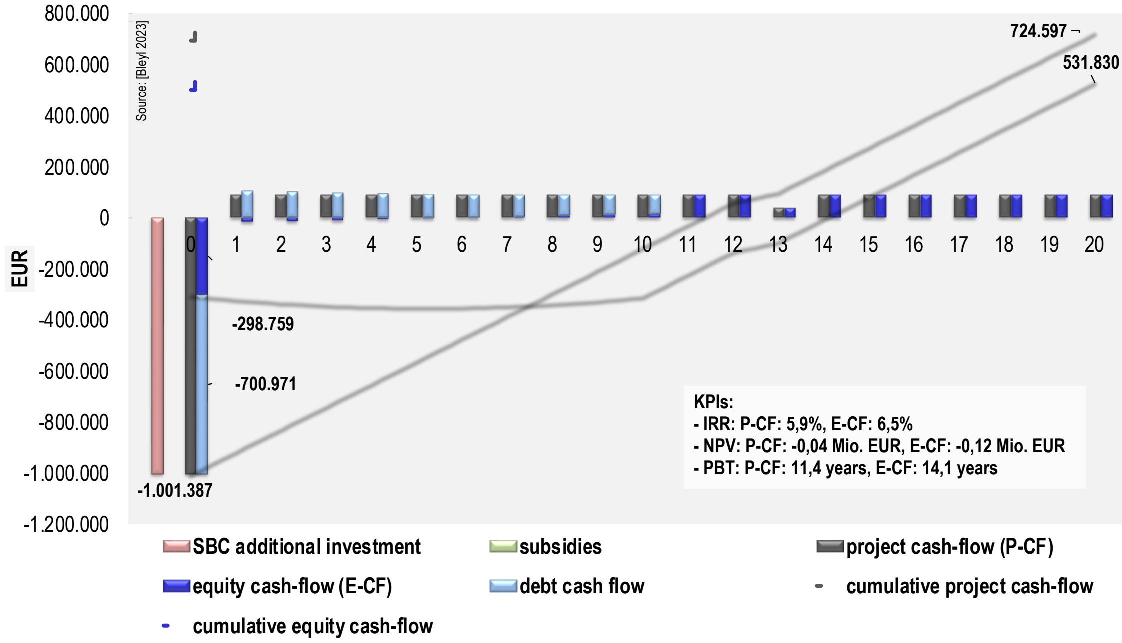


Figure 5: SBC vs. standard DE-absorption chiller: Dynamic Cash Flow model including carbon pricing @90 EUR/t CO_2

Regarding financing, the debt service (including interest payments) for the 700 T.EUR loan can be covered from the net savings. After the 10-year loan repayment, the net surpluses (dark blue bars) accrue to the equity investor and amount to a surplus of 532 T.EUR with an IRR of the equity CF of 6.5%.

4.5 Sensitivity Analyses of SunBelt vs. Double Effect Chiller Comparison

The sensitivity analysis in the figure below shows the influence of a percentage change of selected input parameters like investment cost (CAPEX), operating cost (OPEX), project duration or revenues from savings on the project IRR.

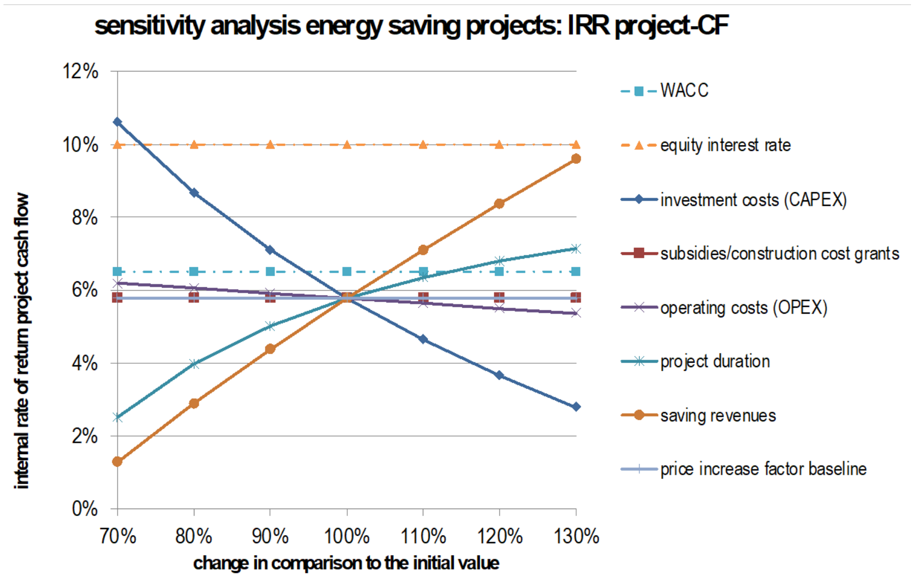


Figure 6: Sensitivity of project IRR to relative change of input parameters for SBC vs. standard DE absorption chiller: (including carbon pricing @90 EUR/t CO2)

As shown in the Figure 6 above the most sensitive input parameters to relative changes are CAPEX (negative correlation) followed by revenues and project duration (both with positive correlations). For a break-even with the

WACC (=> NPV = 0), the CAPEX would need to be decreased by about 5% or the revenues (from savings and avoided CO2-payments) increased by about 5%, or a through a 10% longer project duration.

The influence of variations of input parameters on the NPV of the project cash flow is depicted below in Figure 7:

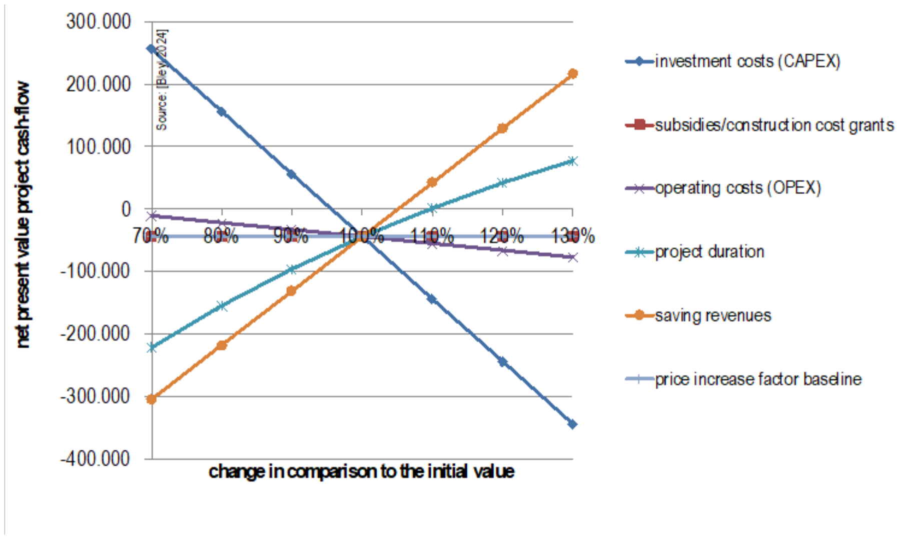


Figure 7: Sensitivity of project net present value to relative change of input parameters for SBC vs. standard DE absorption chiller: (including carbon pricing @90 EUR/t CO_2) (Source: Energetic Solutions)

Similarly, investment costs, followed by saving revenues and project duration are the most sensitive to relative changes of input parameters. The LCCBA investment model provides a similar analysis for the equity IRR and NPV, which is not presented here.

4.6 PV powered vs. Fossil Fuel Cooling and Heating System

Similar to the setup of the previous case studies, life-cycle costs and benefits of the PV-powered business case (ZAE option 2) are modelled over a 20-year project cycle, taking the conventional fossil fuel cooling and heating system (ZAE option 1) as a reference case (baseline). The LCCBA results are depicted below in Figure 8:

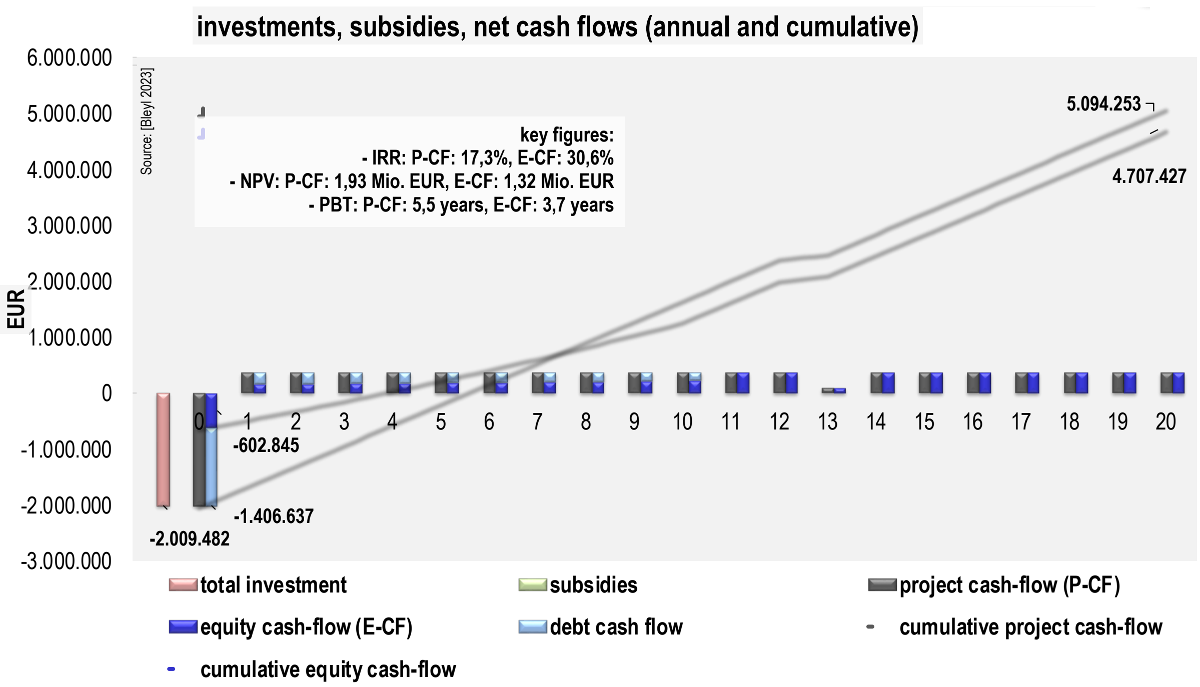


Figure 8: PV-powered vs. standard fossil heating and cooling system: Dynamic Cash Flow LCCBA model results

Based on the initial PV investment cost of 2 million EUR, the project-CF reveals a cumulative net surplus of 5.1 million EUR after 20 years. It's internal rate of return (IRR) stands at 17.3% and a dynamic payback period of 5.5 years.

