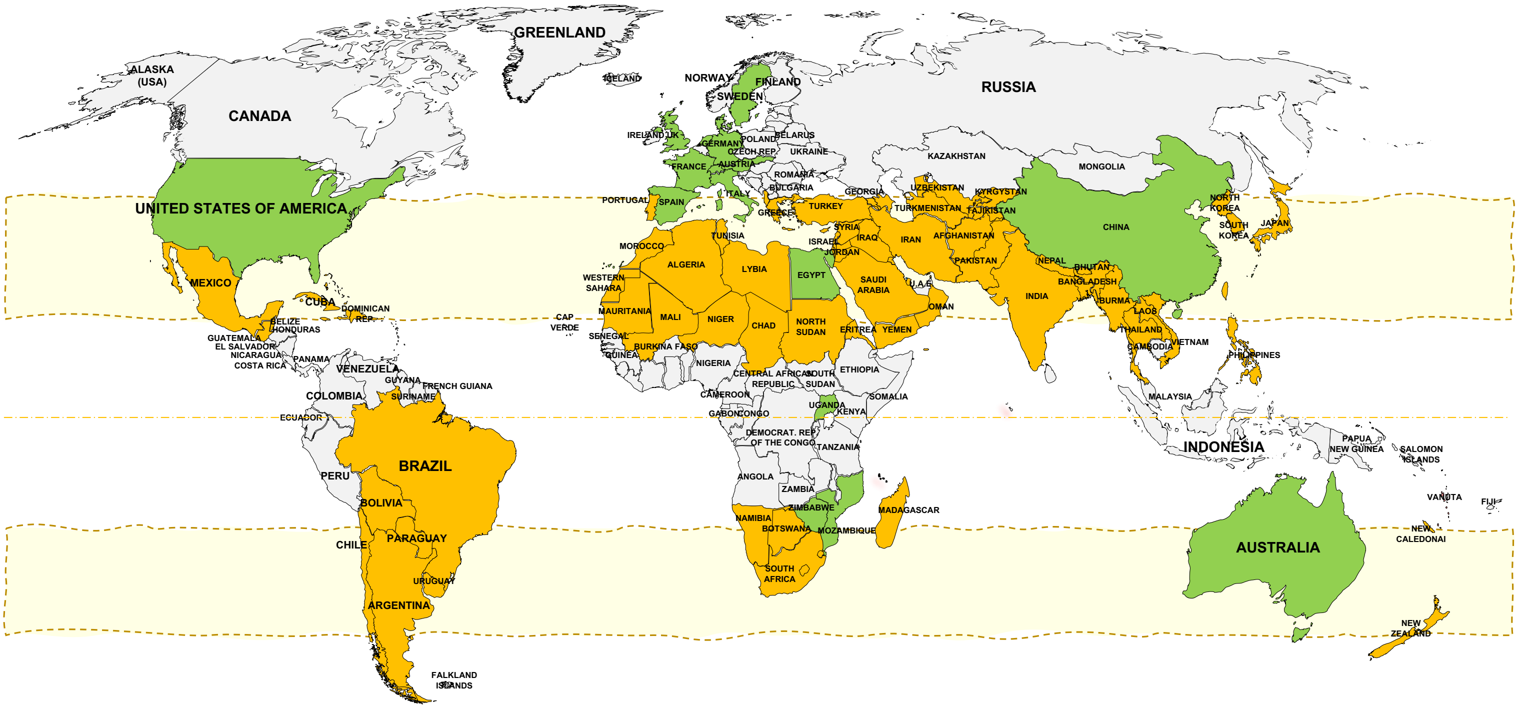
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Adapted Assessment Tool & Collection of Technical and Economic KPIs



IEA SHC TASK 65 | SOLAR COOLING FOR THE SUNBELT REGIONS

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Adapted Assessment Tool & Collection of Technical and Economic KPIs

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

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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

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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
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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.

During the past IEA SHC Tasks, the standardized assessment of monitored and simulated solar heating and cooling systems was initiated and developed step by step. The resulting assessment tool (T53E4-Tool) offered a simple method that can analyse various systems on a monthly base. The aim is to provide technical and economic key data that is comparable with conventional and widely used indicators, but with the option to provide deeper analysis of the systems. The T53E4-Tool is used to post process simulated or monitored data under predefined conditions including seasonal effects of boundary conditions. It enables a standardized analysis of entire HVAC systems and allows benchmarking of solar driven, and other renewable concepts in terms of technical and economic performance. Main results are provided in a normalized way (compared to a defined reference) trying to avoid a discussion of absolute magnitudes and correct choice of boundary conditions. The main drawback is the simplified provision of energy balances, ignoring thermodynamic influences (e.g. temperature level, etc.) as well as the non-renewable primary energy as main base for the technical key figures. The conversion factors for primary energy are changing over time and are not necessarily physically defined, i.e. legislative influence is evident though challenging to quantify. Furthermore, major effort is needed to keep the economic database up-to-date, thus economic projections may be inaccurate or become quickly outdated. However, revealing and comprehensive studies can be performed if the results are analysed with the background knowledge of the chosen method, and its simplification and boundaries.

The T53E4 tool was used extensively in the IEA SHC Task 53 and adapted to IEA SHC Task 65 needs (system (load) optimization) to analyse some projects for heating and cooling systems.

An existing life cycle cost-benefit analysis (LCCBA) tool was systematically further developed for the specific requirements of modelling solar cooling systems. The adapted LCCBA model is based on a dynamic cash flow model.

Solar cooling installations for the high-volume market segment calls for equipment with low cooling capacities - which can hardly justify time consuming detailed studies and related costs. In order to accommodate the need by end users for evaluating the environmental impact and economic feasibility of adopting sustainable cooling technology from PURIX, a simple-to-use assessment tool offers a reliable evaluation and benchmark with baseline systems, i.e. equipment which otherwise would be installed.

