IEA SHC Task 49

SolarPACES Annex IV

Solar Process Heat for Production and Advanced Applications

Performance assessment methodology and simulation case studies

Deliverable C.3

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Author: Werner Platzer

Contents

1 IEA Solar Heating and Cooling Programme

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. Its mission is *"to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.*

The members of the IEA SHC collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 57 such projects have been initiated, 47 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45, 55)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56)
- Solar Thermal & PV (Tasks 16, 35)
- Daylighting/Lighting (Tasks 21, 31, 50)
- 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)
- Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are special activities:

- SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding – working agreement with solar thermal trade organizations
- Workshops and seminars

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2 Description of IEA SHC Task 49

Solar Heat for Industrial Processes (SHIP) is currently at the early stages of development. By the end of 2015, the worldwide SHIP-plant database of IEA Task 49 [1] listed around 160 operating systems with a total capacity of about 100 MW_{th} (140,600 m^2). Many of these systems are of experimental nature, and are relatively small scale. On the other side large plants with several thousand square-meters field size exist. This indicates that there is a great potential for market and technological developments expected, as for example 28 % of the overall energy demand in the EU27 countries originates in the industrial sector, majority of this is heat of below 250 °C.

The methodology which has been developed in order to realize thermal energy supply in industry with minimal greenhouse gas emissions is based on a three step approach:

- Technological Optimization of the processes (e.g. increased heat and mass transfer, lower the process temperature) and solar thermal system (e.g. operation of solar field, integration schemes, control, safety issues etc.)
- System Optimization (enhancing energy efficiency using e.g. Pinch Analysis for heat exchanger network for a total production site)
- Integration of renewable energy/solar thermal energy (based on exergetic considerations).

In the last two years the awareness for solar process heat in the industry increased and some new solar thermal systems were installed. This positive development should be supported now by further research and development in the key research questions of solar process heat.

In order to be able to compare different system approaches and projects we needed to develop a performance assessment methodology reaching from the documentation of input assumptions, definition of necessary evaluation criteria to the presentation of results in a defined output sheet. For that a proper definition of subsystems and interfaces has to be given.

Especially the comparison of high-temperature concentrating collector systems and non-concentrating integration schemes possibly using generic study collector types, regions, temperature levels and costs is a current interest. The different fluid and steam networks have to be specified for those cases.

The objectives of Subtask C with relation to the performance assessment are:

• to develop a performance assessment methodology for a comparison and analysis of different applications, collector systems, regional and climatic conditions

• to support future project stake holders by providing design guidelines, simplified fast and easy to handle calculation tools for solar yields and performance assessment

3 Performance assessment methodology

3.1 System boundaries

Performance of a solar system or any other energy conversion system in general is often being considered in a too simplified way. Simple performance indicators or metrics like efficiency are often taken without any description of the operating and application conditions, of the system boundaries considered for its calculation.

The performance of a system however can be described in a broader sense as a concept including energetical, economical and environmental aspects of a system operation for a defined time period. The system boundaries considered should be clearly defined, and the operating conditions according to the application should be specified.

Table 1: Different methods for SPH system assessment with basic characteristics

+++	High
++	Medium
+	Low

	Performance assessment		
	Forecast		Evaluation
	Simulation	Lab test	Monitoring
Complexity	+++	+++	++
Equipment	+	+++	++
Required time	+	++	+++
Accuracy	++	+++	++
Required knowledge about system	+++	+	+
Required knowledge about components	+++	+	+
Suitability for system optimization	+++	+	++
Comparability	+++	+++	+
Repeatability	+++	+++	+
Suitability for labelling	++	+++	+

With such a broad approach it is impossible to provide only one performance figure giving enough information for all aspects. On the other hand a minimum amount of well-defined and broadly applicable performances figures and reporting procedures. The aim is a fair and transparent comparison of different technologies and system concepts, making possible their analysis and optimization.

Depending on the goal of the performance assessment, different system boundaries may be convenient, and the choice of reporting metrics may vary. For example a collector performance may be described by efficiency curve if no application can be specified. However if the application (heat use for a specific industrial process, at a specific location and time period) is known, then this information is not sufficient any more.