The key figures and KPIs are summarized below:

		project cash-flow	equity cash-flow
project duration	years	20	
total investment	EUR	2.009.482	
invested equity	EUR	-	602.845
invested debt capital	EUR	-	1.406.637
cumulative cash-flow	EUR	5.094.253	4.707.427
interest rate for discounting	%	6,5% (WACC)	10% (equity interest rate)
net present value	EUR	1.934.202	1.322.778
internal rate of return (IRR)	%	17,3%	30,6%
payback period (dynamic)	years	5,5	3,7
Loan Life Cover Ratio	-	-	3,0

As in the other case studies, the most sensitive input parameters to relative changes are CAPEX (negative correlation) and revenues from energy cost savings (positive correlations). However due to the much lower CAPEX, even negative deviations of as high 50% will still result in IRRs above the 10%-WACC, making the PV business case very robust against negative developments of core economic input data.

The case study reveals the following CO_2-savings in comparison to the conventional fossil fuel system (ZAE option 1):

CO_2 reductions and revenues		total over project duration	% savings
CO_2 reduction electricity savings	t | t/a	18.252	45,7%
CO_2 revenues electricity savings	EUR | EUR/a	0	
CO_2 reduction natural gas savings	t | t/a	4.126	5,0%
CO_2 revenues natural gas savings	EUR | EUR/a	0	
Total CO_2 reduction	t | t/a	22.378	18,3%
Total CO_2 revenues	EUR | EUR/a	0	

4.7 Summary of Results

The goal of the case studies was an investment-grade economic and ecological assessment of three partly decarbonized and renewable cooling and heating supply options. These were evaluated in comparison to a conventional fossil fuel system, taking the use case of an energy-intensive industrial production process (e.g. typical for food industry).

The key results of the three LCCBA-comparisons of the renewable options (O2, O3, O4) against the conventional, fossil cooling and heating supply option (O1) are summarized below. The first table provides results economic and financial KPIs excluding carbon pricing:

Table 3: Results table of comparative analyses (without CO_2 tax)

Life-Cycle Cost-Benefit Analyses: Key figures and KPIs (@ **0** EUR/ton CO_2)		PV **O1 vs. O2** (CC vs. PV + CC + PtH)		Sunbelt Chiller **O1 vs. O3** (CC vs. Fresnel + SBC)		Double Effect Absorption Chiller **O1 vs. O4** (CC vs. Fresnel + DE)	
		Project Cash Flow	**Equity Cash Flow**	**Project Cash Flow**	**Equity Cash Flow**	**Project Cash Flow**	**Equity Cash Flow**
Project duration	years	20		20		20	
Total investment	EUR	2.009.482		6.661.873		5.660.487	
Invested equity	EUR	-	602.845	-	1.998.562	-	1.698.146
Invested debt capital	EUR	-	1.406.637	-	4.663.311	-	3.962.341
Cumulative cash-flow	EUR	5.094.253	4.707.427	4.743.377	3.460.967	4.354.259	3.264.616
Discounting rate	%	**6,5%** (WACC)	**10%** (equity interest rate)	**6,5%** (WACC)	**10%** (equity interest rate)	**6,5%** (WACC)	**10%** (equity interest rate)
Net present value (NPV)	EUR	1.934.202	1.322.778	-378.431	-907.953	-143.109	-633.601
Internal rate of return (IRR)	%	17,3%	30,6%	5,8%	6,3%	6,2%	6,9%
Payback period (dynamic)	years	5,5	3,7	12	14	11	14
Loan Life Cover Ratio (LLCR)	-	-	3,0	-	1,4	-	1,5

In the case of carbon pricing @ 90 EUR/ton CO2, these results would improve substantially as depicted in the next table.

Table 4: Results table of comparative analyses (including CO_2 tax @90 EUR/t)

Life-Cycle Cost-Benefit Analyses: Key figures and KPIs (@ **90** EUR/ton CO_2)		PV **O1 vs. O2** (CC vs. PV + CC + PtH)		Sunbelt Chiller **O1 vs. O3** (CC vs. Fresnel + SBC)		Double Effect Absorption Chiller **O1 vs. O4** (CC vs. Fresnel + DE)	
		Project Cash Flow	**Equity Cash Flow**	**Project Cash Flow**	**Equity Cash Flow**	**Project Cash Flow**	**Equity Cash Flow**
Project duration	years	20		20		20	
Total investment	EUR	2.009.482		6.661.873		5.660.487	
Invested equity	EUR	-	602.845	-	1.998.562	-	1.698.146
Invested debt capital	EUR	-	1.406.637	-	4.663.311	-	3.962.341
Cumulative cash-flow	EUR	7.108.301	6.721.476	9.055.046	7.772.636	8.263.336	7.173.692
Discounting rate	%	**6,5%** (WACC)	**10%** (equity interest rate)	**6,5%** (WACC)	**10%** (equity interest rate)	**6,5%** (WACC)	**10%** (equity interest rate)
Net present value (NPV)	EUR	3.047.546	2.184.915	2.005.011	937.706	2.017.784	1.039.723
Internal rate of return (IRR)	%	22,8%	46,3%	10,1%	13,9%	10,7%	15,2%
Payback period (dynamic)	years	4,3	2,3	8,5	10,2	8,2	9,3
Loan Life Cover Ratio (LLCR)	-	-	3,8	-	2,0	-	2,1

Economically, the SBC investment still requires a long-term business case perspective. Feasibility is greatly increased by a remuneration for avoided CO_2-emmissions (and other 'Multiple Project Benefits' such as reduced fossil fuel consumption). It is also interesting to note, that the SBC payback period is just 6 month longer than a standard DE solution (in comparison to a conventional compression chiller + natural gas heating solution). In any case, availability of long-term and reasonably cheap (WACC ≤ 6.5%) financing options are a key pre-requisite (as for many renewable, decarbonized supply options).

The following Figure 9 depicts the solar cooling coverage of the three renewable options:

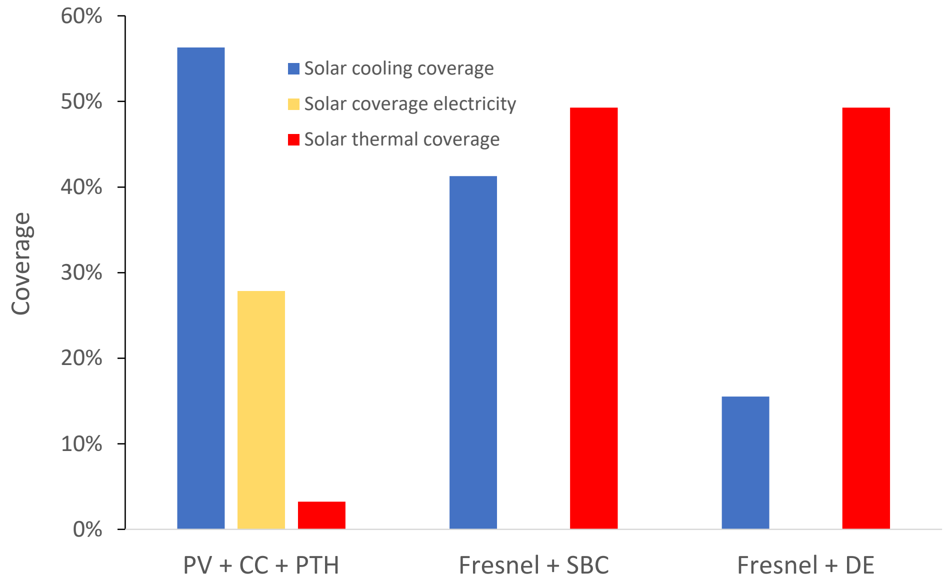


Figure 9: Solar energy coverage rate of different decarbonisation supply options (in comparison to fossil fuel option) (Source: ZAE Bayern)

As a key result, the SunBeltChiller can nearly triple the solar cooling coverage rate compared to a DE-System.

The SBC is one of only a few solar thermal cooling systems equipped with a dry re-cooling tower, that can reach a significant solar cooling coverage and CO_2-emissions savings, despite high ambient temperatures. CO_2-savings are almost three times higher compared to a similar solar cooling system with a DE chiller.

