

AirCow

Solar Air Heating Collector Field
Calculator and Optimizer
for instantaneous Working Points

Manual

Version 3.00

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Nomenclature

Latin letters

A_{coll}	Cross-section area of channel, m ²
A_{field}	Area of collector considered for thermal efficiency model (gross, aperture, absorber), m ²
$A_{syschan}$	Cross-section area of channel, m ²
C_1	Coefficient for temperature dependent heat loss, W/(m ² K)
C_2	Coefficient for quadratic temperature dependent heat loss, W/(m ² K ²)
C_{1max}	Coefficient for temperature dependent heat loss at infinite mass flow, W/(m ² K)
C_{2max}	Coefficient for quadratic temperature dependent heat loss at inf. mass flow, W/(m ² K ²)
C_m	Coefficient for mass flow dependent heat loss, h/kg
$costs_{auxiliary\ electricity}$	Energy price of electricity for auxiliary, cent/(kWh)
$costs_{net\ saved\ costs\ per\ time\ per\ field\ area}$	Net saved costs per time and per field area, W
$costs_{replaced\ energy\ carrier}$	Energy price of replaced energy carrier of conventional system, cent/(kWh)
$f_{p\ auxiliary\ electricity}$	Primary energy factor of electricity for auxiliary, 1
$f_{p\ replaced\ energy\ carrier}$	Primary energy factor of replaced energy carrier of conventional system, 1
$Faktor_{F'_{o,max}}$	Mass flow dependent factor on the collector efficiency factor at infinite mass flow, 1
$G_{b,d_{coll}}$	Beam and diffuse radiation on collector plane, W/m ²
K_{hem}	Incidence angle modifier for irradiance not normal to the collector field plane, 1
$L_{e1,i1}$	Linear coefficient for measured leakage mass flow (e = exit, i = inlet), kg/(h*Pa)
$L_{e2,i2}$	Quadratic coefficient for measured leakage mass flow (e = exit, i = inlet), kg/(h*Pa ²)
$\dot{m}_{i,e}$	Mass flow at field inlet or outlet, kg/h
\dot{m}_{row}	Mass flow of serial collectors in one row, kg/h
$\overline{\dot{m}}_{row}$	Average mass flow of serial collectors in one row, kg/h
$\dot{m}_{rowi,e}$	Mass flow of serial collectors in one row at inlet or outlet, kg/h
$\dot{m}_{coll_{Le,Li}}$	Measured leakage mass flow of one collector not flown through (e = exit, i = inlet), kg/h
$n_{large\ volumes}$	Number of large volumes considered for dynamic pressure losses, 1
p	Pressure, Pa
$P_{fan, electric\ for\ air\ heating\ system}$	Electric power demand of total air heating system, W

$P_{\text{net saved primary power per field area}}$	Net saved primary power per field area, W
$P_{\text{net saved site power per field area}}$	At site boundary net saved power per field area, W
$P_{\text{net saved system power per field area}}$	At system boundary net saved power per field area, W
$p_{\text{sys dyn}}$	Dynamic pressure in channel at outlet into large volume, Pa
\dot{Q}_{field}	Thermal power at field outlet, W
r	Ambrosetti parameter, 1
R_1	Linear pressure drop coefficient, Pa/(kg/h)
R_2	Quadratic pressure drop coefficient, Pa/(kg/h) ²
R_S	Specific gas constant, J/(kgK)
$R_{\text{sys before, after}}$	Quadratic pressure drop coefficient of remaining system before and after field, Pa/(kg/h) ²
\dot{V}_{fan}	Volume flow through fan, m ³ /s
$\dot{V}_{i,e}$	Volume flow at field inlet or outlet, m ³ /h or m ³ /s

Greek letters

Δp_{coll}	Pressure drop per collector, Pa
$\Delta p_{\text{sys before, after}}$	Pressure drop of remaining system before and after field, Pa
ΔT	Difference of mean fluid temperature and ambient temperature, K
$\Delta \eta_{L \text{ field}}$	Efficiency reduction caused by the leakage enthalpy loss at the field, 1
$\Delta \eta_{L \text{ load}}$	Efficiency reduction caused by the leakage enthalpy loss at the load, 1
η	Instantaneous collector efficiency, 1
η_0	Conversion factor, 1
$\eta_{0 \text{ max}}$	Conversion factor at infinite mass flow, 1
η_{fan}	Electro-mechanic-hydraulic efficiency of fan, 1
$\eta_{\text{system replaced}}$	Efficiency for energy conversion of system to replace, 1
θ	Incidence angle on collector surface, °
ϑ_a	Ambient temperature, °C
ϑ_e	Fluid temperature at collector field outlet, °C
ϑ_i	Fluid temperature at collector field inlet, °C
ϑ_m	Mean fluid temperature of collector field, °C
$\rho_{i,e}$	Density of air at field inlet or outlet, kg/m ³

1 Introduction

This Microsoft Excel workbook contains a thermal and hydraulic curve model for covered solar air heating collectors with under-flown absorber. The model considers mass flow dependent thermal efficiency, pressure losses, leakage, system aspects, climate, and incidence angles at instantaneous working points. The model coefficients can be fitted from measurement data or test reports according to DIN EN ISO 9806 [5] or from simulation data within the workbook.

The workbook calculates and optimizes whole solar air heating collector fields, resulting in sets of matching mass flow and air collector field length and field width besides other data. For deeper insight, like for scientific studies, all possible intermediate and final results are visible. It makes fair and repeatable comparison of air collectors possible.

These calculations are further used to convert the coefficients of air collectors including pressure drop and leakage to the three coefficients of the efficiency curve model of liquid heating collectors. These can be used in simulation environments, which contain a liquid heating collector model only, such as ScenoCalc.

In this workbook, also key results are summarized to support system design. Figure 1 gives an overview on the main input and result data and which fields the results benefit. The four main features are described below.