Table 2: Performance assessment options and related system boundaries

System boundary	Purpose	Target group
Overall system performance including national energy system	Evaluation of system impact on the energy, economy and environment of a country; overall final and primary energy balance, energy trade, energy safety, emissions to be specified	policy makers, statistical evaluators, funding institutions
Overall system performance for specific application	Energy-, economy- and ecology-related evaluation of the complete local system including energy production (solar thermal, PV) and energy distribution and use in the application (industry or services company level)	planners, users, plant owners, ESCO, funding institutions
Overall solar system performance without detailed application	Energy-, economy- and ecology-related evaluation of the solar thermal system alone with prescribed boundary conditions describing the user (no energy efficiency measures, no consideration of internal distribution system)	planners, solar system and component manufacturers
Performance of each component in the specified solar system	Performance of each unit under real conditions gives information on efficiency, possible optimization and failures	component and subcomponent manufacturers, installers
Performance of each component under standardized conditions	Performance of each unit under standard conditions gives well-defined comparable generalized information on efficiencies without consideration of special application case (e.g. Solar Keymark)	component and subcomponent manufacturers, installers, users

Performance assessment of a system can be in general either a forecast using simulation which is based on certain assumptions of the system and its environment plus relevant characterization of components usually based on testing, or an evaluation of a monitoring campaign using measurement data from real operation of the system. [2]

Performance figures may be given for components as well as for the complete system. In both cases the operating or testinmg conditions have to be described, or referenced. Otherwise misunderstandings and false application of the product may be the case.

Whereas in Subtask A generally the performance of the component „solar collector" is being discussed, in Subtask C we deal with system performance. Here generally we focus on yearly / seasonal performance factors.

3.2 Performance assessment for a solar process heat system

For a system performance assessment of a solar process heating system the system boundaries proposed are excluding the processes in detail. Optimization of processes is not a part of this consideration and performance analysis.

For a solar system supplying heat to a distribution system the boundaries are schematically shown in Figure 1. Here the interface data needed are the supply and return temperature and enthalpy flows of the distribution system supplying the different processes. With this information the heat demand profiles of the complete heating system can be described.

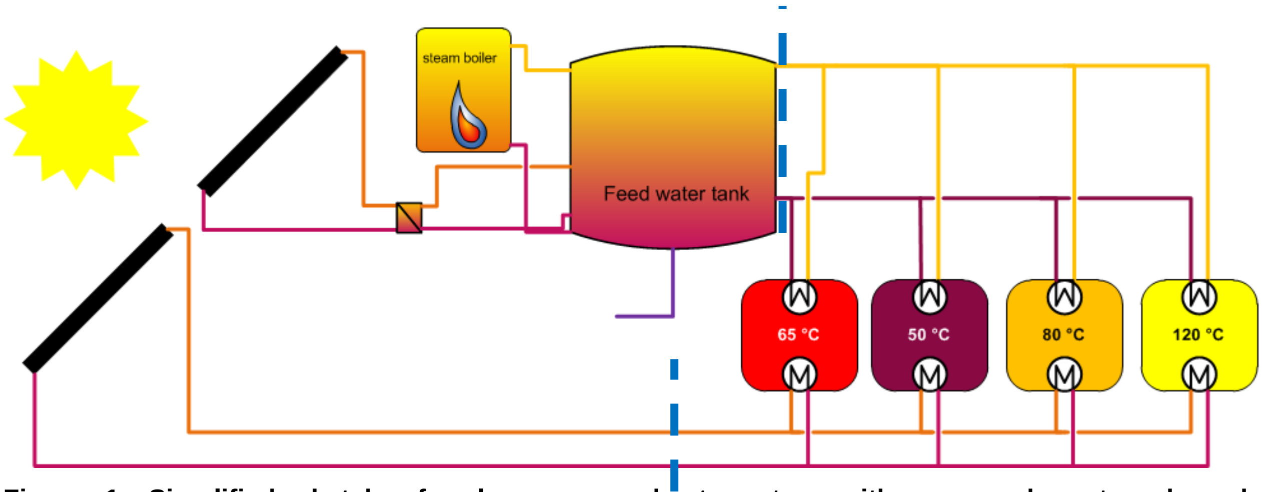

Figure 1: Simplified sketch of solar process heat system with proposed system boundary (blue dashed lines) for supply to distribution system

For a solar system supplying heat to individual processes, the situation would be different. Here the interface data needed are the supply and return temperature and enthalpy flows for the different processes. With this information the heat demand profiles of the considered processes can be described.

The conventional energy supply and storage should be included in the system boundary of the investigated system as storage charging states (temperatures or fill levels) and efficiencies of conventional heat supply components (e.g. of a boiler) may change due to different operation when a solar system is present.