Regarding CO_2-reductions the 4 options compare as follows:

Table 5: Summary and comparison of CO_2 emissions

CO_2 reductions and revenues (@ **90** EUR/ton CO_2)		**PV** **O1** vs. **O2** (CC vs. PV + CC + PtH)		**Sunbelt Chiller** **O1** vs. **O3** (CC vs. Fresnel + SBC)		**Double Effect ACM** **O1** vs. **O4** (CC vs. Fresnel + DE)	
		Totals over project duration	**% savings**	**Totals over project duration**	**% savings**	**Totals over project duration**	**% savings**
CO_2 reduction electricity savings	t | t/a	18.252	45,7%	7.309	18,3%	2.836	7,1%
CO_2 revenues electricity savings	EUR | EUR/a	1.642.721		657.807		255.215	
CO_2 reduction natural gas savings	t | t/a	4.126	5,0%	40.598	49,2%	40.598	49,2%
CO_2 revenues natural gas savings	EUR | EUR/a	371.327		3.653.862		3.653.862	
Total CO_2 reduction	t | t/a	22.378	18,3%	47.907	39,1%	43.434	35,5%
Total CO_2 revenues	EUR | EUR/a	2.014.048		4.311.669		3.909.076	

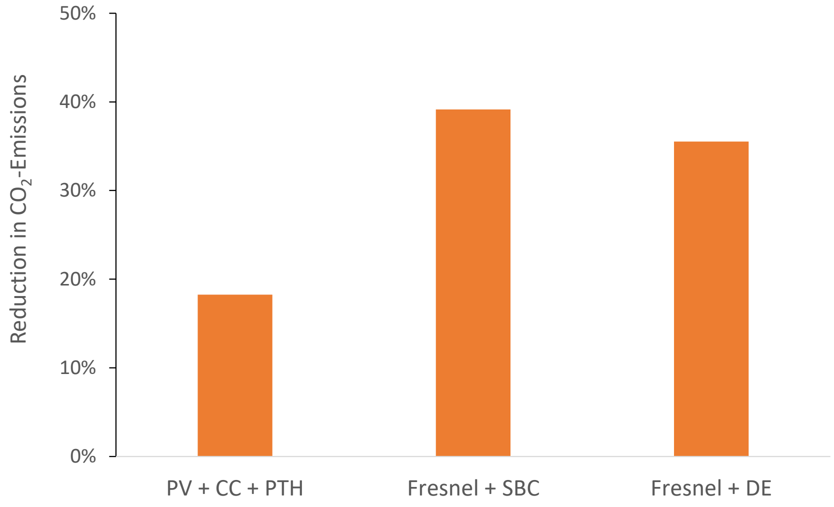


Figure 10: Comparison of CO_2-emissions reductions of different decarbonisation supply options (in comparison to fossil fuel option) (Source: Source: ZAE Bayern)

Whereas the PV option (O2) achieves close to 20% CO_2-savings compared to the fossil fuel business case, both absorption cooling options (O3, O4) achieve close to 40% respectively 35% CO_2-savings. It can also be noted, that deeper de-carbonization (%-CO_2-reduction) require deeper investments, which may be attributed to increasing marginal CO_2 abatement cost.

4.8 Economic and Policy Recommendations

From an economic and policy perspective, the following general conclusions and recommendations can be drawn:

1. **PV investments for own consumption** are most likely a ‚no-brainer' (technical feasibility provided).
2. **Deeper de-carbonization** (%-CO_2-reduction) requires deeper investments (increasing marginal abatement cost).
3. **SBC and DE ACM decarbonization investments** require a very long-term business perspective (>15 years) and rather low expectations on economic returns. In other words: Standard economic and financial KPIs are not attractive to standard investors. However green investors may find these figures attractive enough, provided project risks can be managed.
4. **CO_2-pricing:** Economic feasibility is greatly increased by accounting for remunerations for avoided CO_2-emmissions (e.g. CO_2 tax @90 EUR/t in case study examples).

Combinations of PV + solar thermal powered ACM cooling options: From a techno-economic perspective, assessment of combinations of PV + solar thermal powered ACM cooling options could be of interest, with the following guiding questions: Deeper de-carbonization possible?
=> Cross-subsidies from highly profitable PV project?

From the **sensitivity analyses** in section 4.5 the following general conclusions can be derived:

- Highest sensitivity to reductions in CapEx.
  => Are investment cost reductions possible for absorption chiller systems?
- Energy prices => High price countries should be targeted first.
- Reasonable debt financing cost and availability of third party long-term financing?

From a policy perspective the following recommendations can be drawn:

I. Support availability of long-term (10-15 years) and reasonably cheap (WACC ≤ 6.5%) financing options through concessional loans (e.g. development financing) and possibly subsidies.

II. Introduce ‚Carbon Pricing' as a market-based instrument to incentivize de-carbonization investments (EUA Futures prices since 2021 range between 60 and 100 EUR/ton).

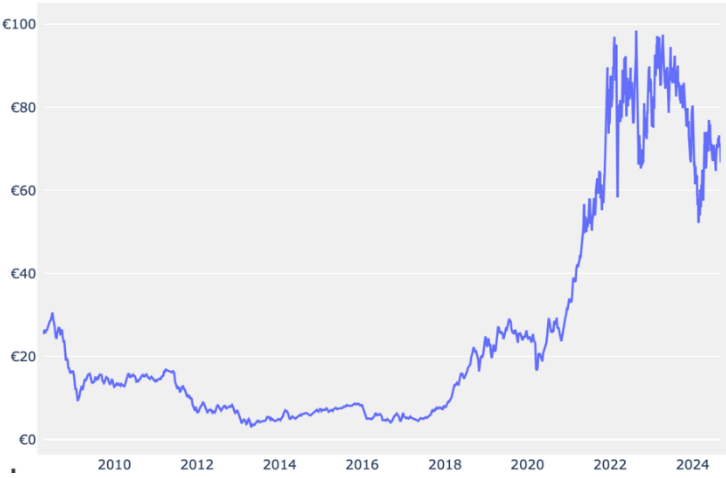


Figure 11: Carbon market pricing of EUA Futures (Source: https://sandbag.be/carbon-price-viewer/)

III. De-risking of investments, e.g. through partial risk guarantee facilities.

In addition, accounting for 'Multiple Project Benefits' (Bleyl, 2018) of reduced fossil fuel consumption (e.g. Carbon neutral company strategies | Reduced import dependence | Green image | Supply chain requirements for exporters ...) may greatly support the business case.

5 PURIX

5.1 Introduction

PURIX provides sustainable cooling technologies, leveraging R718 (water), a natural, non-flammable refrigerant, to develop environmentally friendly air conditioning and cooling systems. These systems utilize conventional absorption cooling technology, enabling the use of low-temperature heat sources as the primary energy input. By replacing electricity with thermal energy sources and the use of natural refrigerants, this system offers the opportunity to reduce peak loads in electricity grids and greenhouse gas emissions.

Unlike most absorption cooling manufacturers, this system targets high-volume market segments with modular systems designed for smaller capacities and multiple usage points. These Plug & Play configurations simplify installation and are ideal for sectors such as hospitality, retail, residential buildings, offices, clinics, educational institutions, and agribusiness.

These systems are versatile, powered by renewable and sustainable energy sources, including solar thermal energy, waste heat, district heating, and central heating. The modular, air-cooled design is particularly well-suited to phasing out F-gas refrigerants, reducing peak electricity demand, and cutting greenhouse gas emissions, whether in on-grid or off-grid settings.

Case studies highlight the diverse applications and effectiveness of PURIX systems:

- **Residential** Solar Cooling: Integration with existing solar installations enhances energy efficiency, showcasing adaptability and alignment with sustainable energy goals.
- **Hospitality** Sector: A 70 kW solar cooling system installed in a Mexican hotel demonstrates feasibility and efficiency in reducing environmental impact.
- **Retail Solar Cooling**: A Latin American retail chain implemented a 15 kW system, reducing emissions and enabling scalable, repeatable designs.
- **Retail Heat Recovery**: A EU retailer installed a 10 kW absorption cooling system, reducing summer cooling losses through strategic R744 heat recovery.
- **Agribusiness**: Off-grid cooling solutions using 5 kW solar-powered systems support post-harvest storage, minimizing losses and enhancing cost-effectiveness.

This approach not only delivers cutting-edge cooling technology but also emphasizes broader sustainability strategies:

- Scaling Deployment: Expanding applications across diverse market segments.
- Continuous Innovation: Enhancing system efficiency and adaptability.
- Community Engagement: Promoting awareness and adoption of sustainable cooling solutions.
- Policy Advocacy: Supporting regulations to phase out F-gas refrigerants.
- Robust Monitoring: Ensuring systems deliver measurable climate benefits.

PURIX represents a significant step toward sustainable cooling, with its unique integration of natural refrigerants, renewable energy sources, and user-friendly designs. This aligns with global efforts to mitigate climate change while addressing the cooling needs of various industries.

5.2 Residential

Background

Combining solar thermal for production of domestic hot water and space cooling appliances is a unique opportunity for maximising the utilisation of the investment in a solar thermal installation.

The system is designed for integration with an existing solar heating installation in a household in Italy.

System configuration

The system has a chiller cooling capacity of 5kW in combination with a thermal energy storage (cold) and three indoor devices (fan coils) in different rooms. The cold storage, applying phase change materials and direct-contact technology, provides cooling to end users outside daylight hours as well as for hours with a cooling peak load exceeding the nominal cooling capacity.

The cooling system receives a supply of heating water from an existing solar heating system.

Impact

Integrating solar thermal technology for domestic hot water and space cooling maximizes energy efficiency, reducing overall consumption and carbon emissions. The dual functionality promotes sustainable practices, while the innovative cold storage system ensures effective peak load management. The holistic impact includes cost savings, environmental responsibility, and enhanced resident comfort.

Feasibility

The system's feasibility is rooted in technological compatibility, seamlessly integrating with existing solar heating installations. Leveraging Italy's abundant solar resources ensures reliable energy generation, and user-friendly operation simplifies adoption. Adaptability to pre-existing infrastructure and the dual-purpose design make it an economically viable choice, offering long-term cost savings and promoting sustainable energy solutions.

5.3 Hospitality Sector

Background

The upgrade and refurbishment of the utility systems in a hotel in Mexico (80 rooms) was a unique opportunity for adopting and integrating sustainable cooling technology with a solar thermal system for production of domestic hot water.

System configuration

This integrated system has a nominal cooling capacity of 70 kW for the chillers, in combination with 260 kWh thermal energy storage (cold) applying direct contact phase change materials (6 m^3). Cooling is distributed to the individual rooms with a chilled water circuit of 13°C.The supply of heating for powering the cooling system is integrated with the solar heating system for production of domestic hot water.

Impact

Upgrading Mexico's 80-room hotel integrates sustainable cooling (70 kW) with solar thermal for hot water, signaling a notable shift toward eco-friendly practices. This advanced system enhances energy efficiency, slashes the carbon footprint, and prioritizes guest comfort through environmentally conscious measures.

