Total Performance Assessment Method for Industrial Process Heat Systems

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Abstract

A combined performance indicator is developed for specific renewable energy technology solutions, such as industrial process heat, with the target of being able to compare different technology scenarios including energy efficiency measures and supply options in a fair and transparent way. The combined indicator is a sum where the individual parts are obtained for each scenario from individual energy simulations, economic cost calculations and calculation of CO_2 emissions. The combined performance can be presented as a cost figure in € related to the total heat demand of all processes in the company. This also enables a simple comparison of energy efficiency measures with renewable supply options. Monetarizing energy and environmental performance by giving primary energy consumption external costs and CO_2 emission as prize is a country and company specific task because the structure of fuel and electricity has an impact on emissions and external costs. Finally, the financial results can also be related to a production specific value. This leads to benchmarking and is an easy way to show industrial managers the energy and environmental profile of their products. A fictitious example case is presented also to illustrate the methodology.

Keywords: Solar process heat, performance assessment, decision making, market uptake

1. Introduction

Today's reality is still far from a climate neutral energy supply with 100% renewables. It is well-known that heat plays a decisive role as nearly 50% of the world's final energy demand is needed as heat. While the rapid progress of photovoltaics and wind in the electricity market is supporting the strive for the 1.5 K target in the threatening climate change, in the giant heat sector – 50% of the Total final energy demand TFD - solar heat up to now plays a small role.

One of the biggest theoretical global potentials has solar heat for industrial processes (SHIP), but several barriers inhibit progress in the market. About 85 EJ (22%) of the TFD (377 EJ in 2018) is being used for industrial heat, and more than half for temperatures lower than 400°C (Fig. 1).

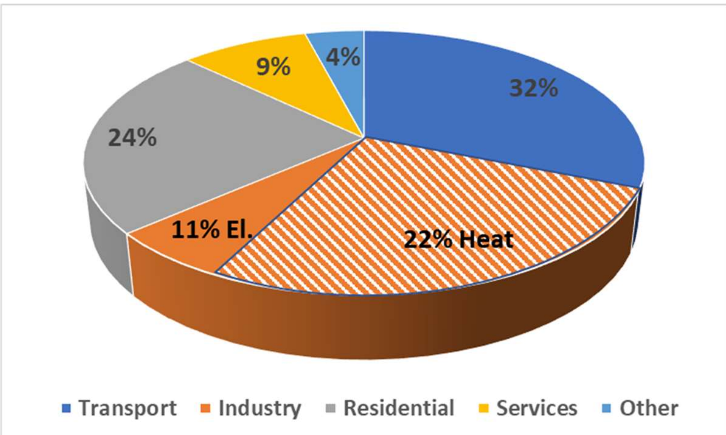

Fig. 1: Global Total Final Energy Demand (TFD) 416 EJ (377 EJ energy supply plus 38 EJ non-energy purposes)

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The complexity in this sector compared to electricity or fuels supplied as final energy is that heat dissipates and mainly must be supplied locally. Although this may favor decentralized solutions on building or district level using solar radiation, alternative solutions e. g. based on the electrical grid are fully conceivable. Other complexities are the required temperature levels of heat, the possibility to replace processes for example in industry using heat by alternative solutions without that requirement, and moreover the reduction of demand by heat recovery and process intensification.

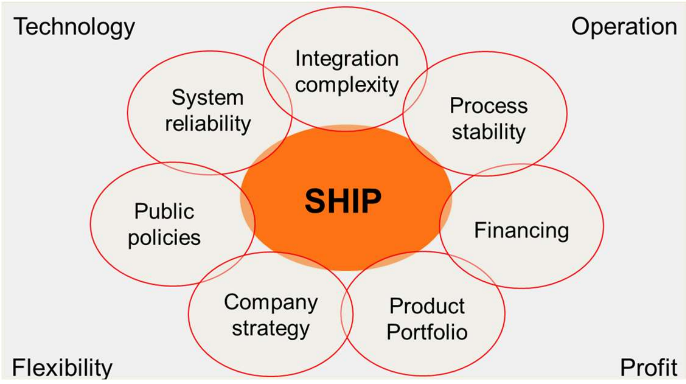

Fig. 2: Risk categories in SHIP projects

Risks in technology selection, industrial production, costs and adaptation to market and policy changes lead to question-marks related to profit (Fig. 2). Perceived risks are barriers to an uptake of a new technology, however also other factors may contribute.