3.3 Performance indicators

3.3.1 Energy performance

For energy performance of a solar thermal system for process heat several criteria have been used in the past. Performance indicators are

Table 3: Energy performance indicators for defined period (e.g. a year)

Performance indicator (metric)	Definition	Discussion
Solar collector field gain Q_{field}	Difference between enthalpy flows between inlet and outlet of solar field	- Only part system - includes no storage and HX losses - inefficiency can be compensated by size
Solar system gain Q_{sys}	Difference between solar heat delivered at system boundary to consumer	- Conventional and solar heat difficult to separate in some cases - Inefficiency can be compensated by size
Solar fraction S_F	Solar system gain divided by load / heat demand	- Inefficiency can be compensated by size
Saved energy Q_{save}	Saved energy delivered from auxiliary system to cover heat demand of consumer	- Efficiency drop in auxiliary system not accounted for
Saved fuel/secondary energy	Savings in fuel or bought electricity with and without installation of solar system	- Not directly measurable; simulation needed - includes possible efficiency changes in auxiliary system
Saved primary energy	Savings in primary energy with and without installation of solar system	- Fair comparion of different energy forms possible (e.g. electricity, gas, ,...) - dependent on energy system in country/region
Utilization factor	Solar system gain related to solar energy incident on aperture of solar collectors	- Gives an indication of system efficiency

All the energy indicators in Table 3 can be made also specific (e.g. per aperture area, or per investment).

In order to be able to compare a solar thermal process heat installation in combination with energy efficiency measures, which is often recommended and also often the case, the suggested energy performance metric for SPH should be based on fuel and electricity consumption for the reference process heat supply

3.3.2 Economic performance

As economic performance indicators (or metrics) many different figures are used in practice depending on the type of investment and financing. In general a combination and critical usage of these figures is important. The following give a short description on the most important indicators:

- amortisation time (statical, dynamical) AT
- internal rate of return IRR
- Levelized cost of energy LCOE
- Cash flow CF
- net present value NPV

Cost categories

In the economic evaluation the cost for the components within a regenerative energy plants and the costs for energy efficiency measures have to be included. This includes not only the pure component or material costs, but the investment costs include as categories the direct investment costs for materials and components, but also the indirect investment costs due to planning and installation which are labour costs.

On top of the investment costs occuring in year one of a new plant (or for a refurbishment) there are annual operation and maintenance costs (which include energy/fuel costs, insurance fees etc.)

For the complete project lifetime the best way to assess the economic impact is to sum up the life cycle cost during the operation of the plant (usually excluding external cost before project start and for destruction and disposal after the plant is stopped).

Performance indicators

Adequate for an investor is the indicator **Net Present Value NPV**, where future capital flows will be discounted to the year of investment. The discounting diminishes the “value” of future capital flows so that alternatively an investment with an expected interest rate equal to the discount rate would yield the same capital flow.

$$C_0(i) = -I + \sum_{t=1}^{T} \frac{Z_t}{(1+i)^t} + L \cdot (1+i)^{-T}$$

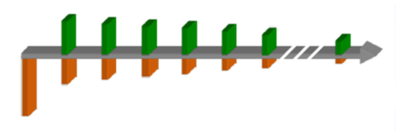

Figure 2: Idealized discounted future capital flows along the time axis

Cash flow and Net Present Value are also indicators for expected profit, but allow also a feedback on the total profits to be made over time. Especially for renewables the ”Golden End” of an investment is important - that is the period where all the profits exceed the initial investment costs or the loan has been paid back, so every kWh of renewable energy just adds to the profit of the owner. For Cash flow CF the annual numbers are not discounted with a discount rate, whereas for the net present value NPV this is actually done.

Adequate for a plant owner who needs a loan from a bank to finance a certain plant is the indicator of **average annual total cost** (based on the annuity method). Here a fixed monthly/yearly cash flow shall serve to pay back a credit with fixed interest rate and period.

$$C_{ann} = C_0 \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - i}$$

Generally one may say the economic performance depends often on the situation. The **amortisation time** is an indicator for a risk. When the time is very long, the prediction is not without problem on both sides - the performance of the plant, the existence of the company and the general economic situation in a country.

The **internal rate of return** serves as an indicator for an investor for the expected profit. It is defined as the discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. One may say that an if an investor has a specific IRR for a project, the discounted profit is the same as if he would have invested his money with the annual fixed interest rate IRR.