Feasibility

Feasibility hinges on critical factors: a robust 70 kW cooling capacity, a substantial 260 kWh thermal energy storage with phase change materials, and seamless integration with existing solar heating. This adaptable technology aligns with the hotel's sustainability goals, streamlines implementation, and promises substantial long-term operational cost savings. The chilled water circuit distribution at 13°C ensures both guest comfort and ongoing energy efficiency.

5.4 Retail Solar Cooling

Background

A convenience store chain in Latin America has adopted solar cooling applying natural refrigerant for cutting greenhouse gas emissions and for phasing out F-gas based refrigerants. Both GHG emission reduction and phase out of F-gases are subject to a corporate ESG target setting. Operating thousands of stores in the region, the potential accumulated environmental impact by replication of the individual installations is considered substantial by the management.

System configuration

Applying ducted HVAC system design for the stores, offers a unique opportunity for installing a 15 kW solar cooling chiller capacity, 30 m2 solar thermal collectors and a 50 kWh thermal energy storage (cold) capacity for supplying cooling around the clock as the stores are open 24 h. Cooling is distributed in store through air ducts and the installation of a cooling coil installed in existing air duct.

Impact

The convenience store chain in Latin America's adoption of solar cooling with natural refrigerants is a pivotal step in reducing greenhouse gas emissions and phasing out F-gas based refrigerants. Aligned with corporate ESG targets, this commitment reflects a significant environmental impact. Operating thousands of stores, the cumulative effect of these installations underscores the management's dedication to substantial emission reductions and sustainability goals. By utilizing a 15 kW solar cooling chiller, 30 m2 solar thermal collectors, and a 50 kWh thermal energy storage, the chain actively contributes to a greener future.

Feasibility

The feasibility of this solar cooling system is grounded in strategic design choices. The application of a ducted HVAC system in the stores creates a unique opportunity for the installation of a 15 kW solar cooling chiller, 30 m2 solar thermal collectors, and a 50 kWh thermal energy storage. This design not only aligns with the 24-hour operation of the stores but also ensures consistent and efficient cooling. The use of air ducts and cooling coils within existing infrastructure streamlines implementation. Given the substantial environmental impact across numerous stores, the feasibility of replicating these installations is evident, aligning with corporate ESG targets and emphasizing the practicality of the chosen solar cooling technology.

5.5 Retail R744 Heat Recovery

Background

In retail, refrigeration systems applying CO2 (R744) as refrigerant, has become mainstream in many countries, supplying cooling to frozen goods, refrigerators or for maintaining a cold space for fruits and vegetables. Many R744 refrigeration plants have integrated heat recovery systems for utilising recovered thermal energy for space heating during winter, or for production of domestic hot water. This leader in retail in the EU faces challenging and high temperatures inside the store during summer, and consequently increased product loss of e.g. pharmaceutical products, sweets as well as fruits and vegetables.

System configuration

An air-cooled absorption cooling system with 10 kW nominal capacity is installed for the supermarket. Powered with waste heat recovered from the store refrigeration plant, reduces the load and electricity consumption for the cooling tower connected to the refrigeration plant. Cooling generated by the PURIX cooling system is distributed in a closed loop chilled water circuit and supplied to the store in conventional fan coils (4-way cassettes).

Impact

The retail leader in the EU addresses challenging summer temperatures impacting product quality through the implementation of an innovative cooling system. In many countries, CO2 (R744) refrigeration systems have become standard for cooling various goods. However, the increased temperatures inside the store during summer posed a threat to product integrity, particularly pharmaceuticals, sweets, and fresh produce. To counter this, the introduction of an air-cooled absorption cooling system with 10 kW capacity, powered by waste heat recovered from the refrigeration plant, is a strategic move. This not only enhances product preservation but also reduces electricity consumption and contributes to sustainable heat recovery practices.

Feasibility

The feasibility of this cooling system is evident in its design and utilization of waste heat. By incorporating an air-cooled absorption cooling system with 10 kW capacity, the supermarket optimally utilizes waste heat from the refrigeration plant, reducing the load on the cooling tower and lowering overall electricity consumption. The closed-loop chilled water circuit and conventional fan coils ensure efficient and practical cooling distribution within the store. Given the existing prevalence of CO2 refrigeration systems, the integration of this innovative cooling solution aligns with industry standards, providing a feasible and energy-efficient approach to mitigating temperature-related product losses in high-temperature retail environments.

5.6 Agribusiness

Background

Post-harvest losses in agriculture are a key challenge to the food supply chain. Particular in warm and hot climates, access to on-grid as well as off-grid cold storage capacity for intermediate storage of fruits and vegetables results in substantial product losses.

System configuration

Designed for a de-central product storage facility constructed with locally available materials, the purpose of these off-grid storages is to temporarily store fruits and vegetables during the period of time from harvest to collection by refrigerated trucks, or between harvest until the goods are sold at the most attractive price.

For each storage building of 6 m x 3 m a 5 kW solar cooling system is installed, accommodating 10 m2 solar thermal collectors and a 20 kWh thermal energy storage (cold) with 0.5 m3 phase change material and direct-contact technology. The thermal energy storage supplies cooling outside daylight hours and provides additional cooling capacity during peak load hours. A small Photovoltaic system with a battery supplies 300 W for the fans and circulation pumps.

Impact

Addressing post-harvest losses in agriculture, especially in warm climates, is crucial for optimizing the food supply chain. The implementation of off-grid cold storage facilities, designed for decentralized product storage, presents a strategic solution. In regions with limited access to on-grid storage, these facilities aim to minimize substantial product losses during the critical period from harvest to transportation. The deployment of 5 kW solar cooling systems, integrated with 10 m2 solar thermal collectors and a 20 kWh thermal energy storage, significantly contributes to reducing post-harvest losses. The inclusion of phase change material and direct-contact technology ensures efficient cooling, providing a sustainable and accessible solution for agricultural communities.

Feasibility

The feasibility of these off-grid storage facilities lies in their design and adaptability. Tailored for de-centralized product storage, the buildings are constructed with locally available materials, emphasizing cost-effectiveness and accessibility. Each storage building, measuring 6 m x 3 m, accommodates a 5 kW solar cooling system with 10 m2 solar thermal collectors and a 20 kWh thermal energy storage. The incorporation of phase change material and direct-contact technology ensures reliable cooling during non-daylight hours and additional capacity during peak load periods. The small photovoltaic system with a battery, supplying 300 W for fans and circulation pumps, further enhances the feasibility by providing an independent power source. This holistic approach to off-grid cold storage demonstrates a practical and sustainable solution for minimizing post-harvest losses in agriculture.

5.7 Summary

PURIX offers sustainable solutions by leveraging low-temperature heat sources, such as solar and waste heat, with the objective of reducing greenhouse gas emissions across multiple sectors. The systems, which are designed for high-volume markets through Plug & Play configurations, demonstrate significant energy efficiency and environmental benefits in a variety of applications, including residential, hospitality, retail, and agribusiness. Case studies illustrate successful implementations of their technology, such as solar-integrated cooling in homes, efficient energy systems in hotels and retail stores, and off-grid cold storage solutions in agriculture. These applications contribute to the phase-out of F-gas refrigerants and enhance sustainability.

6 SolarHybrid

6.1 Introduction

As part of the SolarHybrid project, functional models for an ammonia/water (NH_3/H_2O) single-/half-effect (SE/HE) absorption chiller were adapted based on the previous DAKtris project and a new NH3 compression chiller was built. The two functional models have been installed in the laboratory and are being subjected to stationary and dynamic tests in individual and hybrid operating modes. The two functional models and systematic hydraulic layout can be seen in Figure 12 below.

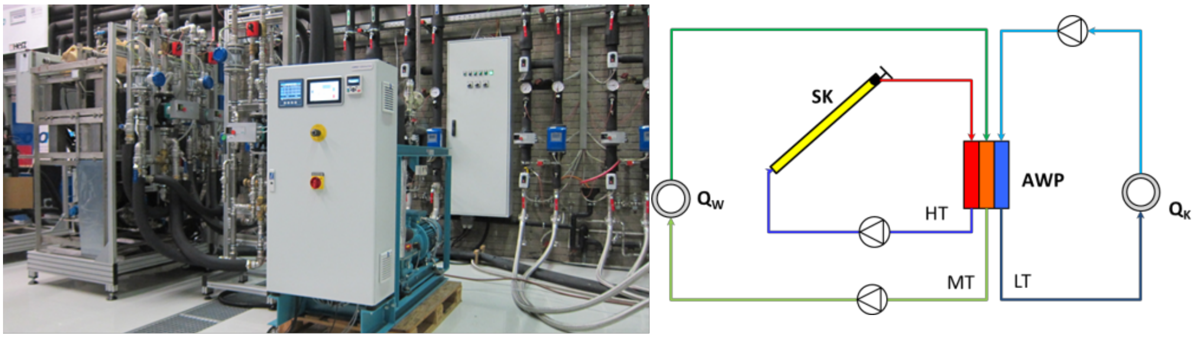


Figure 12: Picture of lab assembly and simplified layout of the solar hybrid concept (Source: UIBK)

The solar directly operated absorption heat pump / absorption chiller (AHP/ACM) shows a very high potential for achieving high primary energy savings. Although the systems are currently significantly more expensive than a standard reference system for the climatic conditions in Innsbruck, the initial situation is promising in terms of falling investment costs through sensible system integration and further optimization.

Electrical coefficients of performance of > 10 can be achieved in the system even on winter days with medium to high solar fractions. Although the concept without storage was also demonstrated here, the simple possibility of storage is a major advantage of solar thermal energy over PV. Storage tanks can be integrated into the system at different temperature levels or positions.

The dual use of cooling and re-cooling energy is always advantageous, and the SE/HE AKM offers an ideal prerequisite, as sensibly usable temperature levels (e.g. 35°C space heating (SH), 60°C domestic hot water (DHW)) can be provided for different loads. The overall system must be specifically designed and the collector array and the AKM in particular must be correctly matched to each other. Low fresh water temperatures are required for AWP operation in order to achieve the high DHW temperatures (low average temperatures on the MT side). The mass flows can be controlled on the MT and LT side, the AKM reacts very insensitively to solar fluctuations.