Through discussions in subtask B (Activity B3) and subtask C (Activity C3), it is evident a need to include several extra KPIs but at the same time to simplify the key messages and to select understandable KPI. The discussion between different stakeholders led to a clear view that a unique benchmarking/performance ratio would be of high value, but due to complexity of the systems as well as different targets, experts would rather prefer their own set of KPIs, tools and methods.

2 Scope of Activity B3 & C3

Although the key performance indicator definition has been discussed before , there is still no standard and throughout the entire solar cooling community often a mix of non-comparable KPIs is used to express the quality of systems. This is not only confusing for end-users / operators / policy makers but also misleading the discussion among the experts.

A review of existing tools (other IEA SHC Task, …) and methods for technical (SPF, PER, fsav, etc.) and economic (LCC/CAPEX/OPEX, LCOH/LCOE, LCCBA etc.) assessment provides the bases to select the necessary KPIs for different project phases and stakeholders.

Finally, three tools were analyzed and adapted for use in Task 65, with the adaptation of the methods and the integration of the database (from Activity C2) being the core activities. The focus was on providing the appropriate methods for the analyses and not on creating a specific new tool.

3 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 provide guidance on optimized system design and implementation, and show the level of performance ~~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 and 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. PV vs. ST, SE vs DE, etc.).

A thorough technic-economic-financial analysis based on a Life Cycle Cost (LCC) assessment answers 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 (FI) (ix) subsidy or funding demand calculations (amount and timing) for policymakers … and many more (Bleyl et al., 2018).

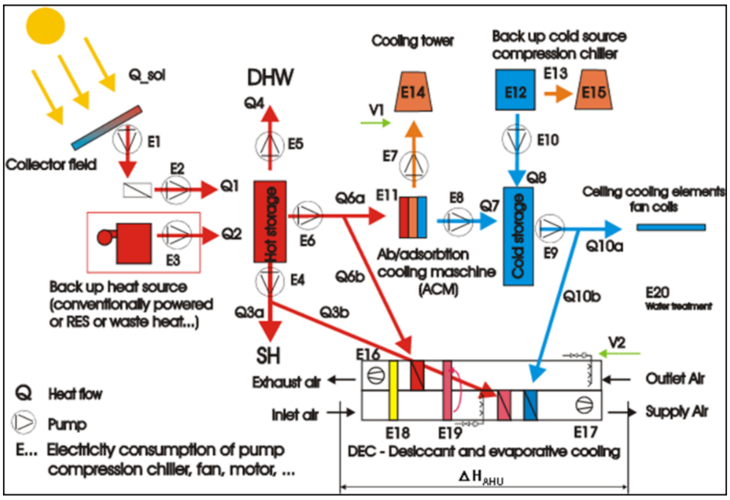
Several tools, models, and methods are available, which need to be screened, evaluated, and adapted for solar cooling in Sunbelt countries. A great number of these tools and methods are well known or even developed by previous IEA Task participants. However, considering the targeted countries and the 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 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.

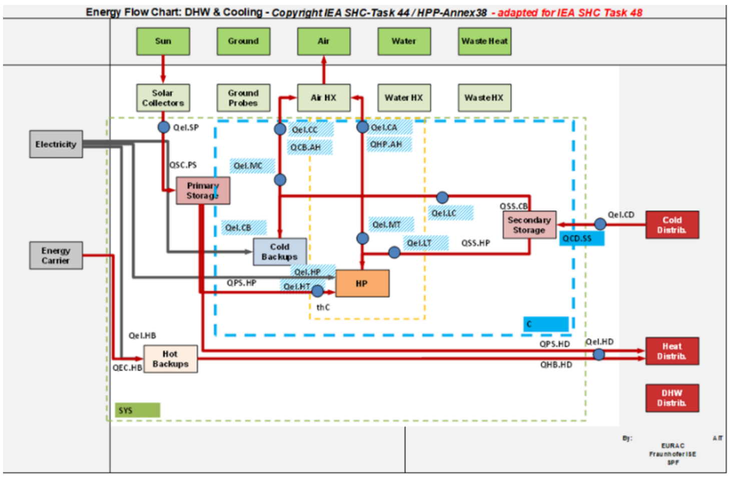
4 Previous Tasks

From previous IEA SHC Task the following progress of method and KPI evolution can be noted and is serving as baseline for discussions and further developments.

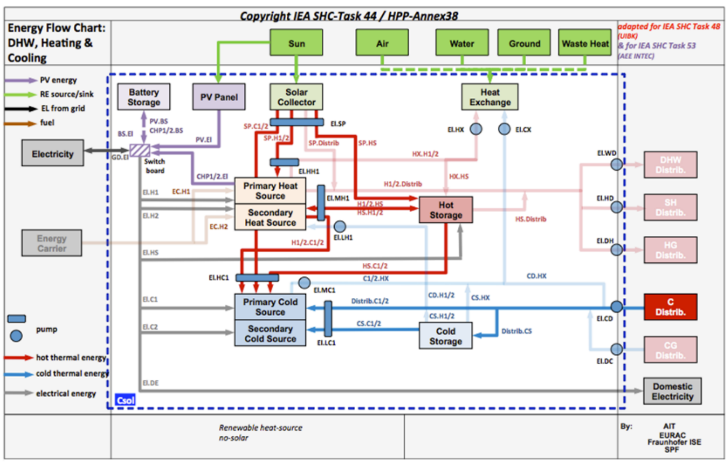
IEA SHC Task 38: 3 level approach of monitoring and KPIs starting from system and basic level broken down to component level and efficiency of them. It includes nomenclature following the graph on the right hand side for parasitic electricity demand of pumps, fans, etc. and the energy flow from one to the other component to the final use for space heating, space cooling and dried air.



IEA SHC Task 48: was elaborated in alignment with HPP Annex 38 and include a more generic nomenclature approach for more complex systems. A tool was created to allow total system and subsystem analyses and assessment, according to available data (as in Task 38 approach). This tool included a common data base for economic analyses of the entire systems based on their energy balance and average component costs.