One of the problems that may hinder decision makers in companies when choosing and implementing a solar process heat system is the multitude of approaches to lower energy bills and reduce carbon footprint: energy efficiency measures and a multitude of system solutions from cogeneration via heat pumps to direct electrification of processes.

A fair and integral performance assessment method including energetic, economic and environmental criteria could support a transparent decision process thus helping the implementation of solar process heat systems.

A simple metric to assess the performance of one system against alternatives is not available. Simple approaches as the levelized cost of heat (LCOH) are falling much too short to provide a full assessment. In this article, therefore, the author presents a total performance assessment method that considers energy, financial and environmental performance. The method needs to be applicable for all technological solutions in the sector. It may help to shape rational decisions of investors.

2. Methodology

The scope of the methodology described covers developing an integrated performance assessment method for technological solutions leading possibly to lower fossil energy consumption, lower emission of greenhouse gases (GHG) like CO_2 at reasonable cost. Energy, environment, and economics (EEE) are addressed, but this is only a selection of possible impacts of a technology. Other important factors like impacts on social life, chance equality, creation of jobs, cultural issues, political power, and many more can be included in an evaluation of a technology. However, in this article the scope will be limited, it is not the idea to develop a full political technology impact assessment. We consider only energy, environment, and economics in relation to alternative investments from the perspective of a company, and secondly, only within the operational phase of a system. If the impact of different systems from cradle to grave shall be evaluated, the method lends itself easily to an extension, if the tool for the individual assessment is available.

The objective of the methodology described here is the assessment of a technology solution for a company to cover the process heat demand in an industrial production. Nevertheless, the approach taken can be equally applied to heating of houses, or to electricity supply of consumers or energy for transport solutions. For the methodology described in the following it is important that a specific purpose of the technology is addressed. This provides the reference system. Multiple purpose solutions therefore will be reduced to the contribution for a specific purpose.

The advantage is that the whole chain leading to a specific aim can be investigated and assessed in the full complexity, for example the investment in energy efficiency measures, new energy saving technologies in production, several solar generation technologies and even energy converters like heat-pumps. The disadvantage is that multiple purpose measures like installing a PVT collector which provides hot water for showering and electricity for say charging an electric vehicle cannot yet be covered with this approach.

A further characteristic of a methodology relates to system boundaries. As already described, we focus here on a company site, and will not investigate impacts on district level or even larger entities like regions or states. This would need a thorough discussion of a suitable output of such an entity, which is beyond the limits of this work. Also, in our example the system boundary excludes the detailed processes used in the industry, because we want to avoid the complex topic of process intensification and alternative production technologies. However, we will keep in mind, that the ultimate goal is to integrate even such issues into the overall assessment.

In summary the methodology presented here is an approach which may be extended in future, if more and more integrated views will be needed. The approach taken is a modular one: aspects may be included or not in an appropriate way, but the principles developed here are only exemplary on the basis of

- Primary energy consumption (fossil fuels and electricity) -for energy performance
- CO_2 equivalent emissions during operation for environmental performance
- Levelized costs during the operational lifetime for financial performance

Many individual performance indicators (PI) have been developed and presented for energy, environment and financial feasibility (Kourkoumpas et al. 2018; Ruegg und Short 2007). Energy PI are manifold, and especially for renewables often used metrics are energy payback time, saved energy, solar fraction, saved fuel, efficiency, or utilization factor. Energy management relies on such metrics which have been already been described and classified in the ISO 50006 standard. Environmental PI often not only include the operation of a system but also the full lifetime from cradle to grave. Life cycle analysis LCA is already a fully developed methodology also described in standards: Concerning products, the leading standards for Life Cycle Assessment (LCA) are ISO 14040 and ISO 14044 (ISO 14044; ISO 14040). However, a full LCA is too complex and costly for a comparison of different conceivable investments. To evaluate the measures, the life cycle assessment of all machines and products used to reduce the energy and environmental footprint in a factory would be required. In LCA many inputs are based on averages and not on the actual processes and supply chains. For the moment, therefore, a restricted and limited indicator is used, for example CO_2 equivalent emissions or Global Warming Potential GWP. Financial assessment of renewable energy investments uses indicators like amortization time AT, internal rate of return IRR, net present value NPV, or levelized cost of energy LCOE. The latter is already an example of a combined PI as it relates energy performance to investment and operational costs.