Further potential is seen above all with regard to controller optimization, automatic SE/HE changeover (depending on temperature level) and coordination of the existing outputs in the system (e.g. stagnation avoidance). The multiple use of direct solar-fired AKM (in summer for cooling and DHW, in winter for heating and DHW) can be an interesting option, especially in a central European climate and with a corresponding profile.

Overall, the sensitivity analysis of both cooling and heat pump operation shows a high potential for further improving the cost ratio and increasing the $f_{sav.NRE}$ (non-renewable primary energy savings, cp. Deliverable C3: Adapted Assessment Tool & Collection of Technical and Economic KPIs (Neyer et al., 2024). This potential is relatively robust compared to an optimization of the reference system and thus represents a promising starting point for further work.

6.2 Case Study sol.e.h²

It was shown that a primary reduction in the building's cooling load and then covering the remaining demand with solar cooling can achieve outstanding performance both technically and economically.

The project partner presented an office building made of modular containers arranged in a U-shape with an energy reference area of 540 m² as the initial object. The open access corridors located outside cause a huge cooling and dehumidification load. Closing this open corridor and preventing leaks in the containers proved to be the most important measure. This is the only way to achieve the necessary separation of the interior spaces from the external climatic influences.

Subsequently, the newly defined thermal and airtight building envelope was optimized by means of thermal insulation, the use of so-called cool colours (low absorption coefficient of the exterior paint), reduction of the proportion of transparent components, use of solar control glass, installation of temporary shading and moisture recovery in the mechanical ventilation system to such an extent that the cooling load peaks could be smoothed out. The drastic reduction in building cooling loads is the key to the economic efficiency of solar-hybrid cooling systems worldwide.

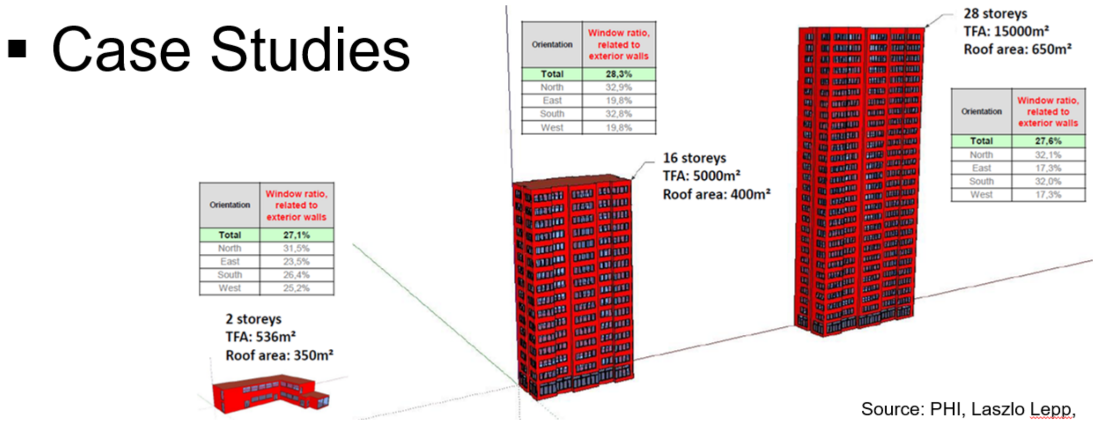


Figure 13: Different large variants that were first optimized in terms of building physics and then the solar cooling systems were designed, optimized and evaluated technically, economically and ecologically (Source: UIBK)

For the optimizations of the two storeys office building towards a passive house, approx. € 45,000 in additional costs are estimated, this sum results from the additional costs of the optimization measures (thermal insultation, window quality, etc.) and the reduced costs due to reduced window areas. Due to the smaller solar-hybrid system, which is possible due to load reduction, and despite the additional construction costs, approx. 30% of the annual annuities can be saved. This leads to a cost ratio (ratio of annual cost of solar compared to a reference system) of 0.75 to 0.8. In terms of primary energy, this results in a total saving of approx. 88%, on the one hand due to the lower energy demand and on the other hand due to the highly efficient coverage of the demand by the solar-hybrid energy supply.

The results are shown in the main result graph of IEA SHC Task 53, activity C3: Monitoring data analysis on technical issues & on performances (Köll and Neyer, 2018). The overall assessment of the technical and economic performance of the SHC systems is shown as coherence of the non-renewable energy savings (f_{savNRE}) 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.

The general format is used 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 zero 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.

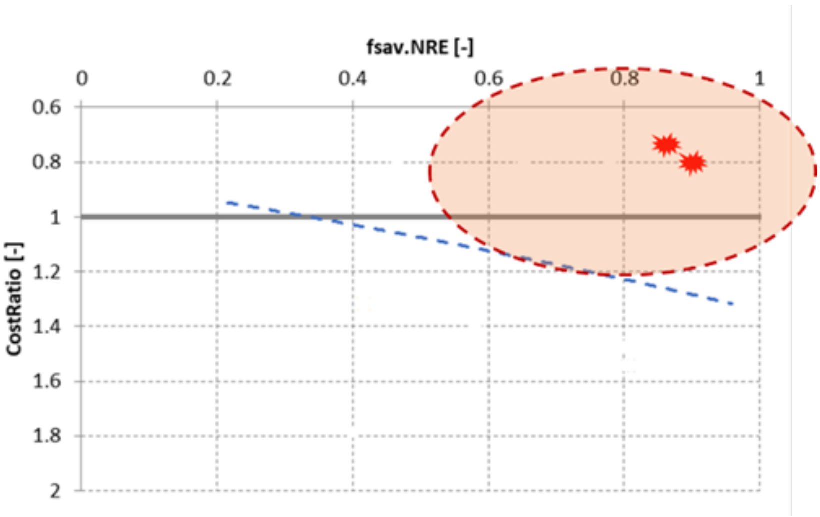


Figure 14: Comparison of the economic (cost ratio) and technical/environmental ($f_{sav.NRE}$) results with the IEA SHC Task 53 values (trend line) (Source: UIBK)

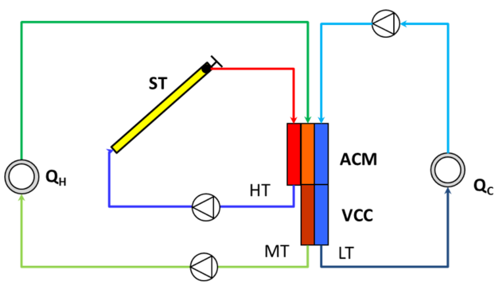
6.3 Case Studies SHC Academy

The small-scale solar hybrid configuration was elaborated for the SHC Academy trainings with CCREEE Barbados, SOLTRAIN in Stellenbosch and TTMD in Turkey, the results are based on simulations, with models borne through Hardware-in-the-Loop test during the SolarHybrid and sol.e.h.[2] project at University of Innsbruck. Each result is compared to the main results of IEA SHC Task 53, activity C3 (Köll and Neyer, 2018), where all 29 system and system configurations (shown in the Figures 15, 19, 20 and 21) and the general trendline of those results are shown.

6.3.1 Barbados

Following graphs show the boundary conditions and results for the Barbados case study.

- 75 m² HT flat plate collector
- 15 kW Absorption Chiller
- 15 kW Vapour compression chiller



- Operation as soon as Irradiation >200W/m²
- Only cooling (no heat usage, could be additional benefit)
- Simulation in TRNSYS with HiL-validated models
- Climate: Meteonorm 7.2 - Barbados, husbands.tm2

- $Q_{LT.ACM}$ 42 MWh/a
- $Q_{el.aux.ACM}$ 3 MWh/a
  - $SPF_{el.sol} = 14$

- $Q_{LT.VCC}$ 108 MWh/a
- $Q_{LT.sys}$ 150 MWh/a
- $Q_{el.aux.VCC}$ 21 MWh/a
  - $SPF_{el.sys} = 7{,}2$

→ $f_{sav.NRE} = 0.58$
→ CR = 0.87

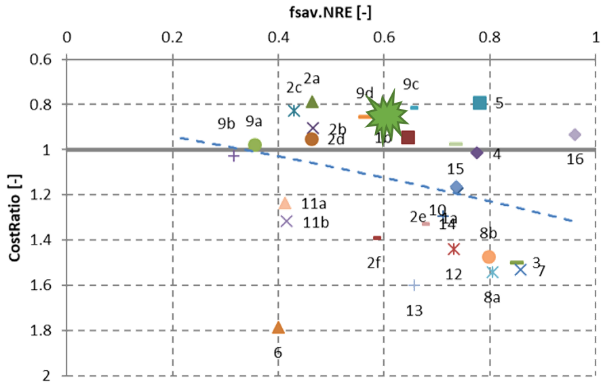


Figure 15: Boundary conditions and main results using the Task 65 method for Barbados SolarHybrid case and comparing it to the main results of IEA SHC Task 53, activity C3 (Köll and Neyer, 2018) (Source: UIBK)

The results show for the configuration of 75 m² collectors and 2 times 15 kW Absorption and vapor compression chiller non-renewable primary energy savings of ~60% at a cost ratio of 0.87. Thus, this configuration can safe 13% cost during the entire life time while saving 42% primary energy.

The analyses have also been elaborated with the LCCBA tool with the following boundary conditions.