The **levelized cost of energy** is a very popular indicator. However for renewables and energy efficiency measures it is not the best metric. The reason is that all the future profits which are extremely large with renewables (see the Golden End) are discounted to very small numbers. Also the future rise in fuel prizes is minimized. For a company owner however this may be very important - changing the risk of future fuel prices against an investment for a certain number of years (the amortisation period) whereas afterwards the company profits are large. Of course this is only valid for sustainable company concepts, not for companies which are only interested in short term profits.

3.3.3 Environmental

Also for environment the figures of merit can be very individual and many options are possible:

- Savings of CO_2-, SO_x, NO_x-emissions and other for life cycle
- Resource consumption of non-replenishable materials
- Life cycle analysis

In principle it is desirable to have a full LCA on the cradle to the grave time line, including all impact categories and allocation methods and the whole life cycle inventory, thus appraising all environmental impact from the winning of raw materials, their transport, the construction and operation to the deposition of waste materials.

In our analysis however we restrict ourselves to the assumed time period of operation of the system. A complete life cycle analysis including the resource consumption due to production and installation of the system, and the recycling or deposition effects on the environment is not within the scope of this paper. Of course these issues may be added for a real project following the standard for LCA [3,4].

An indicator for the positive impact of renewables during operation is the reduced primary energy consumption (making it possible to treat on an equal basis the different energy forms like low-temperature heat and electricity). Generally, the lower the primary energy consumption, the lower the impact on the climate and environment. Of course this is a very coarse metric as the impact of different fuel production and combustion on the environment is not taken into account. Therefore concentrating on the most climate relevant emission in energy systems, the CO_2-emissions, we try to evaluate the performance with this indicator.

3.3.4 Combined criteria

Single factor are most specific and give the most information. A whole number of indicators might be needed to support a well reasoned decision. However due to the complexity an assessment using a single combined indicator might be helpful for non-technical decision makers who do not want to go into the details of engineering on the one side and on financing tools on the other side. Generally a combined indicator might be useful for a quick performance assessment of a plant and first screening of concepts, where a selection of components and dimensioning of plant economy and energy performance is crucial.

One indicator mixing already energy performance and financial performance is the levelized cost of energy indicator, when it deals with the generation of one form of energy (heat, electricity):

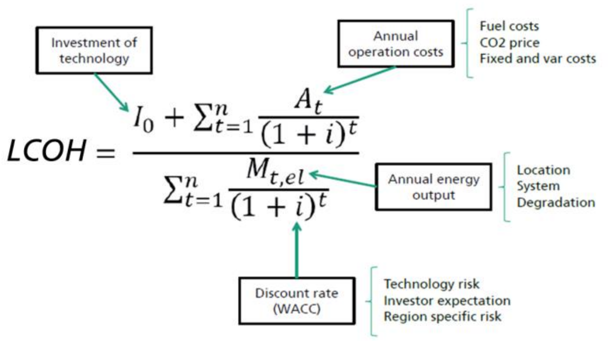

Figure 3: Levelized cost of energy LCOE (either heat LCOH or electricity LCOE)

LCOH/LCOE does not give the full picture on a renewable investment. It systematically rates low the future benefits (the golden end) of a renewable investment, where – after having paid back the investment – a huge benefit waits until the end of the lifetime of the system due to the low operating costs. In conventional investments this specific benefit is less pronounced. The total cash flow therefore should be looked at, being summer up. Therefore we suggest a different indicator for combined performance assessment of Solar Process Heat plants.

There are possibilities to combine different performance indicator to one single number, e.g. environmental perfromance indicators can be added to the economic indicator LCOE by adding the CO2-emissions with a certain weight – the economic value of avoided CO2-emissions. Also different ways to combine economic and energy performance have been proposed [5].

3.3.5 Suggested performance criteria in IEA Task 49

The basic idea here is that we start from **3 main individual indicators** in the areas of **energy**, **economy** and **environment**. It is also possible to derive then a **combined indicator**. As well individual indicators as the combined indicator may be compared to the ones of a standard reference system ("the typical solution"). But on the other hand reference systems have the disadvantage that the "standard" may be very different in various locations and countries. When the standard is already very efficient a renewable and energy efficiency solution may be underestimated. Therefore it is suggested to use the sum of the individual existing process heat demands within the process heat system as reference, and then further relate that to the number of certain production units (say a hectolitre of beer, or a ton of yoghurt, or a ton of metallic copper with purity 99.99%).