The basic idea here is that we start from **three main individual indicators** in the areas of **energy**, **economy** and **environment**. It is also possible to derive then a **combined indicator** (Henning 2012). Basically, this is done via monetization of the environmental and energy performance using a weighting factor. 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 hectoliter of beer, or a ton of yoghurt, or a ton of metallic copper with purity 99.99%).

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

In the second level – relating that to the **number of production units** – this indicator 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**.

Fig. 3: Approach to a combined performance indicator

The approach to define an integrated total performance indicator not only looking at one aspect but all three factors mentioned is to use a combined PI. Ratio indicators like the LCOH have been proposed to include at least two aspects in an analysis. However how to deal with three (or more) aspects? The solution is the weighted combination of individual PI_k in a combined one:

$$CPI = \sum_{k=1}^{N} f_k \cdot PI_k \qquad \text{(eq. 1)}$$

The weighting factors f_k can be adapted and improved depending on new research or new emphasis on one specific performance. For the specific case of investment in environmentally friendly solutions to provide the heat for industrial processes in a factory three factors are proposed.

Suggested Performance indicators - referenced to total process heat demand D:

Energy performance
-> Primary energy consumption (fuel, electricity) per process heat demand PECD [MWh/MWh]
Financial performance:
-> Levelized cost per process heat demand LCD [€/MWh]
Environmental performance:
-> CO_2 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 need to add a cost number for using a lot of primary energy. We use a monetary factor f_{PE} [€/MWh] representing external costs for high primary energy consumption, and a second monetary factor f_{CO2} [€/t] appraising the cost of CO_2 emissions. Here we might use as a first guess the (momentarily rather low) price of CO_2 certificates.

The use of primary energy in the energy performance 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 burning of gas in the plant. Similarly renewable heating should not lead to high consumption of auxiliary electricity for pumps.

3. Procedure for evaluation

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.

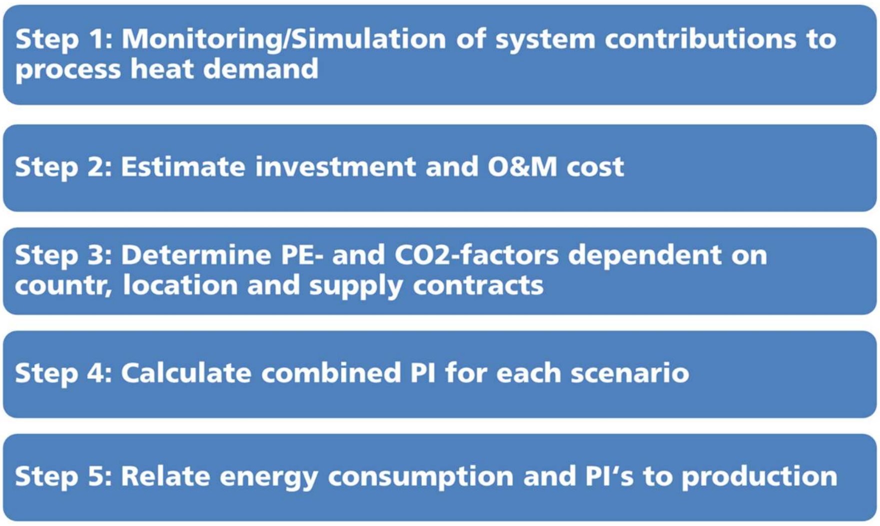

Fig. 4: Steps in the evaluation procedure for the comparative combined performance indicator

In a comparative assessment of two or more cases, the following steps must be performed (the calculation of individual PI is not required):

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

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

The following intermediate energy indicators may be additionally 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 hectoliter beer)

STEP 2: Estimate the investment cost and the annual operation and maintenance cost for the plant with (and without) solar process heat (SPH) and energy efficiency measures (EEM). Calculate using the results of Step 1 also the economics of the plant with and without SPH and EEM. The difference of determining LCD to calculating the Levelized Cost of Heat LCOH is that the cost of a scenario is related to the total process heat demand, not the heat delivered.