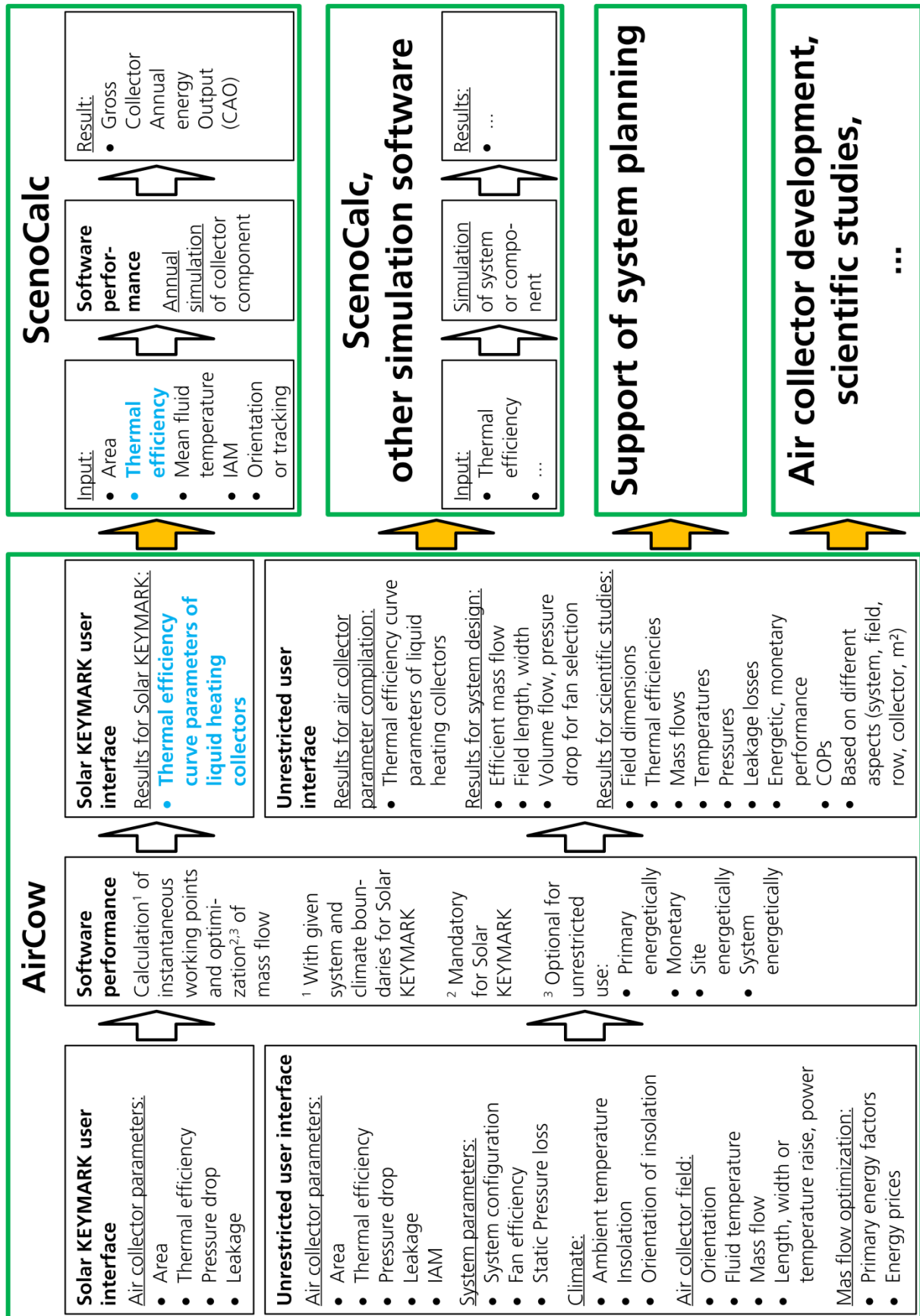


Figure 1: Flow chart of AirCow and its benefiting fields (blue font: manual interface for Solar KEYMARK)

1.1 Features

Pre-calculation for Solar KEYMARK

This workbook performs a pre-calculation of solar air heating collectors for Solar KEYMARK, the quality labeling of solar thermal products in Europe. Data from the collector measurement according to DIN EN ISO 9806 [5] are needed as input. A printable clearly arranged data sheet, which contains the pre-calculation results, is the result. From the input data, the air collector model coefficients are determined automatically. The following pre-calculation considers a system and an instantaneous working point. The coefficients of the air collector modeling will be converted to the coefficients of the efficiency curve model of liquid heating collectors. These coefficients are considered for simulations in the Microsoft Excel workbook ScenoCalc [1] (see blue fond in Figure 1). In ScenoCalc, the Solar KEYMARK benchmark Collector Annual Output, CAO, can be determined at different collector operating temperatures and under weather conditions of different locations. The CAO allows comparing different air collectors fairly. Figure 2 gives an overview on the procedure. For details see chapter 1.3.

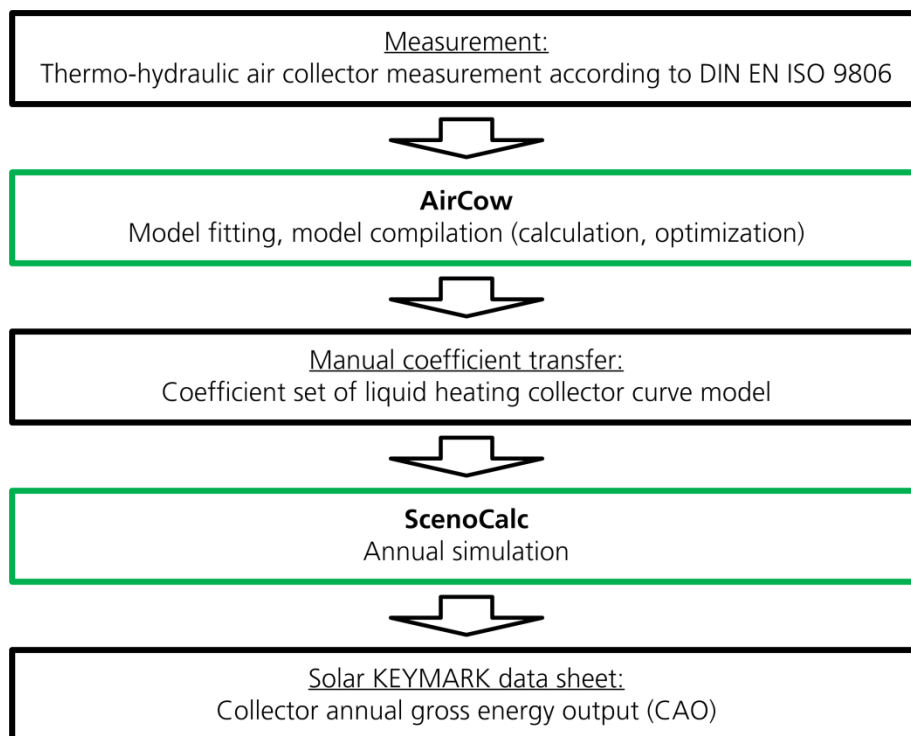


Figure 2: Flow chart for pre-calculation for Solar KEYMARK

Pre-calculations for simulation software

The pre-calculation of the coefficients of the efficiency curve model of liquid heating collectors can be performed with fewer restrictions also. It is possible to vary more than the air collector coefficients, like in the Solar KEYMARK procedure, as there are the system parameters and the climate. For example, the mass flow can be optimized primary energetically, monetarily, site energetically, or system energetically, or it can be given by the user. The resulting efficiency curve model of liquid heating collectors can be used in ScenoCalc or in other simulation software to simulate the component collector or systems. For details see chapter 7.3.6.