The first step – referencing to the **sum of existing process heat demands** - ensures that also energy efficiency measures reducing the fuel and electricity demand of the plant will positively influence the indicator.

The second step – relating that to the **number of production units** - leads even further and establishes a comparison between different production methods also. Introducing a new process intensification step in the production also lowers the heat demand per produced unit and lowers the benchmark for energy use in production.Therefore this step in a natural way leads to **benchmarking**. Let therefore be:

- D=heat demand of installed processes in a factory, a building, …
- EPU=energy demand per production unit

Suggested Performance indicators - referenced to total process heat demand:

Energy performance
-> Primary energy (fuel, electricity) per process heat demand PECD [MWh/MWh]
Financial performance:
-> Levelized cost per process heat demand LCD [€/MWh]
Environmental performance:
-> CO2 emission per process heat demand CO2D [t/MWh]

Combined performance per process heat demand CPD [€/MWh]:
-> CPD = LCD + f_{PE} * PECD + f_{CO2} * CO2D

As the fuel and electricity price is already included in the LCD, we only have to add a cost number for using a lot of primary energy. Using a monetary factor f_{PE} [€/MWh] external costs for high primary energy consumption and a factor f_{CO2} [€/t] appraising the cost of CO2- emissions. Here we might use as a first guess the (momentary too low) price of CO2 certificates.

The use of primary energy in the energy perfromance indicator is motivated in the necessary fair comparison of different energy sources. For example replacing heating energy from a gas boiler by electrical heating may reduce the energy consumption, but – depending on the national electricity production – the electricity might be produced by gas, and due to the efficiency losses of the heat engines and the distribution grid this might be less efficient than the direct buring of gas in the plant. Similarly renewable heating should not lead to high consumption of auxiliary electricity for pumps.

In a second step we relate the different metrics with a factor describing the heat demand per unit produced (a benchmark figure for the industry) to the energy demand per produced unit EPU, leading to indicators PECU, LCU, CO2U and CPU in €/Unit.

Energy performance
-> Primary energy (fuel, electricity) per production unit PECU [MWh/MWh]
Financial performance:
-> Levelized cost) per production unit LCU [€/MWh]
Environmental performance:
-> CO2 emission) per production unit CO2U [t/MWh]

Combined performance) per production unit CPU [€/MWh]:
-> CPD = LCD + f_{PE} * PECD + f_{CO2} * CO2D

4 Procedure for a Total Performance Assessment

A total performance assessment TPA may be done for a planned project in a feasibility study, or it may be performed for an existing and installed plant for real operation. In the latter case experimental monitoring may be used for acquiring the energy data of the plant, and real costs are available for investment and operation. On the other hand it is difficult to compare that to a different case (say without or with improved solar process heat integration and energy efficiency measures). When using simulation and cost estimates one may however include **several scenarios for a comparison of alternatives**, trying to **rank the performance** of those with a combined performance indicator or by weighting individual indicators with a factor and summing up the points in a table.

For both cases we define the following steps to be followed.

STEP 1: Simulate or monitor a SPH-system including energy efficiency measures (EEM) introduced into the plant over a representative year in order to have annual contribution of solar and conventional heating system to total process heat demand in the plant. Also fuel consumption and savings due to the solar thermal system integration should be evaluated

It is not sufficient to estimate annual output of partial systems (collector-loop, thermal energy storage), the whole plant should be included in the analysis including the conventional heat supply.

Within IEA SHC Task 49 within Subtask C simulation case studies have been performed which have yielded results to be used in this step.

The following energy indicators should be presented for each scenario:

- Total annual heat demand Q_{demand}
- Total annual fuel and electricity consumption $Q_{ann,fuel}$ and $Q_{ann,el}$
- Solar and conventional heat fraction to annual heat demand $f_{solar} = 1 - f_{conv}$
- Heat demand per produced unit in the plant $q_{spec,unit}$ (e.g. kWh per hectolitre beer)

STEP 2: Estimate the investment cost and the annual operation and maintenance cost for the plant with (and without) solar thermal process heat (SPH) and energy efficiency measures (EEM). Calculate with the results of STEP1 also the economics of the plant with and without SPH and EEM. Use the metrics your customer is familiar with, but include if possible the following financial indicators

The following financial feasibility indicators should be presented for each scenario:

- Total cost over project lifetime $C_{pd,total}$
- Initial capital cost C_{invest}
- Cost for Business-as-usual $C_{pd,bau}$
- Profit/Savings Incurred $C_{pd,sav}$
- Project IRR
- Net present value (NPV) of project

- Payback period [years] $t_{payback}$
- LCOH of SPH energy over duration of project
- LCOH of plant energy over duration of project

STEP 3: Calculate for the location and country the savings in primary energy PE and CO2. This gives an indicator for environmental performance. Use country-specific primary energy factors for fuel and electricity and CO2-emission.