	Solarhybrid	VCC
Investment (incl. chiller, Solar, auxillaries,…)	100.000 US $	51.000 US $
Replacement (VCC in year 10)	21.500 US $	30.000 US $
Maintainance	1.900 US $	880 US $
Insurance	0,5 %	0,5 %
Electricity Energy	235 US $/MWh/a	
	5.000 US $/a	12.500 US $/a
Electricity Power	144 US $/kW/a	
	1.100 US $/a	2.200 US $/a
Loan	70%	10a @ IR 7%
Equity ratio	30%	@ IR 10%
Subsidies	0%	

Figure 16: LCCBA boundary conditions for the Barbados SolarHybrid Case

Table 6: Main results of the LCCBA comparison of the solar hybrid and conventional vapour compression chiller system

		project cash-flow	equity cash-flow
project duration	years	15	
total investment	USD	49,702	
invested equity	USD	-	14,911
invested debt capital	USD	-	34,792
interest rate for discounting	%	7.9% (WACC)	10% (equity interest rate)
net present value	USD	17,325	13,180
internal rate of return (IRR)	%	13.0%	18.5%
payback period (dynamic)	years	6.9	7.1
Loan Life Cover Ratio	-	1.9	-

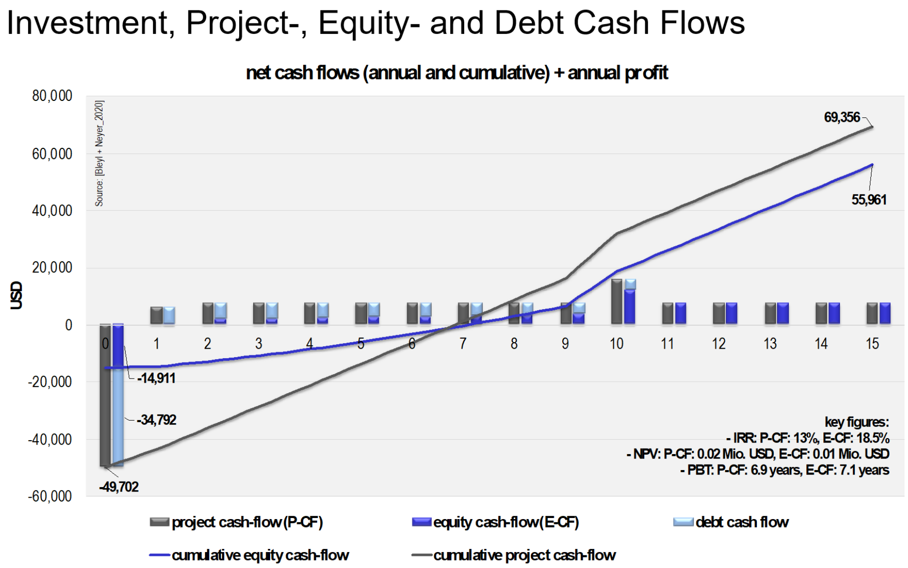


Figure 17: Main results out of the cash flow analyses of the LCCBA comparison of the solar hybrid and conventional vapour compression chiller system (Source: UIBK)

The highest sensitivities on IRR with positive gradients are saving revenues, project duration and negative gradient the investment costs. With an increase of 10% on savings revenues the IRR could reach 15% and with a decrease of investment by 30% the IRR could almost reach 20%.

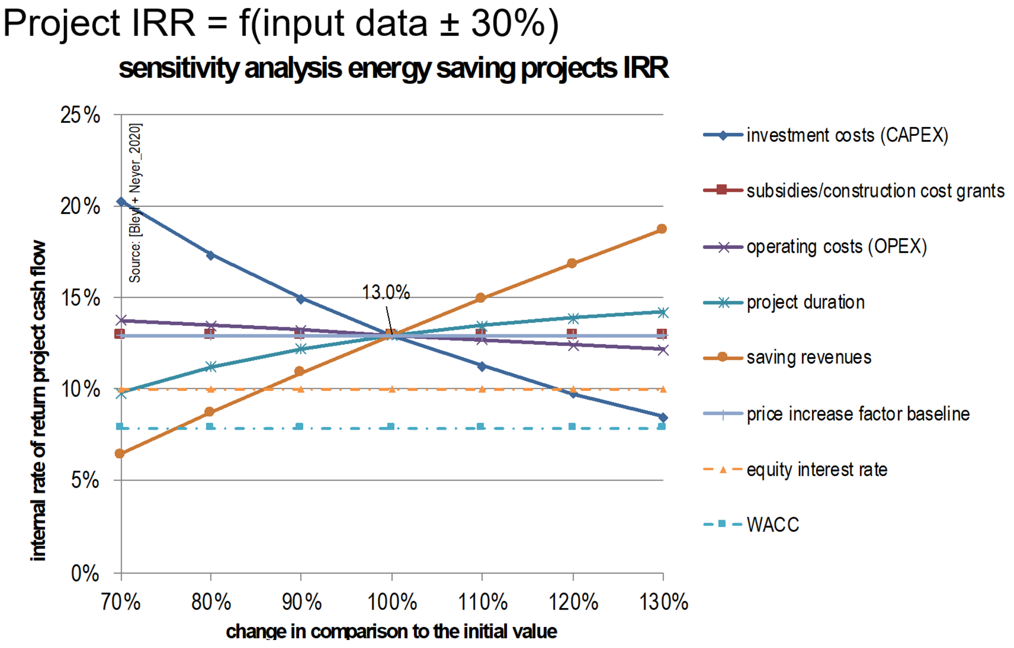
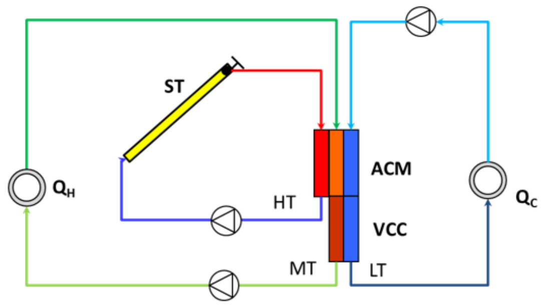


Figure 18: Sensitivity analyses of Internal rate of Return of LCCBA comparison of the solarhybrid and conventional vapour compression chiller system (Source: UIBK)

6.3.2 Stellenbosch

With the same configuration as above, similar results can be achieved under Stellenbosch boundary conditions. The following graphs show the boundary conditions and results for the simulation study provided for the Soltrain training in Stellenbosch.

- SolarHybrid in Stellenbosch
  - 75 m² HT flat plate collector
  - 15 kW Absorption Chiller
  - 15 kW Vapour compression chiller



- Operation as soon as Irradiation >300W/m²
- Only cooling (no heat usage, could be additional benefit)
- Simulation in TRNSYS with HiL-validated models
- Climate: Meteonorm 8.0 – South Africa, Stellenbosch.tm2

The results are analyzed for two case Cooling only (green results) and parallel heat&cold demand (orange rsults) for three different solar fractions of 40, 55 and 100% respectively.

▪ SolarThermal in Stellenbosch (SF = 100%)

- $Q_{LT.ACM}$ 38 MWh/a
- $Q_{el.aux.ACM}$ 2.5 MWh/a
  - $SPF_{el.sol}$ = 15

- $Q_{LT.VCC}$ 0 MWh/a
- $Q_{LT.sys}$ 38 MWh/a
- $Q_{el.aux.VCC}$ 0 MWh/a
  - $SPF_{el.sys}$ = -

→ **$f_{sav.NRE}$ = 0.89 / 0.85**
→ **CR = 1.12 / 0.91**

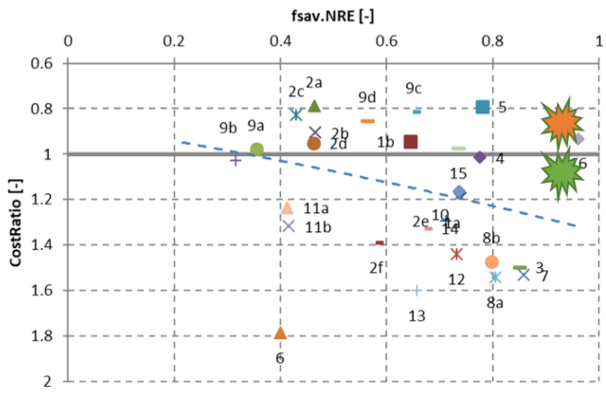


Figure 19: boundary conditions for the Stellenbosch Case of 100% solar fraction and main results using the Task65 method and comparing it to the main results of IEA SHC Task 53, activity C3 (Köll and Neyer, 2018) (Source: UIBK)

▪ SolarHybrid in Stellenbosch (SF ~ 55%)

- $Q_{LT.ACM}$ 38 MWh/a
- $Q_{el.aux.ACM}$ 2.5 MWh/a
  - $SPF_{el.sol}$ = 15

- $Q_{LT.VCC}$ 30 MWh/a
- $Q_{LT.sys}$ 68 MWh/a
- $Q_{el.aux.VCC}$ 7 MWh/a
  - $SPF_{el.sys}$ = 9.7

→ **$f_{sav.NRE}$ = 0.61/ 0.59**
→ **CR = 1.05 / 0.72**

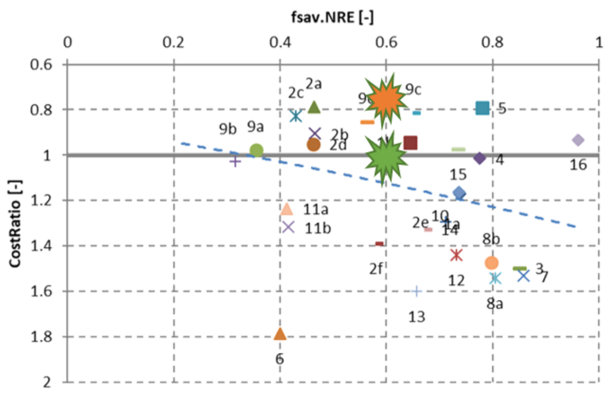


Figure 20: boundary conditions for the Stellenbosch Case of 55% solar fraction and main results using the Task65 method and comparing it to the main results of IEA SHC Task 53, activity C3 (Köll and Neyer, 2018) (Source: UIBK)