System planning

For system planning, the set of mass flow, field length and field width can be optimized for given system aspects. The results volume flow and total pressure rise can be used for fan selection. For instructions, see chapter 6.

Scientific studies

In the end, it can be chosen between different input parameters, e.g. air temperature rise vs. field length, the orientation of the field and the sun can be chosen, and all possible intermediate and final results are arranged clearly. Fair and repeatable comparison of air collectors is possible under different boundary conditions. Since input and results of one case fit one column, and the column can be copied on the worksheet, results of different cases are row-wise easily comparable. The extent of variability and freedom supports scientific studies.

It must be mentioned, that all results of all features are not furnished with a guarantee.

1.2 Model

This chapter explains the model parts and the fit of coefficients. What is considered by the model parts is summarized in the sub chapters too.

The core of the model is the air collector field with its thermal performance, pressure drop, and leakage. Significant aspects of the solar air system and the global system beyond are considered additionally.

The modeling originates from [2,3,4]. The air collector coefficients can be gained from measurements or test reports according to DIN EN ISO 9806 or from simulations. Additional to the standard, the mean ambient pressure during leakage measurement should be given.

If certain coefficients cannot be gained, please see how to deal with that in chapter 4. There, the input and the influence of the coefficients are described, and how to come around or into which restrictions missing coefficients possibly can lead, for example, if the coefficients for leakage or pressure drop are missing.

1.2.1 Thermal model

The thermal efficiency model of air collectors (1) is considered as an efficiency map in contrast to the efficiency curve of liquid heating collectors, because of its two x-values – the reduced temperature difference T^* and the mass flow \dot{m} . It considers the average mass flow of one air collector or one row, while it is sufficient to measure just one air collector. The measurement or simulation points must represent turbulent flow. This model does not fit laminar flow well. The coefficients $\eta_{0,max}$, $c_{1,max}$, $c_{2,max}$ and c_m as well as the valid (measured) mass flow range are needed as input.

$$\eta(\Delta T/G, \dot{m}) = \left(1 - e^{-c_m \cdot \bar{m}_{row}}\right) \cdot \left(\eta_{0,max} - c_{1,max} \cdot T^* - c_{2,max} \cdot G_{b,d_{coll}} \cdot T^{*2}\right) \quad (1)$$

with

$$\bar{m}_{row} = \frac{\dot{m}_{row_i} + \dot{m}_{row_e}}{2} \quad (2)$$

and

$$T^* = \frac{g_m - g_a}{G_{b,d_{coll}}} \quad (3)$$

and

$$g_m = \frac{(g_i + g_e)}{2} \quad (4)$$

The measurement must be performed with different mass flows. Preconditioned air is necessary to realize measurement points on a range of different reduced temperature differences. For this, an inlet channel must be applicable. That means covered air collectors with transpired cover are excluded. Additional information: It was not tested yet, if the thermal efficiency model can be applied to air collectors, which were measured, when soaking in ambient air only. If this will be tried, only ambient air soaking systems can be calculated, where the inlet temperature equals the ambient air temperature and the air collector row length equals the measured length. The coefficients $c_{1,max}$ and $c_{2,max}$ are not expected to represent the heat loss coefficient in this case.

The efficiency model does not consider a wind dependency. Therefore significant wind dependent air collector constructions like uncovered air collectors can be calculated only for single wind speeds, for which data are available. AirCow was not tested with uncovered air collectors. For covered air collectors with over-flown absorbers, this model is not validated either. It was not tested with the small mass flow dependency of liquid heating collectors too.

Summary of applicable air collectors:

- with transparent cover
- with under-flown absorber
- mass flow range with turbulent flow
- measured with preconditioned air

The thermal performance should be measured with the same channel setting before and after the collector like in the pressure drop test. Depending on the flow conditions before and directly after the collector, the measured pressure drop can be very different. For the thermal performance, a similar dependency is expected. The same grade of turbulence and the same flow distribution on parallel flow paths in the collector are necessary in both tests for the fair thermo-hydraulic evaluation within this workbook.

The model calculates steady state situations, since it does not consider a thermal capacity. That implies that evaluations with very low thermal efficiencies (low irradiance or high fluid temperatures), when an air collector field would need a modulating system control, cannot be performed.

For the coefficient determination, a method of minimizing the squared errors, similar to that stated in annex D.3 of DIN EN ISO 9806 [5] is used. Since the method of the standard fits linear models, which are linear with respect to its coefficients, the method is extended to approximate the coefficients of the actual non-linear model iteratively [6] (pp. 799-801).

It is possible to determine the coefficients from measurement or simulation points or from efficiency curves of the model of liquid heating collectors. For the latter, the reduced temperature difference for zero efficiency is calculated in the background for each curve. Efficiency points are calculated for 10 %, 30 %, 50 %, and 70 % of the calculated reduced temperature difference, which are used for fitting.

The standard deviation for the coverage factor $k = 2$ and the confidence level of $p = 95$ % is given on the sheets for fitting. For measured covered flat plate collectors, the experience showed standard deviations of

- $\sigma = 2.0 \dots 3.0$ %-points for the linear fit from measured points,
- $\sigma = 1.6 \dots 3.0$ %-points for the quadratic fit from measured points,
- $\sigma = 0.8 \dots 2.6$ %-points for the linear fit from measured linear curves, and
- $\sigma = 1.3 \dots 3.7$ %-points for the quadratic fit from measured quadratic curves.

The standard deviation from curves can be smaller compared to that from points, if the points scatter much and were smoothed by the curve fitting. It can be bigger, if the calculated reduced temperature differences of 10 %, 30 %, 50 %, and 70 % of the one of zero efficiency differ much from the measured reduced temperature differences. This can be the case for vacuum tube air collectors for example, which are measured only at low reduced temperature differences due to temperature restrictions of the test

facility. Then the curves can diverge at higher non-valid reduced temperature differences and cause a high standard deviation.

The standard deviations mentioned above were from both from data of three indoor and three outdoor measurements. It was not possible to determine, which of both conditions tended to smaller or bigger standard deviations; the standard deviations of both conditions scatter and overlap. If the number of curves or measurement points is increased, the standard deviation will increase too. If data are fitted, which include one laminar mass flow with four reduced temperature differences, the standard deviation easily doubles.

Fitting the coefficients for mode A.

- Enter the coefficients of the linear or quadratic efficiency curves considered for the test report into the blue framed cells.
- Check, whether the iterative optimization did succeed.
- Check the diagrams for plausible graphs.
- Select the linear or quadratic efficiency map model e. g. according to the selection requirements of a first or second order curve by the standard.
- The coefficients and the valid mass flow range will be transferred to the sheet "SK Efficiency Curve" automatically.