IEA SHC Task 53: kept the energy flow chart approach but widened it up to a large number of complex renewable heating and cooling systems, also including the domestic electricity demand as output, and thus able to cope with PV driven systems as well. The economic analyses was refined with life cycle cost and sensitivity analyses options. KPIs are focusing on the economic and environmental comparison to standardized reference systems



5 Key Performance Indicators

Through discussions in subtask B (Activity B1-A2 & B3) and subtask C (Activity C3) a need to include several extra key performance indicators (KPIs) but at the same time to simplify the key messages and select understandable KPIs is evident. The discussion between different stakeholders led to a clear view that a unique benchmarking/performance ratio would be of high value, but due to complexity of the systems as well as different targets experts would rather prefer their own set of KPIs, tools and methods. Other examples of sets of KPI's can be found in current EU funded LIFE and H2020 projects, e.g. Cooling Down (Cooling Down, 2023) or HyCool (HyCool, 2019).

The technical and economic assessment of HVAC and renewable systems is a complicated topic due to its vast variety of components and system configurations, the choice of system boundaries in time and range, as well as the influence of boundary conditions. Even experts can become confused or misguided when comparing different KPI used in practice.

Boundary conditions for the measurements or calculation of the KPIs are not always defined properly. However, it is evident that the correct interpretation of one KPI is only possible when the method and defined boundaries are considered. Understanding the various definitions of performance figures is stated to be the key for comparison of different systems by Hadorn (2012). Further when unverified or inaccurate KPIs are applied for comparison or benchmarking of different systems misleading conclusions might be drawn.

Technical Key Indicators

The development of technical key indicators and its boundaries are driven by regulations (e.g. EU, 2010; EU & EC, 2012), by lobbies and stakeholders (e.g. ESTIF; EUROVENT) or with a more scientific background (exergy analysis, life cycle analysis, etc.). The main technical key figures can be classified and distinguished as follows:

- **Quantity/type of energy:** Many KPI's express the performance of an entire component or system with the thermal (e.g. Seasonal Performance Factor, SPFth) or electrical (e.g. SPFel) efficiency. However, if both thermal and electrical auxiliary energy is applied, quality figures can also be based on primary energy input (with or without renewables) or on CO2 emissions. More in-depth analysis is based on exergy or the inclusion of effort of production, transportation, operation and removal (life cycle analysis - LCA) of the entire consideration.
- **System boundary:** A figure can be valid for a single component, a part of a system or the overall system in- or excluding auxiliaries. The system boundary can be drawn individually, thus including certain energy supplies (space heating, cooling, DHW, etc.) on component level, system level, or further including distribution and delivery systems at a building level.
- **State and time:** The state under which measurements can be executed can be steady or dynamic (including start/stop and change of boundaries, etc.). Testing conditions (e.g. temperatures, mass flow rates, etc.) can be defined for several full and part load conditions leading to steady state figures such as COP and EER, but can also be composed of different methods to seasonal key figures like SCOP, SEER, etc.
- **Absolute/relative figures:** the representation of results can be achieved as absolute or relative values. Relative figures compare the results of the entire solar HVAC system to a defined reference or other renewable system. The main impact on this kind of measures is naturally given by the performance of the system that is used for comparison.

KPIs for Heating and Cooling Systems

Key performance indicators (KPIs) for heating and cooling systems in general help in measuring the efficiency and effectiveness of these systems. Here are the most common KPIs for heating and cooling systems:

- **Energy Consumption:** This KPI measures the amount of energy used by the system to provide heating or cooling. Lower energy consumption indicates higher efficiency.
- **Seasonal Energy Efficiency Ratio (SEER):** SEER is a metric used to evaluate the efficiency of air conditioning systems. It is calculated by dividing the cooling output of a typical cooling season by the total electric energy input during the same period.

- **Heating Seasonal Performance Factor (HSPF):** HSPF is a metric used to evaluate the efficiency of heat pumps in heating mode. It is calculated by dividing the total heating output of a typical heating season by the total electric energy input during the same period.
- **Coefficient of Performance (COP):** COP is a ratio of the heating or cooling provided by a system to the amount of energy consumed. A higher COP indicates better efficiency.
- **Indoor Air Quality (IAQ):** IAQ is an important KPI that measures the quality of air inside the building. Good IAQ is essential for the health and comfort of building occupants.
- **Temperature Control:** This KPI measures the system's ability to maintain desired temperatures within a specified range. Consistent and precise temperature control is crucial for comfort and energy efficiency.
- **Maintenance Costs:** Monitoring maintenance costs helps in assessing the overall performance and reliability of the system. Lower maintenance costs may indicate better system efficiency.
- **Customer Satisfaction:** Customer satisfaction surveys and feedback provide valuable insights into how well the heating and cooling system meets the needs and expectations of users.

By tracking these technical and social key performance indicators, building owners and facility managers can evaluate the efficiency, reliability, and effectiveness of their heating and cooling systems, leading to informed decision-making and potential improvements.

5.1 Subtask B1-A2: Key Performance Indicators (KPI)

Various performance parameters used for case studies/experimental evaluation are summarized below in this section. The key performance indicators of component and system level are broadly classified under three subsections, 1) Energy efficiency parameters 2) Environmental parameters 3) Economic parameters.

5.1.1 Energy KPI parameters

All reported performance studies and optimization research primarily considered energy efficiency at the component level and system level. Although COP (Coefficient of Performance) is a basic efficiency measuring KPI, the scope of study deepens with the calculation of SCOP, Exergy studies, and Efficiency ratios. All of these parameters aim to identify the disparity between input and output energies and ways to maximize the utilization of input energy, minimize the loss in energy harnessing capability of devices, and account for storage/auxiliary heating to ensure the continuous operation of components in the absence of solar energy.

Coefficient of Performance (COP)

Solar coefficient of performance (SCOP): It is an indicator used to assess the ability of solar cooling systems to convert solar irradiation into useful energy. It is defined as the ratio of the useful heating or cooling output to the solar energy input required to achieve that output. The higher the SCOP, the more efficient the system is considered.