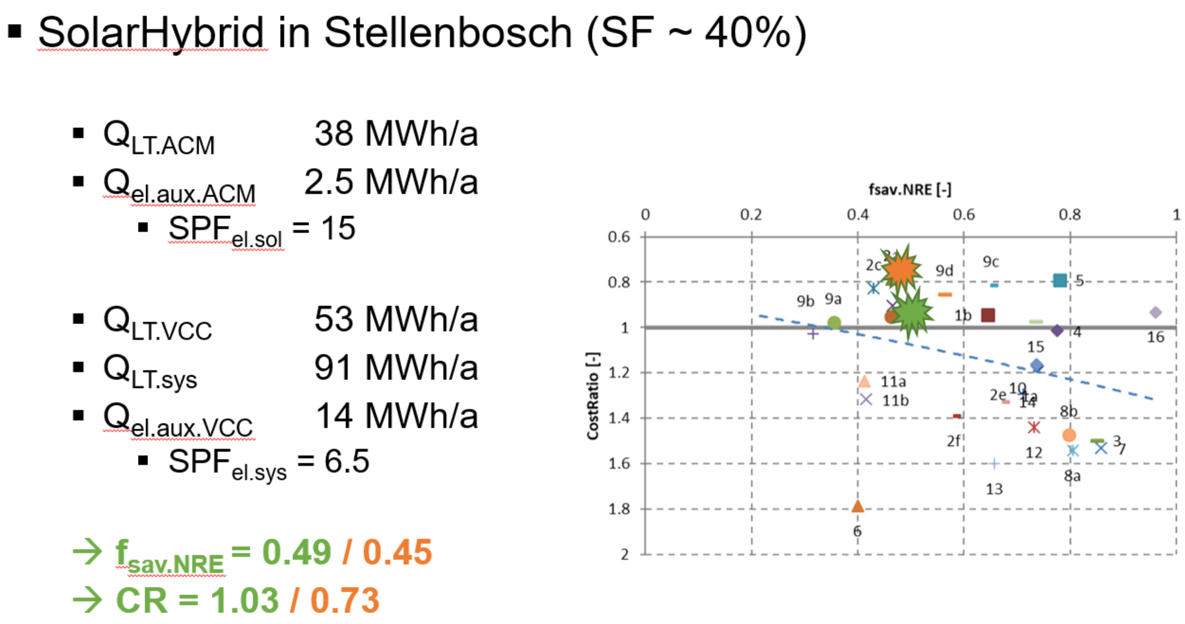


Figure 21: boundary conditions for the Stellenbosch Case of 40% solar fraction and main results using the Task65 method and comparing it to the main results of IEA SHC Task 53, activity C3 (Köll and Neyer, 2018) (Source: UIBK)

Solarhybrid shows promising results from technical and economic point of view, whereas if the additional benefits of heat between 40°C to 65°C are counted the system and its economics are even more promising. Different applications like Hospitals, Hotels, Agri-food processing are most relevant.

Depending on day vs. night operation (storage & backup), loads (Cooling, Cooling+DHW, …), the system layout (chilled water temperature 6/12 vs. 18/22°C) and capacity range the detailed design can be aligned and optimized.

However, there is no standardized product yet, thus a potential in investment reduction is evident and efficiency improvements reasonable. Solar hybrid Cooling can be competitive nowadays under the elaborated climate conditions and boundary conditions.

6.4 Summary

The, within SolarHybrid project, developed and tested concept of combined ammonia/water absorption and compression chillers, demonstrating high potential for primary energy savings despite higher initial costs, with a promising outlook for future cost reductions and system optimization. A case study on a modular office building showed significant cooling load reductions and economic efficiency through solar-hybrid systems, achieving 88% primary energy savings. Another case study in Barbados highlighted a 60% reduction in non-renewable primary energy and 13% cost savings over the system's lifetime, underscoring the competitive edge and potential for further investment reduction and efficiency improvements in solar-hybrid cooling systems.

7 Solar Cooling World-Wide

The latest Solar Heat World Wide report (Weiss and Spoerk-Duer, 2024) and especially chapter 5.6, which is about Solar Air Conditioning and Cooling and was prepared by Task 65 Experts (Prof. Dr. Jakob, Dr. Neyer, Mr. Calderoni), reports about general status of solar cooling in

- Small and medium-sized applications
- Solar Cooling with a cooling capacity larger than 350kW
- Solar Refrigeration for process industry

7.1 Small and Medium-sized Applications

The global market for cooling and refrigeration will continue to grow, particularly in the Global South, and by 2050, 37% of the total electricity demand growth will be for air conditioning (OECD/IEA, 2018). Thus, there is enormous potential for cooling systems that use solar energy, both solar thermal and PV-driven solar cooling and air conditioning systems, as presented, for example, in the GIZ 2022 technical, economic analysis for PV-powered air-conditioning in buildings of 13 developing countries (GCI, 2022), GIZ 2017 feasibility study for social housing buildings in Mexico (Jakob, 2018), and RCREEE/UNDP 2015 study on commercial buildings/ applications in the Arab region (UNEP, 2014).

A major argument for solar thermal-driven systems is that they consume less conventional energy (up to a factor of five) and use natural refrigerants, such as water and ammonia. In Europe, their application is also pushed by the European F-gas Regulation No. 573/2024 to establish the total elimination of hydrofluorocarbons by 2050. Another driver for solar cooling technology is its potential to reduce peak electricity demand, particularly in countries with significant cooling needs and grid constraints. Today, for example, 30% of India's total energy consumption in buildings is used for space cooling, and it reaches 60% of the summer peak load, which is already stretching the capacity of the Indian national electricity supply. In other countries, like the USA, the peak load through air conditioning reaches >70% on hot days.

There are mature cooling technologies grabbing the attention of the OECD and developing countries because cooling demand will continue to grow over the next decades, and national electric grids need protection against overloads. Solar sorption cooling applications are particularly adapted for medium to large-size units (100 kW to several MWs). For several years now, China has been promoting a voluntary policy to develop such green sorption devices. And in 2019, Germany changed its incentives scheme for both vapor compression and sorption based technologies to only support chillers and air conditioners that use natural refrigerants (sorption chillers 5 kW to 600 kW) in combination with a minimum required performance.

Solar thermal cooling is still a niche market, with over 2,000 systems deployed globally as of 2023. Due to changing distribution channels and B2B sales of the sorption chillers, tracking newly installed solar driven systems is difficult and can only be estimated. Small units with a capacity lower than 20 kW are getting more compact (thus cheaper upfront costs) and targeting the mass markets. Medium to large scale projects, 30 kW to 2,000 kW, are dominated by engineered systems. Of the small and medium capacity (<350 kW) solar cooling systems worldwide, 70% are installed in Europe. According to a survey carried out in early 2019 by solrico for REN21, only a few new solar cooling systems in the small and medium range were installed in 2018, mainly in Italy and Germany.

However, awareness of small to medium-scale solar thermal-driven systems is rising. There are several international initiatives (e.g., Global Cooling Pledge, MI IC7, K-CEP, IEA SHC Programme), research projects (e.g., SunBeltChiller, FRIENDSHIP, SHIP2FAIR, HyCool, sol.e.h.², Zeosol) and commercial solar thermal cooling projects (e.g., China, the USA, Mexico, Mali, Uganda, Nigeria, Morocco, Egypt, Jordan, Dubai, Greece, Spain, Austria, Netherlands, Ukraine, India, and Thailand). This is also reflected in the development and activities of small-capacity components and system manufacturers/suppliers targeting the high-volume market segment of cooling and air conditioning devices, i.e., 2.5 kW to 25 kW. A market and sales uptake can be observed at the manufacturing level, with an increase in sales of almost 15% last year. Most of the cooling systems sold are powered by solar thermal systems. Some systems are configured for use with a backup heat supply (e.g., district heating); others are configured with a thermal energy storage system. The global market for low-capacity cooling and air conditioning systems is focused on exporting to Asia, the Middle East, African countries, North and South America, and the EU.

7.2 Solar Cooling with a Cooling Capacity Larger than 350 kW

Solar cooling using thermal absorption chillers with a cooling capacity larger than 350 kW/100 RT has improved significantly in performance and decreased in cost. In addition, there have been significant improvements in the performance of large flat plate collectors at temperatures up to 120 °C. This increase in performance, combined with an economy of scale, makes solar cooling applications cost-competitive for large office buildings, hotels, hospitals, and commercial/industrial applications. The advantage of solar energy for cooling is that the supply, solar radiation, is available when the demand, cooling, is at its peak. In other words, cooling is needed when the sun is shining, which means during peak demand. Solar cooling saves money by avoiding purchasing electricity at its highest cost. Plus, solar thermal energy is an easy way to store the solar heat and shift it for cooling demands in the evenings and nights while keeping the remaining energy for morning cooling.

The electricity a solar cooling system needs to run pumps and a cooling tower is relatively low. Depending on the climate, it may give Energy Efficiency Ratios (kWth/kWel) of 20 to 40 in systems with optimized variable speed-driven auxiliaries. Thus, the electric demand for air conditioning in a building is cut by more than 80% compared to conventional HVAC equipment. Even though the technical and economic conditions for solar cooling and air conditioning have improved significantly, this remains a challenging market, as reflected in the comparatively low number of solar cooling systems built in recent years.

The world's largest solar cooling system with a cooling capacity of 3.5 MW for a packaging factory is in Izmir, Turkey. The plant was commissioned at the end of 2021 and formally inaugurated in June 2022. The installation covers two solar thermal collector fields with a total capacity of 2.5 MWth (5,000 m²). The solar system supplies heat to two double-effect lithium bromide absorption chillers with a cooling capacity of 1.4 MW and 2.1 MW, respectively, to match the size of the associated solar collector fields. The installed double-effect absorption chillers can achieve a COP of up to 1.40.

7.3 Solar Refrigeration for Process Industry

Solar thermal collectors and sorption chillers can also provide cold energy for process refrigeration at industrial sites. From the technical perspective, the main challenge is the lower temperatures often required by refrigeration processes, which can be close to 0 °C or even negative. In turn, this reflects a higher temperature needed for the chiller to drive the sorption process. Medium temperature collectors such as Fresnel, parabolic troughs, and vacuum collectors can be employed to meet such high activation temperatures. Alternatively, hybrid chillers have been tested in combination with solar thermal, connecting an electric chiller and a sorption chiller in series. In this way, the sorption device cools down the condenser of the electric chiller, thus increasing its efficiency without the need for the sorption chiller to reach very low temperatures.