Fitting the coefficients for mode B.

- Either enter the coefficients of at least two linear or quadratic efficiency curves for different mass flows, whereas a mixture of linear and quadratic curves is possible,
- or enter physical data with at least two different mass flows and two or three different reduced temperature differences (inlet temperatures, if ambient temperature and radiation are constant) for a linear or a quadratic efficiency map respectively. This needs at least three or four points respectively. All quantities have a positive algebraic sign.
Additional information: The points must be distributed as a grid on the area of a chart with mass flow and reduced temperature difference. The points should not nearly lie on a straight line like $(\dot{m} [\text{kg/h}]; T^* [\text{K}^2/\text{W}]) = (100;0,1); (200;0,2); (300;0,3)$. For an ambient air soaking collector, the points lie on a slightly bended line, for which the model is not validated.
- Check, whether the iterative optimization did succeed. The success-check does not check a sufficient amount of data points.
- Check the diagrams for plausible graphs.
- The given standard deviation considers the difference of the given data and the model.
- Choose the coefficients of the linear or quadratic model and enter them on the sheet "SAHC Calc.+Opt." in the group "Input" – "Solar air collector".
- The valid mass flow range of the efficiency and the pressure drop model is displayed after the coefficients of both models are determined. This range is covered by the ranges of both models. After the coefficients of both models are determined, copy the range onto the sheet "SAHC Calc.+Opt.".

Further coefficients:

The efficiency map model can be related on different collector areas, e.g. gross, aperture, or absorber area. The area considered for the given efficiency curves or the efficiencies of the points must be given for the air collector coefficient A_{coll} .

The incidence angle modifier, IAM, (5) considers the efficiency reduction in the model, if the radiation is not normal to the collector field plane. The IAM is applied as factor of the maximal conversion factor $\eta_{0,max}$. Either the Ambrosetti parameter r or the modifier at an incidence angle of 50° $K_{hem}(50^\circ)$ must be provided as input, if radiation not normal to the field plane will be considered.

$$K_{hem}(\theta) = \tan\left(\frac{\theta}{2}\right)^{\frac{1}{r}} \quad (5)$$

The specific heat capacity of dry air, used for enthalpy flow calculation, is fitted by a quadratic function over a range of 0 °C to 180 °C, under consideration of the mean fluid temperature.

1.2.2 Pressure drop model

The pressure drop of one air collector is considered with the quadratic function (6). The coefficients R_1 and R_2 as well as the valid (measured) mass flow range are needed as input.

$$\Delta p_{coll}(\dot{m}) = R_1 \cdot \dot{m} + R_2 \cdot \dot{m}^2 \quad (6)$$

For a good fitting ability, it is recommended only to use measurement points of turbulent flow covering the entire valid mass flow range of the thermal model. The point (0;0) in the origin does not need to be considered too, as the curve will lead through this point anyway due to the model structure.

Often the pressure drop of the test stand and the connecting ducts is measured within the testing track together with the collector. This additional pressure drop can be subtracted, if the test stand and the connecting ducts are additionally measured without collector.

As mentioned in the previous chapter, the pressure drop should be measured with the same channel setting before and after the collector like in the thermal performance test as a necessary condition for the fair thermo-hydraulic evaluation within this workbook.

Fitting the coefficients for mode A.

- Enter the data points considered for the test report in the second table.
- Check the diagrams for plausible graphs.
- The coefficients and the valid mass flow range will be transferred to the sheet "SK Efficiency Curve" automatically.

Fitting the coefficients for mode B.

- Optionally, enter at least two points of the measurement of the test stand and the connecting ducts without the collector into the first table. The adjusted mass flows and the number of points of the measurements without and with collector do not need to be equal.
- Enter at least two data points of the measurement or simulation of the collector in into the blue framed cells of the second table. All quantities have a positive algebraic sign.
- Check the diagrams for plausible graphs.
- The given standard deviation considers the difference of the given data and the model.
- Copy the coefficients onto the sheet "SAHC Calc.+Opt." in the group "Input" – "Solar air collector".
- The valid mass flow range of the efficiency and the pressure drop model is displayed after the coefficients of both models are determined. This range is covered by the ranges of both models. After the coefficients of both models are determined, copy the range onto the sheet "SAHC Calc.+Opt.".

Additional information:

If only one point is entered, the quadratic coefficient is determined while the linear coefficient is left zero. A graph is shown in the chart only if the point (0;0) is entered too. Since this range covers also the laminar flow, the stated valid range is not correct.

1.2.3 Leakage model

The outward and inward leakage mass flow of one air collector is considered with separate coefficient sets of the quadratic function (7), one set for overpressure and one for underpressure. The measurement must be carried out with a homogeneous pressure distribution, which can be achieved by avoiding the regular mass flow. The outlet of the collector must be closed, and at the inlet constant pressures with the corresponding small mass flows must be provided. The coefficients L_{e1} , L_{e2} , L_{i1} , and L_{i2} are needed as input. To avoid significant extrapolation errors, the valid (measured) pressure range is needed as well.

$$\dot{m}_{coll,Le,Li}(p) = L_{e1,i1} \cdot p + L_{e2,i2} \cdot p^2 \quad (7)$$

Figure 3 shows typical leakage mass flow curves. The thick parts of the curves are the valid ranges fitted from measurement data, the thin parts are extrapolated. The extrapolation of the outward leakage curve of the second example (blue dotted) is continuously increasing and does not show a maximum. It is assumed that this is due to flexible leakage openings, which are pressure dependent and do further open with increasing pressure. The other curves show, that extrapolation will decrease the leakage after the maximum or minimum of the extrapolated model, and that this can lead to unrealistic leakage mass flows even with wrong algebraic sign.