Renewable energy ratio (RER): The Renewable Energy Ratio (RER) is a parameter used to assess the impact of energy produced from renewable energy sources on a system. It is typically considered in regulations that indicate a required amount of coverage of energy needs from renewable sources. It is evaluated using primary energy values and compares the energy produced from renewable sources to the total energy consumption of the system.

Energy Efficiency

Thermal efficiency: The thermal efficiency of the solar collectors is an important parameter that measures the ratio of the useful energy collection rate to the received solar energy rate. It is crucial in evaluating the performance of the solar cooling system.

Electrical efficiency: The electrical efficiency of the solar collectors is another critical parameter that assesses the efficiency of converting solar energy into electricity. It takes into account factors such as the temperature coefficient of PV cells and the PV cells' temperature at reference conditions.

Primary energy efficiency: The primary energy efficiency considers the difference in thermal and electrical energy grades, as well as the energy consumption of pumps. It provides a comprehensive evaluation of the overall energy conversion process.

Exergy Efficiency

Exergy analysis is useful for understanding the inefficiencies and losses in energy conversion processes, as it provides insights into where and why energy is wasted. It allows engineers and researchers to identify areas for improvement in terms of system design, operation, and efficiency enhancement.

Exergy efficiency - Exergy efficiency is calculated to evaluate and compare the quality of the energy conversion process in solar collectors. It provides a measure of how effectively energy is converted into useful work or output. The exergy efficiency takes into account both the thermal and/or electrical output (in the case of PV/T) of the solar collector, as well as the solar radiation exergy rate. By considering these factors, the exergy efficiency provides a comprehensive assessment of the overall performance of the solar collector system.

Total efficiency ratio (TER) is a performance parameter used to assess the useful effect of a solar cooling system in the production of usable energy for both cooling and domestic hot water (DHW) production where the waste heat can be recuperated. It takes into consideration the energy used for the production of chilled water (cooling load) and the energy recovered from the cooling water for the production of DHW. TER is a more advanced rating method compared to traditional efficiency parameters like COP or EER, especially for absorption chillers with double effects. It is also being adopted by chiller manufacturers and certification companies for performance evaluation. Comparing TER focuses on the efficiency of energy production for cooling and DHW, while RER measures the contribution of renewable energy sources to the overall energy consumption of the system.

5.1.2 Environmental KPI Parameters

CO_2 emission reduction: Direct reduction of CO_2 emissions is the energy saved by the use of renewables to power the thermal chiller. This is a direct method to quantify the positive environmental impact.

Environmental cost saving: The environmental cost saving is then calculated by multiplying the saved GHG emissions by the carbon price. This calculation helps to assess the environmental benefits of implementing the solar cooling system and quantifies the cost savings associated with reducing GHG emissions.

Global warming potential: As a cold backup, a vapor compression system (VCS) can be used in a hybrid system that can operate in low solar insolation days/cloudy conditions. Considering the GWP, the choice of refrigerant that has the least environmental impact can be evaluated.

5.1.3 Economic KPI Parameters

Global cost: The global cost refers to the total cost associated with the solar cooling system, taking into account various factors such as investment costs, energy costs, maintenance, and operational costs. It can be evaluated using the European standard EN 15459-1:2017 and is calculated based on the initial investment cost, annual costs, and annual discount rate. Global cost is an important economic indicator that helps assess the overall financial impact of the energy choices made in the optimization process. It provides a comprehensive view of the total cost of the system over its assumed lifespan of 20 years.

Levelized cost of cooling (LCoC): The LCoC calculates the cost-effectiveness of the solar cooling system by considering the total annual cost and the produced cooling energy. It helps in evaluating the economic viability of the system.

Savings-to-investment ratio (SIR): The SIR represents the ratio of the systems' savings throughout their lifetime to the investment cost. It is a key indicator to assess the profitability of the solar cooling system.

Discounted payback period (DPP): The DPP reflects the time needed to recover the investment cost of the solar cooling system, considering the time value of money. It is an important economic indicator to assess the feasibility of the system.

Payback period- The payback period is a financial metric used to determine the time it takes to recover the initial cost of an investment. In the context of the document, the payback period specifically refers to the time required to recoup the initial cost of a thermal system, such as a solar cooling system. The formula for calculating the payback period takes into account factors such as the rate of inflation of electricity, the initial investment cost, and the amount of energy savings. The payback period is an important indicator of the economic viability of a system and is used to assess the cost-effectiveness of implementing a solar cooling system.

Hourly cost refers to the cost incurred per hour of operation or usage. In the context of the document, it is used to calculate the cost associated with various components and processes in the solar-assisted NH_3-H_2O absorption refrigeration system. The document provides equations and correlations to estimate the hourly costs for different units, such as solar collectors, flashing tanks, absorption cycles, and pumps. These calculations are based on factors like investment costs, operating and maintenance costs, and total annual costs. The hourly costs are expressed in USD/h and are used to evaluate the economic performance of the system.

Thermo-economic product cost cp is the thermo-economic product cost (USD/GJ), cw is the power cost in (USD/kWh) (~0.065), and Wtot is the total cycle power (kW), Exf o is the exergy stream outlet from the system to the user (kW).

5.2 Further Reports and summaries of KPIs

Many other projects also summarize and adapt KPIs for their needs. Two well established examples are given here.