The following environmental indicators should be presented for each scenario:

- Total annual primary energy consumption PEC_{ann}
- Total annual CO2 emissions due to operation $E_{ann,CO2}$

STEP 4: Calculate a combined performance indicator CPD for each scenario and rank the scenarios. Alternatively weight and rank the individual indicators for each scenario and sum up the points achieved in a ranking table.

STEP 5: Relate the individual performance indicators and the combined one using the benchmark figure of heat demand per produced unit in the company to calculate CPU.

5 Discussion and Example Cases

5.1 Component and system energy performance assessment

In a first step we discuss the difference between a component based performance assessment using Scenocalc and a system based performance. In our simulation case 4a we have a much lower solar yield depending on the demand temperature when we simulate the whole system using the specified demand profile. However when we assume a constant heat demand over all day then we are quite close to the Scenocalc result (Figure 4). The difference between the red and green curve is that for the green curve we have simulated 365 working days, but used the hourly heat demand of the process.

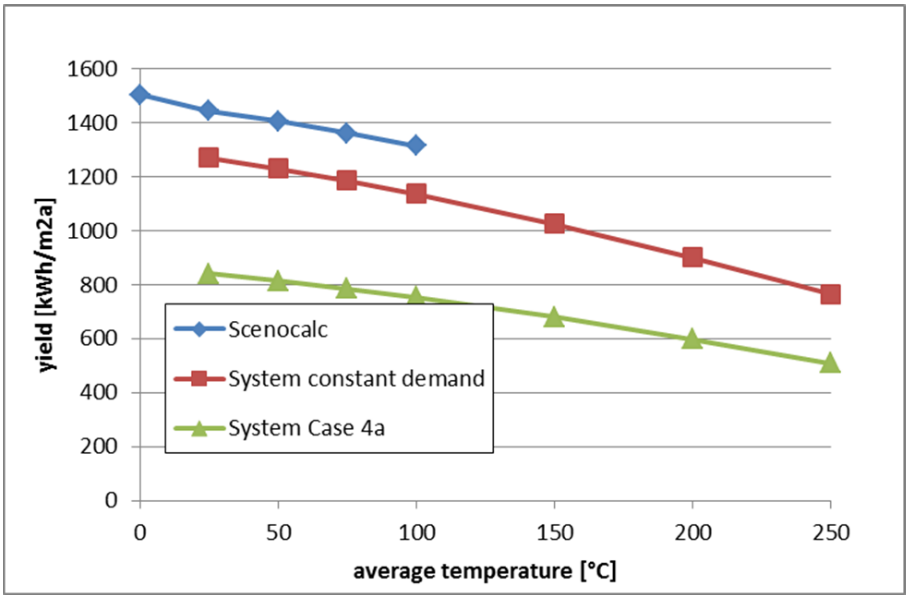

Figure 4: Temperature dependent yields: Scenocalc and Excel (Sevilla, PT-collector)

In Figure 5 one may see that the system yield is even smaller when holidays and weekends are considered, where no production occurs.