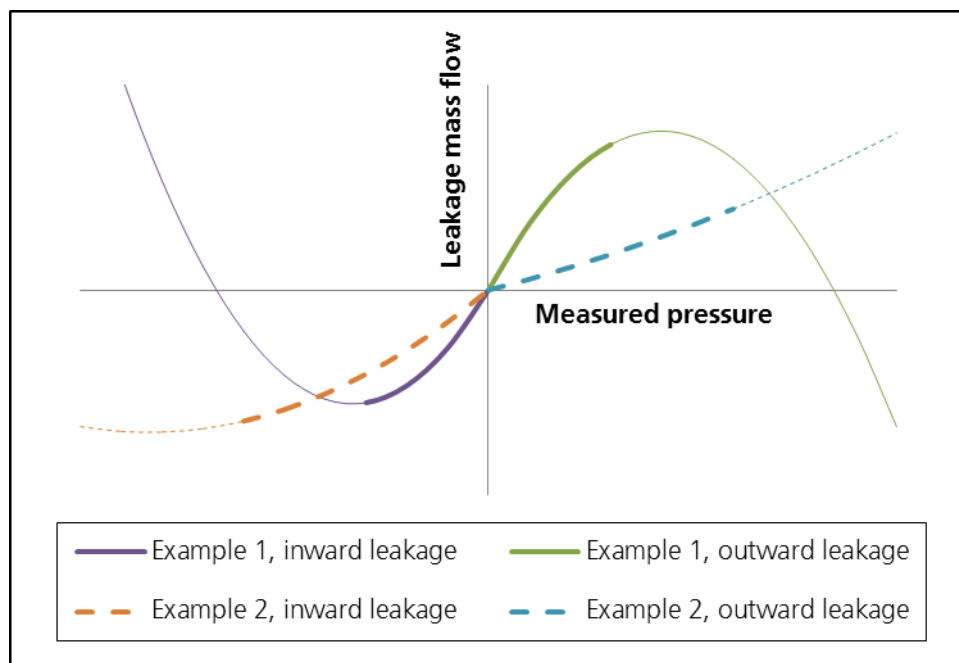


Figure 3: Typical leakage mass flow curves

Measurement or simulation points should range from zero pressure until possible positive or negative pressures. The possible pressures can be estimated by use of the pressure drop model under consideration of the maximum valid mass flow of the efficiency model. The pressure drop of one collector must be multiplied by the number of collectors per row typical for this collector. System components before and after the collector field can raise the field pressure significantly, which should be considered either. The point of zero pressure and zero leakage mass flow does not need to be given. The curves do lead through this point anyway, because the model has no constant term.

It is possible, that the test stand and the connecting ducts show leakage itself, which will be measured together with the collector. This additional leakage can be subtracted, if the test stand and the connecting ducts are measured without collector additionally.

(7) is the basic model used for measurement with a homogeneous pressure distribution and used for fitting the coefficients, whereas this model is further developed for consideration of a practical pressure drop along a field. The complete model in the workbook considers the influence of the pressure

dependent leakage mass flows along the row length on the main mass flow. The pressure drop is calculated from this resulting mass flow. Iteratively, the pressure drop is used for the recalculation of the leakage again and so on, as stated in [4]. In parallel, the optimal mass flow is optimized and the usable thermal efficiency is calculated.

Fitting the coefficients for mode A.

- If the collector is expected not to be leaky, enter "0" in the sheet "SK Efficiency Curve" for the four coefficients and the valid pressure range. Otherwise follow the next points.
- Enter the data points considered for the test report in the third and fourth table.
- Enter the mean air temperature and the mean ambient pressure during the measurement for the conversion of the volume flows into mass flows.
- Check the diagrams for plausible graphs.
- The coefficients and the valid pressure range will be transferred to the sheet "SK Efficiency Curve" automatically.

Fitting the coefficients for mode B.

- Optionally, enter at least two points of the measurement of the test stand and the connecting ducts without the collector into the first and second table. The adjusted pressures and the number of points of the measurements without and with collector do not need to be equal.
- Enter at least two data points of the measurement or simulation of the collector in into the blue framed cells of the third and fourth table. Pressures and flows have positive algebraic signs for overpressure and negative algebraic signs for underpressure in all four tables.
- Check the diagrams for plausible graphs.
- The given standard deviation considers the difference of the given data and the models.
- Copy the coefficients and the pressure constraints onto the sheet "SAHC Calc.+Opt." in the group "Input" – "Solar air collector".

Additional information:

If only one point is entered, the quadratic coefficient is determined while the linear coefficient is left zero. Purely quadratic trends are generally not to expect. The examples in Figure 3 are far from purely quadratic trends too. Coefficients from only one point should not be used.

1.2.4 System model

For the system, the pressure drops before and after the field, the dynamic pressure, and the volume flow through the fan is considered. Heat losses of the system outside the field are not taken into account, except the load leakage if chosen (see chapter 4.4.2).

For the pressure drops before and after the field (8), the flow resistances $R_{sys,before}$ and $R_{sys,after}$ must be given.

$$\Delta p_{sys\ before,after} (\dot{V}) = R_{sys\ before,after} \cdot \dot{V}_{i,e}^2 \quad (8)$$

If the flow resistance values are not available for the system components, but if experience values of pressure drop with the corresponding volume flow are at hand, the flow resistance can be calculated by rearranging (8) with

$$R_{sys\ before,after} = \frac{\Delta p_{sys\ before,after}}{\dot{V}_{i,e}^2} \quad (9)$$

The dynamic pressure (10) considers the flow velocity, whereas either the diameter or the side length of a circular or square channel cross-section can be given. The dynamic pressure is taken into account, if the air flow velocity gets lost by flowing into a large volume. If it flows into several large volumes in series, the dynamic pressure loss multiplies with the number of large volumes.

$$p_{sys\ dyn}(\dot{V}) = n_{large\ volumes} \cdot \frac{\rho_e}{2} \cdot \left(\frac{\dot{V}_e}{A_{sys\ chan}} \right)^2 \quad (10)$$

The volume flow is calculated from the mass flow by (11) with the individual properties at the relevant positions.

$$\dot{V}_{i,e} = \frac{\dot{m}_{i,e}}{\rho_{i,e}} \quad (11)$$

The air density is calculated by (12) for a pressure of 100'000 Pa and a specific gas constant for dry air of 287 J/(kgK). Depending on the situation, the absolute inlet or outlet temperature is considered.

$$\rho_{i,e} = \frac{p}{R_s \cdot T_{i,e}} \quad (12)$$

The site energy auxiliary demand of the fan (13) is received by use of the pressure drop of field and remaining system, the volume flow, the electro-hydraulic fan efficiency, and if applicable the dynamic pressure. If chosen, the primary energy factor or the energy price is applied on this. (13) is considered for the mass flow optimization together with the thermal energy saving in (14) to (17).

$$P_{fan, electric\ for\ air\ heating\ system} = (\Delta p_{sys\ before} + \Delta p_{sys\ after} + p_{sys\ dyn} + \Delta p_{coll}) \cdot \dot{V}_{fan} / \eta_{fan} \quad (13)$$

Further, the position of the fan and whether the load is leaky or not determine the pressure in the field. The field has overpressure with a pressing fan before the field and underpressure with a soaking fan after the field for open loops and for closed loops with a leaky load. The leaking field has over- and underpressure, if the load is air-tight in a closed loop.

The system can be a closed or an open loop. This depends on, whether or not the ambient temperature equals the inlet temperature and whether the field has over- and underpressure because of an air-tight load.