5.2.1 HyCool

The document is the deliverable number D2.5, entitled "Key Performance Indicators for the Machine and process levels", included in the European project "HYCOOL - Industrial Cooling through Hybrid system based on Solar Heat" with project reference: 792073, authors: Alex Grande, Sergio Vel.squez (IDP); contributors: Uli Jakob, Falko Kiedaisch (JER)

https://hycool-project.eu/publications-and-results/project-deliverables/

https://hycool-project.eu/download/d2-5-key-performance-indicators-for-the-machine-and-the-processes-levels/

5.2.2 Cooling Down

The report about "Analysis of the energy efficiency and the performance indicators of cooling systems" Deliverable number: D2.2 Main Authors: Borja Badenes, Javier F. Urchueguía, Authors' affiliation: Universitat Politècnica de València (UPV) can be found here

https://hycool-project.eu/download/d2-5-key-performance-indicators-for-the-machine-and-the-processes-levels/

https://www.egec.org/wp-content/uploads/2023/11/D2.2_Analysis-of-the-energy-efficiency-and-the-performance-indicators-of-cooling-systems_20231030_vf2.pdf

6 Assessment Mechanism

In Subtask C3, **three tools/methods are analysed and adopted** that show a set of criteria and KPIs mentioned in Chapter 5.

1. A unified **technical and economic assessment method** is developed to rate and benchmark new developments at system level. The assessment tool provides a comprehensive data base of boundary conditions that are used in various configurations and applications. Under IEA SHC Task 53, the available systems are used to study the boundary conditions to identify the most favourable technology. Under IEA SHC Task 65 the method was further developed to include building/system (load) optimization.

2. An existing **life cycle cost-benefit analysis (LCCBA) tool** was systematically further developed for the specific requirements of modelling solar cooling systems.

3. **Individual manufacturer tools**: Solar cooling installations for the high-volume market segment calls for equipment with low cooling capacities - which can hardly justify time consuming detailed studies and related costs. In order to accommodate the need by end users for evaluating the environmental impact and economic feasibility of adopting Sustainable cooling technology from PURIX, a simple-to-use assessment tool offers a reliable evaluation and benchmark with baseline systems, i.e. equipment which otherwise would be installed.

6.1 Task 53E4 Tool

Adaptation of the technical-economic analysis tool (E4 Task Tool): The E4 Task Tool is used for the basic evaluation of renewable heating and cooling concepts. A further variation of system configurations can be mapped in the tool and their subsystems (e.g. heating, cooling, hot water, etc.) can be analyzed. The calculated key figures are compared with a task reference system and an individually adapted, specific reference system (Figure 1).

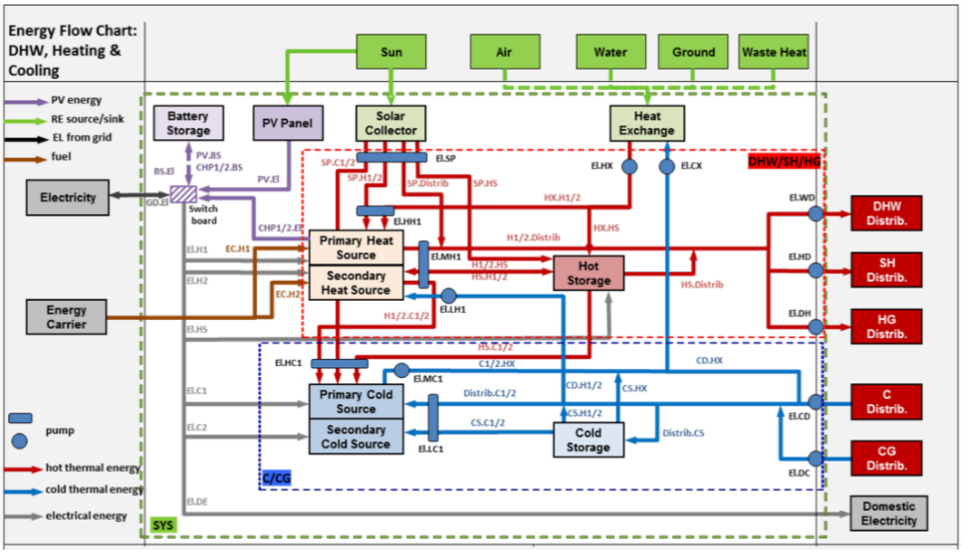


Figure 1: Energy flow chart of the E4 Task Tool

The systems are evaluated according to technical and economic key figures based on energy balances (annual, seasonal or monthly) and can be carried out for the individual subsystems if the data situation permits. The tool has a flexible structure and allows the input of individual parameters, which makes it possible to analyze any configuration of renewable energy integration. The comparison is shown in Figure 2 as a comparison/ratio of the economic (y-axis) to the technical (x-axis) key figures

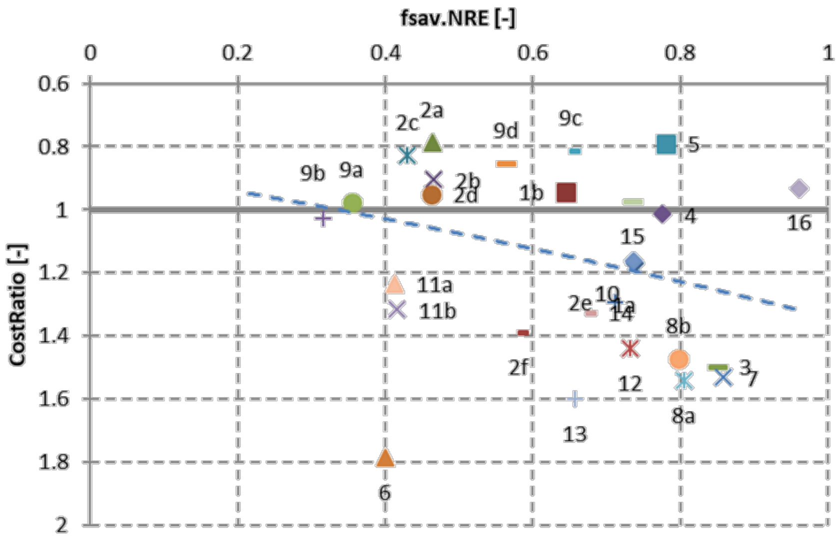


Figure 2: Representation of economic (CostRatio) and environmental (fsav.NRE) results of E4 Task Tool

The tool was expanded primarily with regard to the methodological approach of combined building optimization and adapted solar cooling systems or renewable energy integration:

- Expansion to include the data basis that could be collected through the various projects.
- Expansion to include building optimization and its effects on energy and costs.
- Changed reference system calculation due to changed loads and energy requirements, resulting in effects on investment and operating costs
- If there is insufficient data available for building optimization, the reverse approach can be used and the available funds for a refurbishment that should pay for itself after x years can be calculated.