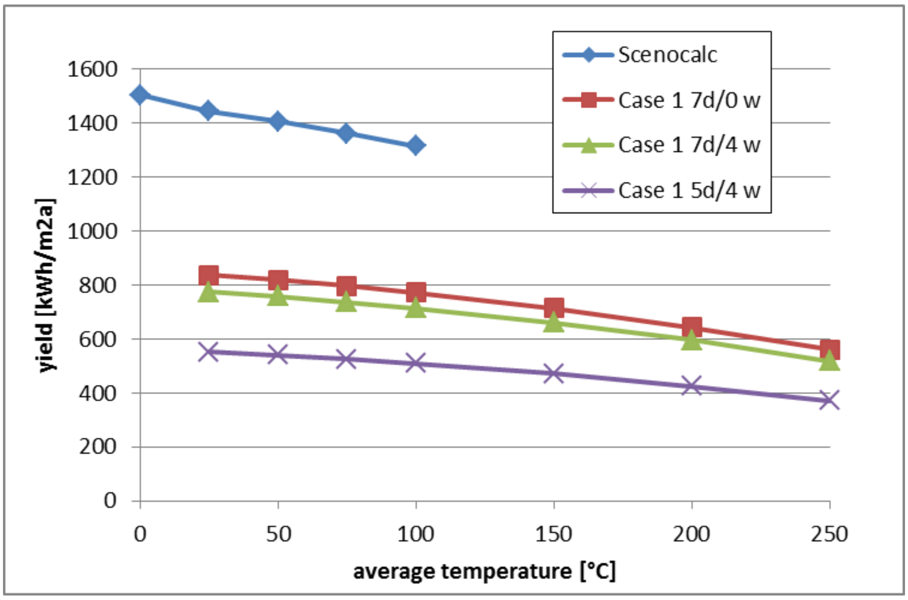

Figure 5: Impact of weekends and holidays

In Figure 6 another effect of system simulation is highlighted. When using a thermal energy storage of sufficient size in the system, heat may be used in the system although the solar collector does not generate the heat when it is needed. Thus the system yield may increase compared to a case without storage.

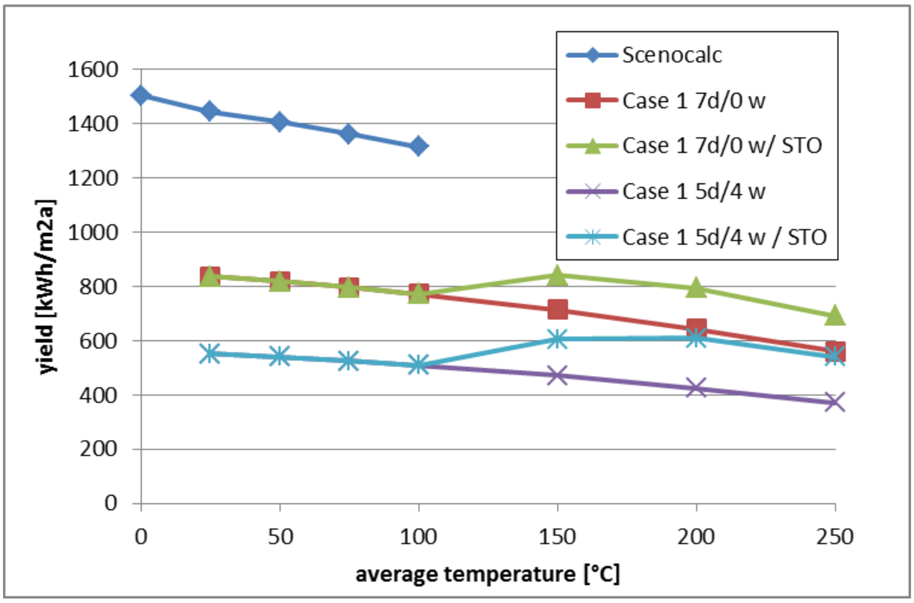

Figure 6: Impact of storage (6h storage)

It is not possible to include effects like that in a simple evaluation tool like Scenocalc where exactly those issues are not to be considered. The only way to include that would be to develop Scenocalc into a - simplified - simulation tool.

5.2 Example of a Total Performance Assessment

In the following we show an example of a **total performance assessment** according to Chapter 2 and 3. The energy performance is taken from Case Study 3.

We assume a company with a total heat demand of 580 MWh heat per year, producing with that a total number of 48000 Units. Case 3 simulates then with the boundary conditions given in (Helmke, Hess, & Platzer, 2013). The resulting solar fraction for the 200 m2 vacuum tube collector field with a 12 m3 storage is 32.6%. For the conventional boiler system we assume 90% efficiency and a fractional electricity consumption of 1%.

Besides the annual energy demand data for fuel and electricity the investment costs for the solar and the non-solar system part has to be specified. The assumed collector field costs were 350 €/m2, the thermal storage costs 800 €/m3 and the remaining balance of plant 1000 € resulting in an investment of 80600 € plus 20% planning and installation indirect costs. The investment costs for the conventional heating system were arbitrarily set at 12000 € plus 20%. This is called the reference case.

The general economical parameters have been set as well and can be seen in Table 4.