According to the EU HyCool project, energy demand for process refrigeration is some 4% of industry's final energy demand end-use in 2015 in EU28 (100 TWh/y). Cold energy is required at temperatures 0 to 15 °C (2%), 1% is required at -30 to 0 °C, and 1% at below -30 °C. Space cooling at industrial sites uses another 1% of industry's final energy demand.

A newly launched EU-HEU-funded project called RE-WITCH will demonstrate advanced thermally driven industrial cooling technologies in four industrial applications (brewery, food, biodiesel, and machinery industry). This includes hybrid systems based on adsorption and absorption processes (different sizes from 40 to 400 kW cooling capacity) driven by an optimized mix of low-grade waste heat and renewable sources (innovative high vacuum flat plate solar collector fields). Another approach for hospitals, such as containerized solutions using natural refrigerant chillers and photovoltaics, is being pursued in the EU-funded project SophiA. A three stage refrigeration cascade with natural refrigerants (propane, CO_2, and ethane) reliably ensures the three required temperature levels. The most spacious room inside the container is cooled down to +5°C. Lockable shelves on the wall allow the storage of medicines and food products. The freezer chamber at –30°C is accessible only through the refrigerated room. Besides the storage possibility, there are two deep freezer boxes that can cool down to -70°C. Everything is powered by the PV panels installed on the roof of the containers.

The potential for solar thermal cooling and industrial applications was investigated in the SunBeltChiller project, using a newly developed GIS tool to amalgamate geographical data in a manner conducive to ascertaining localized reference conditions for solar cooling systems within Sunbelt regions. Moreover, this methodology can be adapted to generate insights into potential deployment sites and the feasibility of specific solar cooling systems. Supplementing this approach with data such as population density, industrial areas, and purchasing power (GDP) lays the groundwork for prospective market studies focusing on particular products or technologies. Consequently, prospective sites can be pinpointed, and economic variables can be factored into identifying current and future markets.

7.4 Trends and Outlook

The demand for cooling and refrigeration will continue its rapid growth, particularly in the Global South (several hundred million AC units are estimated to be sold annually by 2050). This means there is a huge potential for cooling systems that use solar energy, such as thermal and photovoltaic (PV) systems.

Therefore, current and future product development focuses on compact, small-scale solar air conditioning units with air-cooled absorption and adsorption chillers and small-scale and large multi-stage desiccant systems with solar thermal collectors or desiccant-coated components. In addition, the development and market launch of x.N stage chillers (half, single, 1.N, double, triple) with new, medium temperature collectors and thermally driven heat pump systems for heating and cooling, also in hybrid operation with vapor compression chillers. Not to forget the future market penetration of small PV-driven components with new heat pumps/chillers using natural refrigerants like propane.

In the past 15 years, very few large installations were realized each year. A change in this trend is not foreseeable at present. Despite the potential presented in many studies, exploiting it will not be possible until system prices and complexity are significantly reduced. On the other hand, the most recently signed Global Cooling Pledge at the COP28 conference shows that cooling is a very serious and important global issue. According to the Global Cooling Watch 2023 report, cooling-related emissions could be reduced by over 60% compared to normal operations by 2050 while expanding access to cooling to 3.5 billion people. Combined with a decarbonized power grid, emissions reductions could be up to 96%.

8 Summary and Conclusion

The investment in SunBeltChiller and DE ACM requires a long-term business perspective with over 15 years of commitment and low economic return expectations, making them less attractive to standard investors but potentially appealing to green investors, especially if CO_2 emissions reductions are financially rewarded (e.g., CO_2 tax @90 EUR/t). Key considerations for feasibility include potential reductions in capital expenditure, availability of long-term financing, and high energy prices in certain countries. Deeper decarbonization requires greater investments and assessing PV + solar thermal cooling options could be beneficial, particularly if they can be cross-subsidized by profitable PV projects.

PURIX, leading in cooling technology with natural refrigerant R718 (water), offers energy-efficient and environmentally friendly solutions across various sectors. Their Plug & Play systems showcase significant benefits in residential, hospitality, retail, and agriculture applications, effectively reducing greenhouse gas emissions and aiding in the transition away from F-gas refrigerants.

The SolarHybrid project, which tested ammonia/water absorption and compression chillers, showed high potential for primary energy savings and promising future cost reductions. A case study on a modular office building demonstrated significant cooling load reductions and economic efficiency with 88% primary energy savings. Another study in Barbados highlighted a 60% reduction in non-renewable primary energy and 13% cost savings over the system's lifetime, showcasing the competitive edge and potential for further improvements in solar-hybrid cooling systems.

In general policy recommendations should include supporting long-term financing through concessional loans and subsidies, introducing carbon pricing to incentivize decarbonization, and de-risking investments via partial risk guarantee facilities. Recognizing multiple project benefits such as reduced fossil fuel consumption, carbon neutrality, and a green image is essential.

One of the main trends are hybrid system solutions. They will also offer high CO_2 savings in small to medium cooling capacity ranges with good economic efficiency. In addition, there will be solutions with better efficiency and cost-effectiveness in the area of medium-temperature systems (solar collector temperatures around 160-180 °C) and two-stage absorption chillers, as they can achieve an investment advantage through smaller solar surfaces and dry coolers.

Nevertheless, solar cooling is still a small niche market that will expand worldwide by 2030. Due to changing distribution channels and B2B sales of sorption chillers, tracking newly installed solar-powered systems is difficult and can only be estimated. Small systems with an output of less than 20 kW are becoming increasingly compact (and therefore cheaper to purchase) and are focusing on mass markets. The medium to large project range, 350 - 2,000 kW, is dominated by technically specific systems. 70% of small and medium-sized (<350 kW) solar cooling systems worldwide are still installed in Europe.

In order to break out of the niche, the focus on potential markets for solar cooling technologies is therefore becoming increasingly important. The expertise acquired in the OECD countries (Europe, USA, Australia, etc.) in the field of solar cooling, both thermal and PV cooling, must be transferred to the countries of the global South, such as Africa, MENA and Asia, all dynamic emerging markets. New developments and innovations should aim at affordable and reliable cooling systems for the Global South.

The main objective of a potential follow-up task is to focus on commercial and industrial applications from small to large scale applications in countries of the Global South. Industrial applications include agriculture and food, manufacturing and tourism. The new task should focus on countries in regions such as Africa and Latin America as well as South East Asia and the Pacific region. The aim is to develop, disseminate and spread safe and reliable cooling for the Global South (see IEA SHC Strategy, IEA SHC, 2023) and to evaluate solar cooling solutions, including for industrial applications in early stages of industrial development, as a cost-effective and reliable solution for future development.

9 Publication Bibliography

Bleyl, J.W.; Bareit, M.; Casas, M.A.; Chatterjee, S.; Coolen, J.; Hulshoff, A.; Lohse, R.; Mitchell, S.; Robertson, M.; Ürge-Vorsatz, D. (2018), Office building deep energy retrofit: Life cycle cost benefit analyses using cash flow analysis and multiple benefits on project level. Energy Effic., 12, 261–279.

Jakob, U. 2018, Results from feasibility studies of solar cooling systems in Mexcio and the Arab Region, IEA SHC Task 53 Solar Cooling Workshop, Dresden, 2018

Gurtner, Richard; Bleyl, Jan W.; Jakob, Uli (2023). Sunbelt Chiller – An Innovative Solar Cooling Adaption SHC Solar Update, December 2023. http://www.iea-shc.org/Data/Sites/1/publications/2023-12-Task65-Sunbelt-Chiller.pdf

Green Cooling Initiative (2022), Photovoltaic-powered Air Conditioning in Buildings Technical economic analysis, GIZ GmbH, June 2022

Köll R & Neyer D. (2018), Monitoring data analysis on technical issues & on performances, https://task53.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task53-C3-Final-Report.pdf

OECD/IEA (2018). The Future of Cooling: Opportunities for energy efficient air conditioning.

IEA (2019). Multiple Benefits of Energy Efficiency, IEA, Paris https://www.iea.org/reports/multiple-benefits-of-energy-efficiency, Licence: CC BY 4.0.

Neyer, Daniel; Neyer, Jacqueline; Thür, Alexander; Fedrizzi, Roberto; Vittorisosi, Alice; White, Stephen; Focke, Hilbert (2015). Collection of criteria to quantify the quality and cost competitiveness for solar cooling systems; May 21.

Neyer, D. & Koell, R. (2017). Sensitivity Analysis on the Technical and Economic Performance of Thermal and PV Driven Solar Heating and Cooling Systems. In M. Romero, D. Mugnier, D. Renné, K. Guthrie & S. Griffiths (Eds.), Proceedings of SWC2017/SHC2017 (pp. 1–12). Freiburg, Germany: International Solar Energy Society.

Neyer, D., Neyer, J., Mugnier, D. & White, S. (2015). Technical and Economic Assessment of SHC Plants – Compilation of 10 Best Practice Examples of IEA SHC Task 48. In U. Eicker (Ed.), 6th International Conference Solar Air-Conditioning. Rome, Italy, September 24. Regensburg: OTTI, Ostbayer. Technologie-Transfer-Inst.

Neyer D., Ostheimer M., Bleyl W.J., Weiss W., Munkoe L., Jakob U. (2024) Adapted Assessment Tool & Collection of Technical and Economic KPIs, Report D-B3-C3, IEA SHC Task 65

PURIX (2023). https://profiler.purix.com/Chart

United Nations Environment Programme (2014) Assessment on the Commercial Viability of Solar Cooling Technologies and Applications in the Arab Region, UNEP 2014

Weiss, W.; Spoek-Duer, M. (2024) SOLAR HEAT WORLDWIDE, Global Market Development and Trends 2023 Detailed Market Figures 2022, IEA Solar Heating and Cooling Programme, June 2024; DOI: 10.18777/ieashc-shww-2024-0001