6.1.1 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 ($PER_{NRE.ref}$).

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

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 $PER_{NRE.ref}$.

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

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.

6.1.2 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 3. 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 T53E4-Tool.

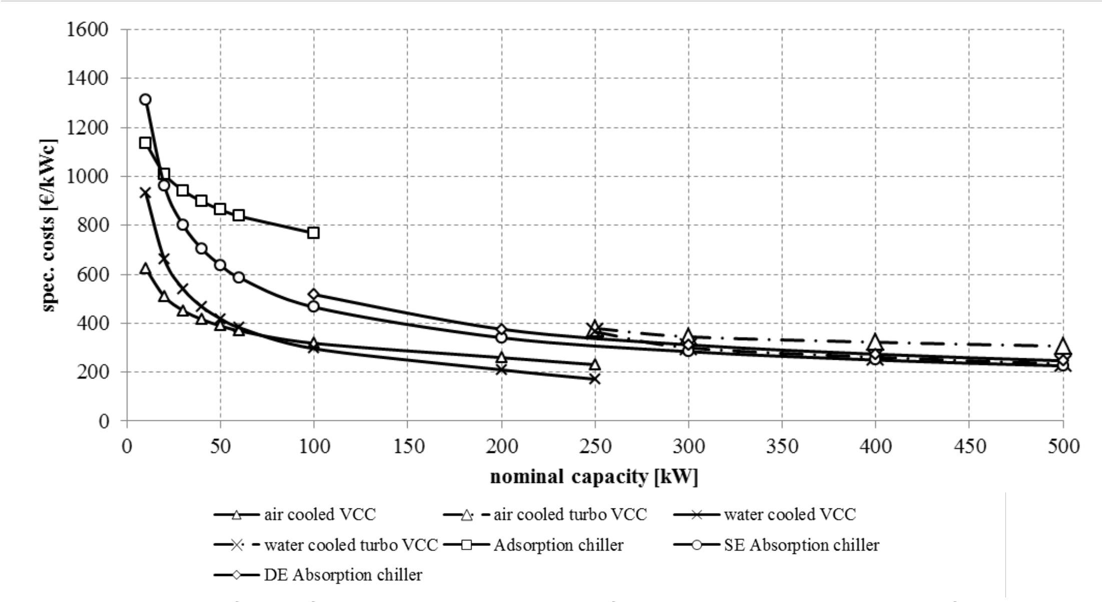


Figure 3: Example of specific investment costs used for T53 standard calculation of investments for thermal and electrical driven chillers (Neyer et al., 2015)

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 1 is showing the prices used for electricity and natural gas.

Table 1: 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 (€/$kWh_{useful\ energy}$) 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 2.

Table 2: 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%

6.2 LCCBA Tool

An existing life cycle cost-benefit analysis (LCCBA) tool was systematically further developed for the specific requirements of modeling solar cooling systems. The adapted LCCBA model is based on a dynamic cash flow model and can take into account the following parameters, among others:

- Technical input and output data of the solar cooling system (either in comparison with a reference system or as a stand-alone production system)
- Revenues from avoided electricity or gas purchases (savings model) or from the sale of cooling (supply model)
- Investment costs (CAPEX) | Variable and fixed operating costs (OPEX) | Replacement investments in the period under review
- Different financing options | Subsidies
- Any price development scenarios
- Variable observation periods of up to 25 years

The existing Excel-Calculation-Tool consists of a variety of spreadsheets. For all projects it is required to enter the input data in spreadsheets 4, 9, 10 and 11. For calculating the economic data for EPC projects, further information has to be entered into spreadsheet 5. If an ESC project is calculated, spreadsheets 6, 7 and 8 have to be filled out. After all the required data is entered, the summary and a forecast are calculated and given in sheets 12 and 13. If the calculated KPIs don't fit the target KPIs further iteration steps have to be performed (Figure 4).

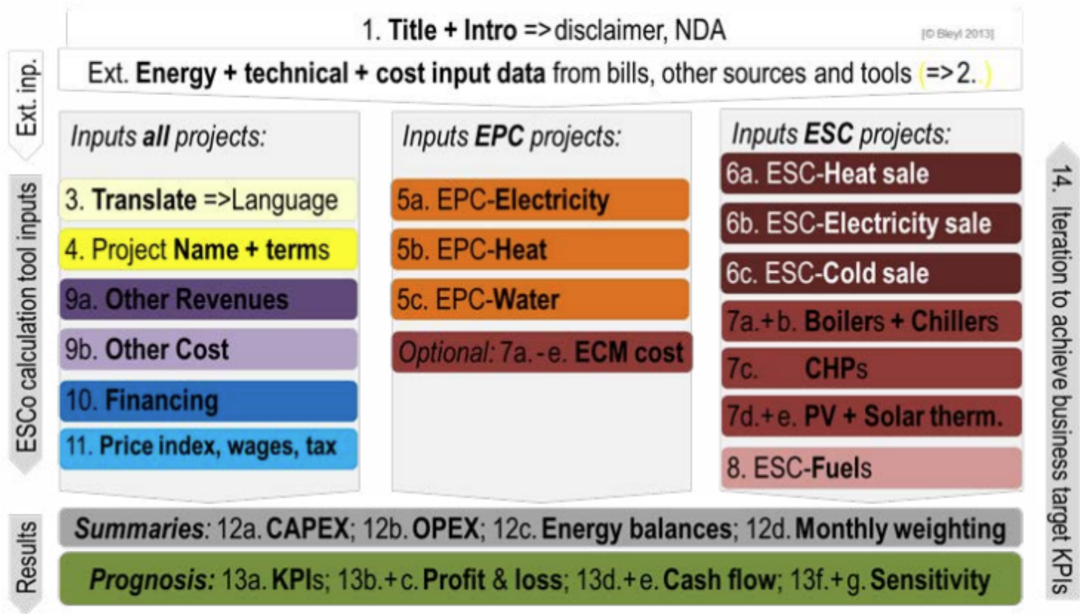


Figure 4: Existing Excel spreadsheet description for EPC projects (GIZ 2015).