Summary of considered system aspects:

- pressure drop before and after the air collector field
- pressure drop of field
- dynamic pressure
- fan efficiency
- hydraulic system configurations leading to air collector fields with
 - overpressure
 - underpressure
 - over- and underpressure
- closed or open loop (indirectly considered)

1.2.5 Mass flow optimization

The energetic and monetary mass flow optimization is for solar air heating systems, which have both, fans run by external energy, like electricity from the main grid, and a conventional heating system in parallel, which heating energy is to replace. The solar air heating system should be separate off other possible air systems of the same load. Other system possibilities are discussed at the end of chapter 4.4.6.

Besides the detailed thermo-hydraulic air collector field model, the global system shown in Figure 4 is considered for the mass flow optimization. This includes the way of primary energy to the site of use represented by primary energy factors or energy prices and includes the energy conversion of the conventional heating system of the replaced thermal energy represented by its thermal efficiency. Since the thermal efficiency of the air collector field strongly depends on the mass flow, the flow resistance of the remaining air heating system components is calculated into a pressure drop, which is considered with the dynamic pressure loss and a constant value for the fan efficiency. Thermal losses of the remaining air heating system components are not considered, whereas the thermal losses and pumping energy for the remaining conventional system after the energy conversion are not considered also. The pumps may run anyway, if the solar air heating system does not replace the conventional heating system completely.

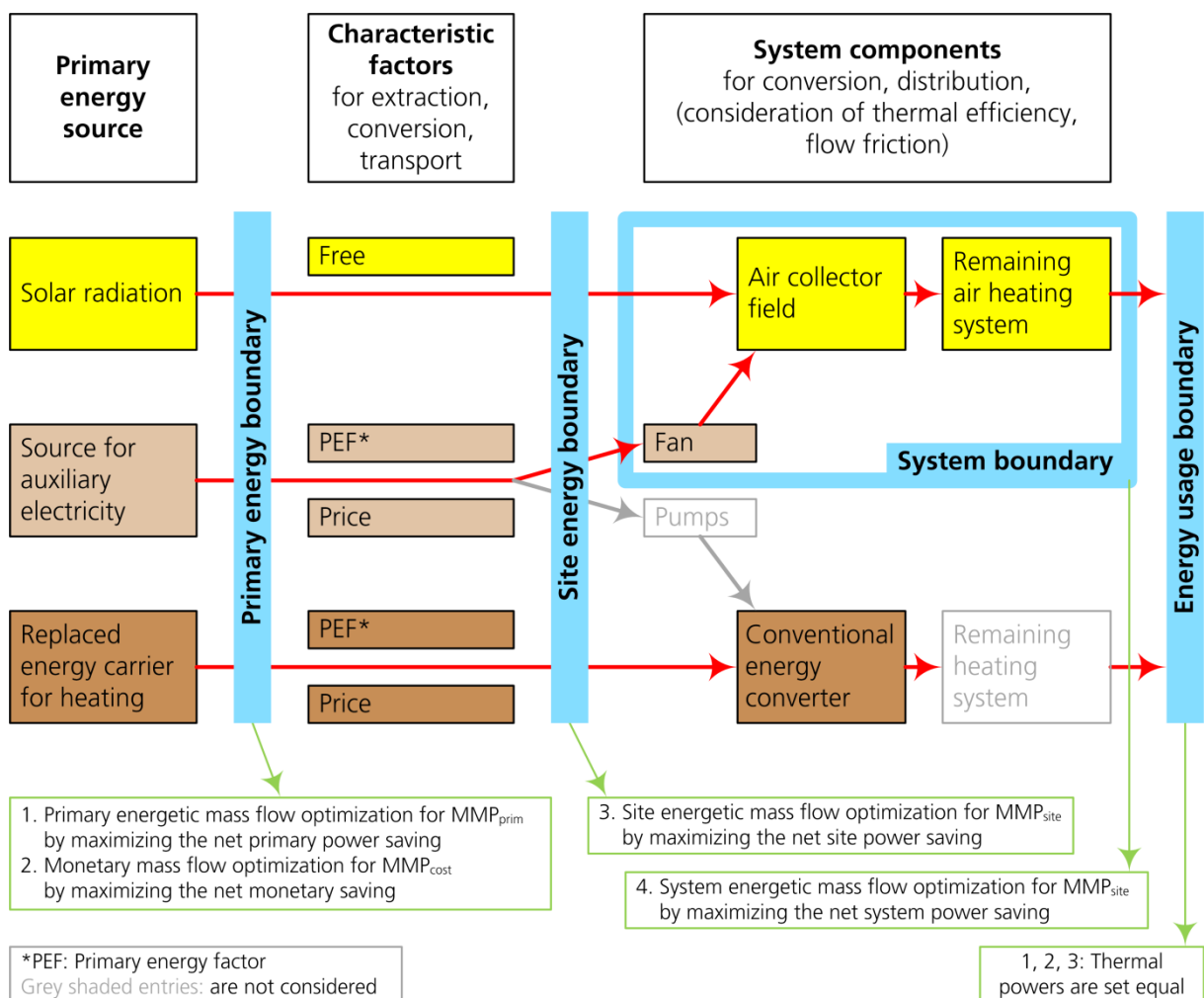


Figure 4: Mass flow optimization for air collector fields within the global system context

The mass flow optimization procedure will maximize the saved power or money, whereas the auxiliary demand is withdrawn as penalty. The global model is sufficient to perform an ecologic or economic mass flow optimization by use of the powers at the primary energy boundary using the primary energy factors in (14) or the energy prices in (15) respectively (1, 2 in Figure 4). By use of the powers at the site energy boundary in (16) and the system boundary in (17), the mass flow can be optimized too, if this seems to make sense (3, 4 in Figure 4).

For the kinds of optimization 1, 2, and 3 in Figure 4, the thermal efficiency of the conventional energy converter is considered, and the replaced thermal energy of the conventional energy converter is set equal with the thermal energy output of the field. For the system energetic optimization 4 in Figure 4, only the powers entering or leaving the air heating system are considered. These optimization methods do not consider the special behavior of all possible loads like drying, heat pump, or cooling. There is one exception for all kinds of optimization, if the field with overpressure is chosen, because the leakage losses of the load induced by field leakage can be considered optionally (not shown in Figure 4).

$$P_{\text{net saved primary power per field area}} = \dot{Q}_{\text{field}} \cdot \frac{f_{\text{p replaced energy carrier}}}{A_{\text{field}} \cdot \eta_{\text{system replaced}}} - P_{\text{fan, electric for air heating system}} \cdot \frac{f_{\text{p auxiliary electricity}}}{A_{\text{field}}} \quad (14)$$

$$\text{costs}_{\text{net saved costs per time per field area}} = \dot{Q}_{\text{field}} \cdot \frac{\text{costs}_{\text{replaced energy carrier}}}{A_{\text{field}} \cdot \eta_{\text{system replaced}}} - P_{\text{fan, electric for air heating system}} \cdot \frac{\text{costs}_{\text{auxiliary electricity}}}{A_{\text{field}}} \quad (15)$$

$$P_{\text{net saved site power per field area}} = \dot{Q}_{\text{field}} \cdot \frac{1}{A_{\text{field}} \cdot \eta_{\text{system replaced}}} - P_{\text{fan, electric for air heating system}} \cdot \frac{1}{A_{\text{field}}} \quad (16)$$

$$P_{\text{net saved system power per field area}} = \dot{Q}_{\text{field}} \cdot \frac{1}{A_{\text{field}}} - P_{\text{fan, electric for air heating system}} \cdot \frac{1}{A_{\text{field}}} \quad (17)$$

The maximization functions are related to the field area. Otherwise and depending on the given field parameters, it can lead to a small mass flow per row, because the accompanying low pressure drop would need a small auxiliary demand.