Table 4: Economic boundary conditions

Project period	TP	[a]	25
Insurance	d	% p.a.	1.0%
discount rate	dr	% p.a.	7.0%
inflation rate	ir	% p.a.	2.0%
energy inflation rate	ie	% p.a.	2.0%
Operation and maintenance	O&M	% p.a.	1.5%
Indirect cost	C_indirect	[%]	20%
resale value		[€]	0
Fuel prize	c_fuel	[€/MWh]	50 €
Electricity price	c_el	[€/MWh]	250 €

It is possible to individually calculate financial indicators for the two cases, investment of a new conventional boiler system or investment of a solar heating system. Other cases may be also constructed, as investment in a heat pump system, or simultaneous investment in a solar and a conventional heating system. In our case we calculated the comparative version, where the savings of fuel due to the solar thermal system gains are calculated as income over the operation years.

Table 5: Comparison case solar thermal system

Initial capital cost for solar project	[€]	96,720 €
Project period	[a]	25
Total cost over project period	[€]	-161,261 €
Total profit over project period	[€]	364,112 €
Cumulated cash flow over project period	[€]	202,851 €
Cumulated net present value NPV	[€]	79,850 €
Project IRR	[%]	9.39%
Payback period (stat)	[a]	11.66
Payback period (dyn.)	[a]	7.88
LCOH_solar	[€/MWh]	47.53 €
LCOH_plant	[€/MWh]	55.25 €
LCOE_plant	[€/MWh]	57.83 €
levelized annual heat costs	[€]	32,044 €
levelized annual energy costs	[€]	33,541 €

As environmental benefit we calculate a primary energy saving of 226.4 MWh and a reduction of 41 t CO_2/year. As the last step the combined performance is calculated - in this case for reference case and for the solar integration case.

Table 6: Combined performance per heat demand

Performance indicator			Case	Reference
Levelized cost per heat demand	LCD	[€/MWh]	57.83 €	60.05 €
PE consumption per heat demand	PECD	[MWh/MWh]	0.849	1.239
CO2-Emission per heat demand	CO2D	[t/MWh]	0.156	0.227
Combined performance	CPD	[€/MWh]	60.70 €	64.23 €

Then with the value of a specific heat demand of 12.1 kWh heat per produced unit one may calculate the final results in Table 7.

Table 7: Combined performance per production unit

Performance indicator			Case	Reference
Levelized cost per heat demand	LCU	[€/Unit]	4,785.87 €	4,969.84 €
PE consumption per heat demand	PECU	[MWh/Unit]	70.274	102.577
CO2-Emission per heat demand	CO2U	[t/Unit]	12.917	18.786
Combined performance	CPU	[€/Unit]	5,023.30 €	5,315.89 €

In a relatively simpe (financial) number the performance of the two different cases may be seen. In this way different cases and alternative concepts could be evaluated.

6 Conclusion

The main idea and purpose of a total performance assessment TPA is to rank different project alternatives (possibly also including the existing status of the plant) in terms of energy, economical and environmental performance. Although more extensive methods exist taking into account the whole life of a plant (life-cycle analysis LCA), we suggest to use a much simpler approach using the CO_2-emissions due to operation as environmental indicator, which requires no data from often confidential production processes of equipment.

For the combination of energy, ecology and economy a combined performance indicator has been defined, however for ranking also the individual indicators may be used where weighting may be done in a individual way suitable for the project and customer in a ranking matrix.

It is suggested that the indicators are either referenced to the total process heat demand (as determined by calculation or by measurment in the whole process heat system) or by relating the performance to production units (e.g. produced cars in a factory or produced hectolitres of beer) in the factory. It may be used also in non-producing companies using service units e.g. in a laundry or in a car-wash utility. The first reference allows to compare as alternatives completely different approaches to improving the performance of the heat distribution system, including energy efficiency measures like heat recovery or heat storage and renewable generation. The second method also allows a comparison including process intensification, i.e. also measures to reduce the heat consumption of a specific process like drying or washing can be included in the metric. This latter method lends itself in a natural way to benchmarking, as energy or cost per produced unit (service unit) will be calculated for the different alternatives of the project.

7 References

[1] Mauthner F., 2015,"SHIP-plants: Database for applications of solar heat integration in industrial processes," http://www.ship-plants.info/.

[2] Hadorn J. C., 2015. *Solar and Heat Pump Systems for Residential Buildings*, Wiley.

[3] ISO 14040, 2006,"Environmental management - Life cycle assessment - Principles and framework,"

[4] ISO 14044, 2006,"Environmental management - Life cycle assessment - Requirements and guidelines,"

[5] Henning H.-M., 2012. *Energetisch-ökonomische Bewertungsgrößen für solarthermische Anlagen*, Kloster Banz.