This existing tool was adapted accordingly to the needs of solar cooling projects and specifically to projects in IEA SHC Task 65 and its subtask accordingly. Details of the calculation methods can be found online in the mentioned publication (GIZ 2015).

Economic indicators are the internal rate of return (IRR), the net present value (NPV) and a dynamic amortization period, in each case for the project cash flow (P-CF) and the equity cash flow (E-CF). In addition, the concept of the "Levelized Cost of Energy" (LCoE) is applied. On the financing side, the influence of typical debt ratios (e.g. 70%) on equity CF and liquidity is examined using the financial ratios "Cash Flow Available for Debt Service" (CFADS) and "Loan Life Coverage Ratio" (LLCR).

The following Figure explains the calculation scheme for the project and the equity cash flow. The big arrows entering and leaving the project box represent the project cash flow. It is calculated by the following Eq. (7):

$$PCF_y = -I_y + S_y + R_y - C_y \tag{7}$$

where PCFy is the project cash flow, Iy the investments, Sy the disbursed subsidies and Cy the costs, each in year y.

Usually a project is partly financed by debt. Thus the cash flow share of the equity investor (in energy contracting projects the ESCo) is smaller than the project cash flow. In the Figure it is represented by the lower circle. The Eq. (8) for calculation is:

$$ECF_y = PCF_y + DL_y - IDP_y \tag{8}$$

where ECFy is the equity cash flow, DLy the disbursed loans and IDPy the interest and debt payments, each in year y. Hence Eq. (9):

$$ECF_y = -I_y + DL_y + S_y + R_y - C_y - IDP_y \tag{9}$$

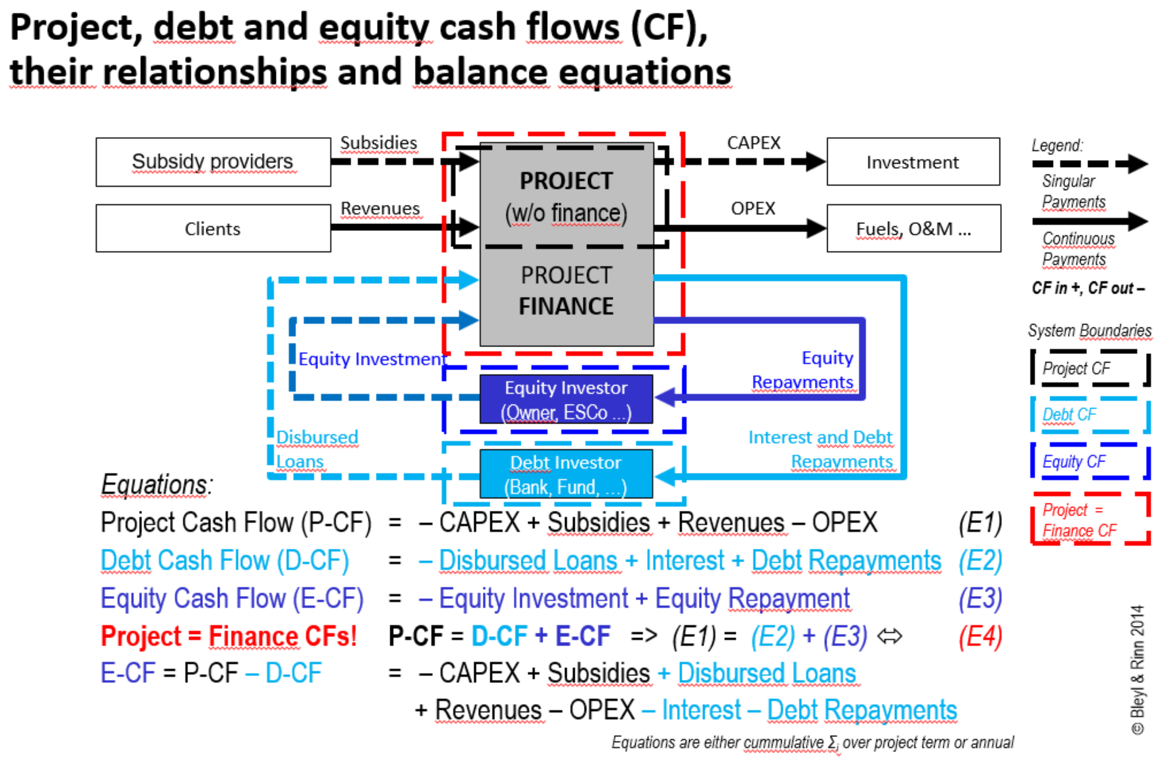


Figure 5: Project cashflow method and main equations (GIZ 2015).

Selected questions that were answered with the tool for specific solar cooling applications:

a. MWh ⇔ EUR: How can technical, highly efficient solar cooling concepts [MWh] be translated into monetary terms [EUR] (and vice-versa)?
b. What are the economic and financial effects of the additional investments for more efficient solar cooling concepts?
c. How do the additional electricity savings affect the business case?
d. What would be the impact of an assumed CO_2 price of 90 EUR/t CO_2?
e. Is the cash flow from the solar cooling project sufficient to service the debt for a 70% loan at an interest rate of 5%?

Over an observation period of 20 years, the Figure 6 shows an example of the project and equity cash flow (annual and cumulative, without CO_2 taxes) of an innovative 'SunBeltChiller' with Fresnel collectors in comparison with a conventional compression refrigeration system and fossil heating.