Optionally, the following intermediate financial feasibility indicators may be presented additionally for each scenario, using the cost estimations from above:

- 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: Determine for the location and country the savings in primary energy PE and CO_2. This gives an indicator for environmental performance. Use country-specific primary energy factors for fuel and electricity and CO_2 emission. For the PE-factor monetizing the use of primary energies for example externalized costs could be taken which try to assess the costs for the society (health, traffic, environmental consumption) of the use of a specific primary energy source. Here the supply contracts for the company make a difference, for example depending on the source of electricity (green or conventional) different factors should be used. For the greenhouse gas emissions (CO_2-factor) the cost of certificates in a trading scheme could be used. The level of emissions depends very much on the primary energy used.

The following intermediate environmental indicators may be presented for each scenario:

- Total annual primary energy consumption PEC_{ann}
- Total annual CO_2 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.

4. Example case study

In the following I want to describe the fictitious example of a **total performance assessment** for a small dairy company located in Madrid Spain (Fig. 5). The total annual heat demand of the milk processing company is 580 MWh. With that 5550 tons of milk will be processed into diverse milk products. In order to show and demonstrate the applicability of the method, two alternative solutions for covering the heat demand of an industrial plant will be described. As a reference system we have an existing process steam system fed by a gas boiler.

The alternative system is a solar thermal collector system raising the feedwater temperature of the gas boiler. For the conventional boiler system, we assume 90% efficiency and a fractional electricity consumption of 1%. The simulation of the solar thermal system uses the assumptions of an IEA Task 49 study (Case 3) described with the boundary conditions in (Helmke et al. 2013). The resulting solar fraction for the 200 m^2 vacuum tube collector field with a 12 m^3 storage is 32.6%.

Fig. 5: Location Madrid for a fictitious dairy industry

Besides the annual energy demand data for fuel and electricity the investment costs for the solar and the non-solar system part need to be specified. The assumed collector field costs were 350 €/m^2, the thermal storage costs 800 €/m^3 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 Tab. 1.

Tab. 1: Economic boundary conditions

Parameter	Symbol	Unit	Value
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	RV	[€]	0
Fuel prize	c_fuel	[€/MWh]	50 €
Electricity price	c_el	[€/MWh]	250 €

It is possible to individually calculate individual financial indicators for the two cases, investment of a new conventional boiler system or investment of a solar heating system plus new boiler. 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.

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. If we want to give a financial value to these savings in the combined indicator we should assess the factors f_{PE} and F_{CO2} for Spain (see Tab. 2).

Tab. 2: Assumed monetizing factors for Spain ((Leoncini 2013; Bradbury und Dender 2016)

Factor			value
Primary energy	f_{PE}	[€/MWh]	2.28 €
CO_2 emissions	f_{CO2}	[€/ton]	20.00 €

Tab. 3: 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
CO_2-Emission per heat demand	CO2D	[t/MWh]	0.156	0.227
Combined performance	CPD	[€/MWh]	62.88 €	67.42 €

Using the annual production of 5550 tons of milk we find the specific heat demand 105 kWh heat per processed ton of milk. Using that we convert results of Tab. 3 to the final results in Tab. 4.

Tab. 4: Combined performance per production unit

Performance indicator			Case	Reference
Levelized cost per production unit	LCPU	[€/Unit]	6.04 €	6.28 €
PE consumption per production unit	PEPU	[kWh/Unit]	88.6	129.4
CO_2-Emission per production unit	CO2PU	[kg/Unit]	16.3	23.7
Combined performance	CPPU	[€/Unit]	6.57 €	7.05 €

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

5. 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, economic and environmental performance. Decision makers in competitive companies dedicated to green products can thus be assisted using the combined performance to improve their products in all three aspects. Although there are extensive methods that consider the entire life of a plant (life-cycle analysis LCA), we recommend using a much simpler approach using the CO_2 emissions due to operation as environmental indicator, which requires no detailed data from production processes of the product, which often contain confidential information.

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 an individual way in a ranking matrix, suitable for the project and customer. The advantage of the combined indicator is the simplicity and transparency. There are no arbitrary weighting factors included. The indicator could be further developed as an international standard.

It is suggested that the indicators are either referenced to the total process heat demand (as determined by calculation or by measurement in the whole process heat system) or by relating the performance to production units (e. g. produced cars in a factory or produced hectoliters 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 version allows to compare completely different alternative approaches to improving the performance of a heat distribution system, including energy efficiency measures like heat recovery or heat storage and renewable generation. The second version also allows such a comparison even including process intensification, i. e. also when the heat consumption of a specific process like drying or washing is reduced by exchanging machinery. Even the reduced demand of an in dividual process step is reflected in the metric. Therefore, the 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.

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