Depending on the chosen kind of optimization, the efficient mass flow per row can be called as:

- **Mass flow per row of Maximum net primary Power saving**, MMP_{prim}
- **Mass flow per row of Maximum net cost saving per time by Power**, MMP_{cost}
- **Mass flow per row of Maximum net site Power saving**, MMP_{site}
- **Mass flow per row of Maximum net system Power saving**, MMP_{sys}

The values of the maximization functions can be used as evaluation criterions besides of thermal efficiency, auxiliary power and coefficient of performance.

Summary of considerations for mass flow optimization:

- primary energy factors or energy prices (as constants)
- thermal efficiency of conventional energy conversion for replaced thermal energy (as a constant)
- flow resistance of remaining air heating system (as a constant)
- fan efficiency (as a constant)

- leakage losses at load induced by field with overpressure (optionally)
- kinds of optimization: primary energetic, monetary, site energetic, system energetic

1.3 System requirements

The workbook was developed on Microsoft Excel 2010 (version 14.0) and Microsoft Visual Basic for Applications 7.0. These versions should be used for evaluations.

It may be possible to run the tool with other versions also. It was tested running but not validated on Microsoft Excel 2013 (version 15.0) and Microsoft Visual Basic for Applications 7.1 too.

Excel on Mac OS is currently not supported.

2 Solar KEYMARK Certificate Pre-Calculation

The Solar KEYMARK certification is a quality labeling of solar thermal products in Europe. For solar collectors, it requires the evaluation criterion Collector Annual Output, CAO, as results of collector simulations in the Microsoft Excel file ScenoCalc. The CAO is simulated for a matrix of different climates and mean fluid temperatures.

ScenoCalc is based on the thermal efficiency curve model of liquid heating collectors but does neither consider the mass flow dependency of the efficiency, nor the leakage and the pressure drop of air collectors. The air collector modeling of AirCow is arranged to convert these characteristics into the thermal efficiency curve model in ScenoCalc as pre-calculation step. The modeling considers covered air collectors with under-flown absorber, which are measured with preconditioned air. The Solar KEYMARK pre-calculation allows air collectors, which can be connected serially and in parallel.

To prepare for the pre-calculation, the air collectors must be measured according to DIN EN ISO 9806. The data for the test report are nearly sufficient to fit the models (1), (6), and (7) of chapter 1.2 for getting the necessary air collector coefficients. Additionally, the ambient pressure during the leakage measurement is necessary to convert the volume flow to mass flow. Figure 5 shows the section with the necessary set of coefficients and valid ranges of the data sheet of AirCow for the Solar KEYMARK pre-calculation.

Model coefficients of solar air heating collector (Input):

Gross area	A_{coll}	m ²	2.222
Conversion factor	$\eta_{0,\text{max}}$	-	0.777
Linear heat loss coefficient	$c_{1,\text{max}}$	W/(m ² K)	7.77
Quadratic heat loss coefficient	$c_{2,\text{max}}$	W/(m ² K ²)	0.00777
Mass flow dependend heat loss coefficient	c_m	h/kg	0.00777
Linear pressure drop coefficient	R_1	Pa/(kg/h)	1.11E-03
Quadratic pressure drop coefficient	R_2	Pa/(kg/h) ²	1.33E-05
Linear outward leakage coefficient	L_{e1}	kg/(h·Pa)	3.50E-02
Quadratic outward leakage coefficient	L_{e2}	kg/(h·Pa ²)	-7.00E-06
Linear inward leakage coefficient	L_{i1}	kg/(h·Pa)	3.50E-02
Quadratic inward leakage coefficient	L_{i2}	kg/(h·Pa ²)	7.00E-06
Minimum valid mass flow for efficiency and pressure drop coefficients	\dot{m}_{min}	kg/h	250
Maximum valid mass flow for efficiency and pressure drop coefficients	\dot{m}_{max}	kg/h	2500
Minimum valid pressure for leakage coefficients	p_{min}	Pa	-2500
Maximum valid pressure for leakage coefficients	p_{max}	Pa	2500

Figure 5: Air collector coefficients (example) and units for Solar KEYMARK certificate pre-calculation

Below that section, the AirCow SK data sheet displays the boundary conditions, which are used for the calculation and optimization (Figure 6).

Boundary conditions of air collector field

Useful power	\dot{Q}_e	W	10000
Temperature rise	ΔT_{rise}	K	25.0
Mean fluid temperature of field	ϑ_m	°C	32.5

Boundary conditions by system

Hydraulic system configuration	Closed loop, field with underpressure		
Flow resistance before air collector field	$R_{sys,before}$	Pa/(m ³ /h) ²	0.000040
Flow resistance after air collector field	$R_{sys,after}$	Pa/(m ³ /h) ²	0.000040
Diameter at channel outlet into heating space	d_{chan}	mm	300
Fan efficiency	η_{fan}	%	57.2
Primary energy factor of electrical energy	$f_{p,aux}$	-	3.0
Primary energy factor of replaced thermal energy	$f_{p,therm}$	-	1.1
Efficiency of system to replace	$\eta_{sys,repl}$	%	90

Boundary conditions by climate

Global irradiance normal on collector plane	$G_{b,d,coll}$	W/m ²	1000
Ambient temperature	ϑ_a	°C	10

Figure 6: Considered boundary conditions

If you open the file, a warning about circular references may appear depending on the setting of previously opened Excel files. The warning can be ignored and closed.

The procedure is quite simple:

1. Press button A. for the appropriate feature.
2. Drop the data into the provided spreadsheets. Follow the steps listed under the sub headlines "Fitting the coefficients for mode A." in chapter 1.2. The fitted coefficients and the valid model ranges will be transferred to the AirCow SK data sheet automatically.
3. Enter the gross area and informative text data in the cells with blue fond in the AirCow SK data sheet.
4. Execute the button "Perform Calculation".
5. Read out the three coefficients of the thermal efficiency curve for liquid heating collectors (Figure 7) to continue with ScenoCalc simulations for the CAO.
6. The result document can be printed, if needed.