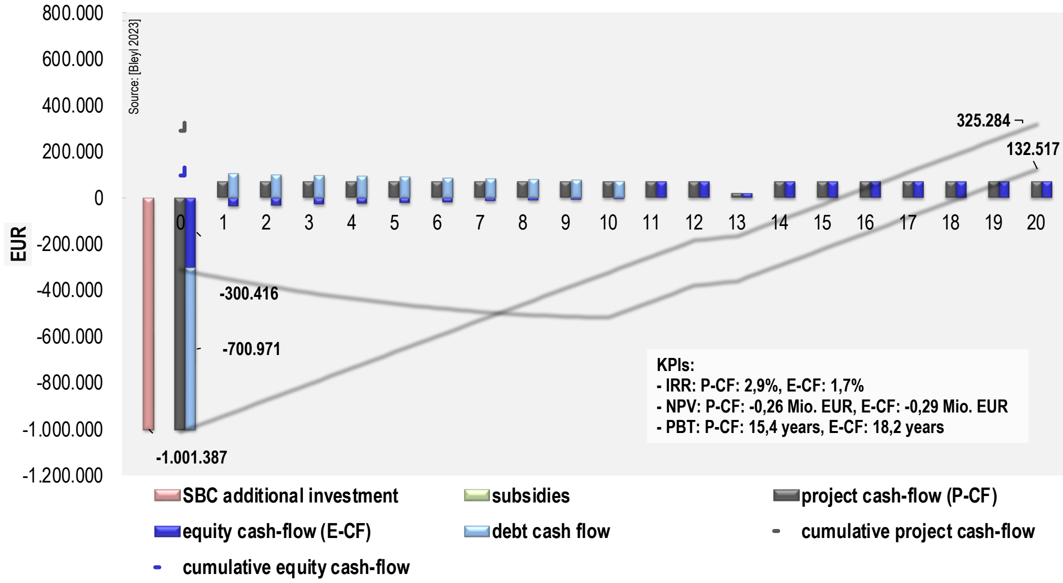


Figure 6: Cashflow representation of the LCCBA Tool

Further applications and results of the LCCBA tool are documented in Subtask C, activity report C4.

Further planned applications of the LCCBA tool in the field of solar cooling systems are

- Strategy development and feasibility assessment.
- Modelling economic efficiency and financing options.
- Production costs of solar cooling generation.
- Business model development (self-direction, ESCo, PPA, pay as you go, ...).
- Variant and scenario evaluation / sensitivities.
- 'What-if' and risk analyses (min/max limits ...).
- Decision-making basis for the implementation of a solar cooling strategy.
- Management and planning support for specific projects or programs.
- Offer negotiations (negotiation targets and scope).

Further developments and applications, especially for calculating the LCCBA tool, are planned in a potential follow-up task "Solar Cooling for the Global South".

6.3 Individual Manufacturer Online Tool

In order to accommodate the need by end users for evaluating the environmental impact and economic feasibility of adopting sustainable cooling technology from PURIX, a simple-to-use assessment tool offers a reliable evaluation and benchmark with baseline systems, i.e. equipment which otherwise would be installed.

Structured and addressing essential parameters such as energy prices, specific GHG-emission for energy, annual cooling demand, coefficient of performance, capital and operational expenditure as well as equipment lifetime, the benchmarking of PURIX vs. a baseline system is at the fingertips of the end users.

In addition, for a high level and easy-to-understand evaluation of the potential for solar cooling at any location across the globe, PURIX offers free access to an on-line tool (https://profiler.purix.com) as a courtesy to solar cooling stakeholders (Figure 7).

Local weather conditions are an essential part for the evaluation the feasibility and environmental impact of any solar cooling application. At PURIX, they decided to publish a simple but powerful and high-level tool, for evaluating the potential for adopting solar cooling technology at any location, applying historical climate data collected from thousands of weather stations across the globe.

Solar cooling installations for the high-volume market segment calls for equipment with low cooling capacities - which can hardly justify time consuming detailed studies and related costs.

Selecting the ambient temperature (in menu) as threshold for requesting cooling, the tool offers a simplified approach to evaluating the number of hours throughout a year, requiring cooling during nights, during daylight hours with sun or without. As a courtesy, and for enabling a more detailed cooling load assessment, hourly weather data can be downloaded for the location of interest.

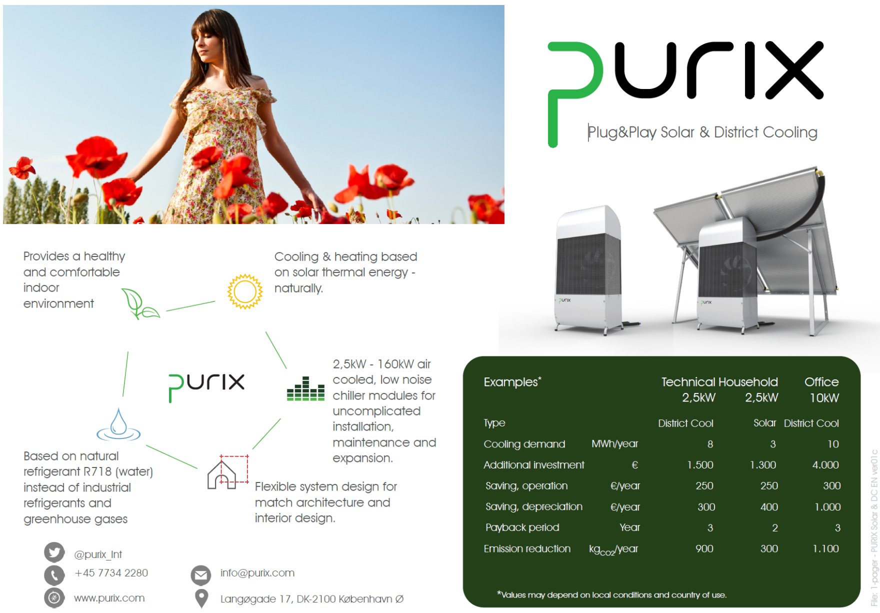


Figure 7: PURIX representation of their plug & play solar & district cooling system

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