Results (coefficients of liquid heating collector model and further values for SK sheet in ScenoCalc):

Conversion factor including leakage	$\eta_{0,L}$	-	0.7714
Linear heat loss coefficient	c_1	W/(m ² K)	7.746
Quadratic heat loss coefficient	c_2	W/(m ² K ²)	0.007746
Efficient mass flow per row in relation to row gross area	$\dot{m}_{e,opt,spec,row}$	kg/(sm ²)	0.024
Efficient mass flow per row in relation to collector gross area	$\dot{m}_{e,opt,spec,coll}$	kg/(sm ²)	0.094
Mean fluid temperature at zero efficiency ($G = 1000 \text{ W/m}^2, \vartheta_a = 30 \text{ °C}$)	$\vartheta_m(\eta=0)$	°C	121

Figure 7: Collector coefficients to use in ScenoCalc

The results include the optimized mass flow per row at the row outlet also, which are in respect to the gross area of either one row or one air collector. At the time, it is not sure, which value should be taken for the Solar KEYMARK sheet in ScenoCalc.

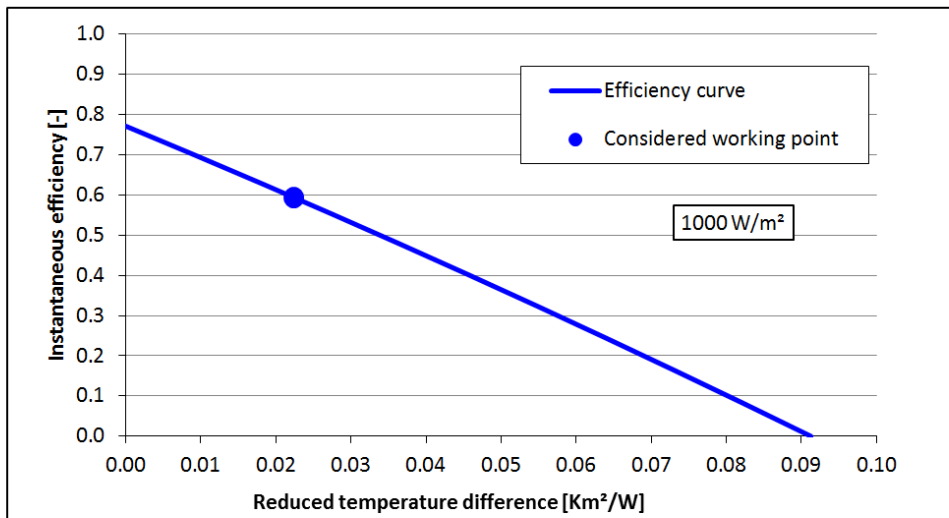
In respect to the gross area of one row, the specific mass flow does vary only little for different air collectors, because the mass flow depends mainly on the temperature rise equally given for the optimization. It depends little on the efficiency, but not on the pressure drop, and the leakage.

In respect to the gross area of one air collector, the specific mass flow is directly proportional to the number of air collectors per row or inversely proportional to the average temperature rise per collector of the row. The dependence on efficiency, pressure drop, and leakage is little. This specific mass flow

expresses mainly whether the collector better suits rather short or long rows. These characteristics can be stimulated and seen well in the B. mode of the AirCow file.

The mean fluid temperature at zero efficiency is displayed, in case the standard stagnation temperature should not be measured but calculated. The offset temperature according to DIN EN ISO 9806 still has to be added.

A few additional key results will be shown, for better understanding of the context (Figure 8). The calculation and optimization will be checked for all possible errors visualized in the B. mode (see chapter 5). For a more comprehensive description of the model compilation see chapter 7.3.6.



Additional results:

Number of air collectors per row	$n_{\text{coll/row}}$	coll	3.97
Number of rows of field	n_{row}	coll	1.91
Fan mass flow of field	\dot{m}_{fan}	kg/h	1430.3
Mass flow of Maximum primary Power (at outlet, per row), MMP_{prim}	$\dot{m}_{\text{e,row,opt}}$	kg/h	748.0
Pressure at field inlet	$p_{\text{i,field}}$	Pa	-56.4
Pressure drop of field	Δp_{field}	Pa	32.4
Reduced temperature difference	T^*_m	Km^2/W	0.023
Instantaneous efficiency of field for final usage	η_{use}	%	59.32
Efficiency loss caused by mass flow	$\Delta\eta_{\text{m}}$	%-points	-0.19
Efficiency loss caused by leakage at field	$\Delta\eta_{\text{L}}$	%-points	-0.32

Figure 8: Additional results

3 Worksheet structure for system planning and scientific use

Grouping of rows:

After choosing the button B for system planning and scientific use, the sheet "SAHC Model" will become visible showing the headlines of the main groups of the sheet in red font. The groups can be controlled on the left side (see Figure 9). Pressing on plus or minus symbols will expand or collapse it. The number of group level is shown above the group symbols (marked by the red oval). Pressing level four will open all groups and show all rows. Pressing level three will collapse all rows containing values, all headlines will stay visible. Pressing level one leads back to the most collapsed position with only the major headlines. Different main groups can be distinguished by different cell frame colors. The first group is considered for all input data. Errors can be checked in the second group, which is followed by the groups containing the results.

Case columns:

The input, error check, and result cells of one air collector operating case are merged in one column. After each change of the input, the input data will be transferred to the model, and the input, error check, and results will be transferred back to the column automatically. The columns can be multiplied by copy and paste and by copy and insert and moved by cut and paste and by cut and insert after marking the whole source or goal column respectively. Empty columns in-between are possible. Each column will be considered separately by the model if changed. The user can compare the input and result data row wise. Input data appearing in the result groups are recognizable by bold font.

Individual formatting:

The cells are filled only with triste grey shades, so that it is possible to highlight interesting cells, rows or columns with vivid colors individually for better orientation.

The grouping can be edited via Menu → Data → Outline. For example, it is possible to set up an own new group.

Diagrams can be prepared for direct post-processing.

To maintain the data transfer to and from the model, it is not allowed to insert, delete, or move rows within the groups "Input" and "Error check". Below these groups, it is allowed.

Calculation speed:

Usually, on a modern PC, the calculation and mass flow optimization time should be less than one second per column and a fraction of that without optimization. If the calculations tend to be slow it may help to close other Excel workbooks. Temporarily, manually set mass flows can be entered for columns intended to change, because it is much faster without optimization, and the optimization can be done finally after the other input for the columns is finished. Instead, in the last row of the group "Input" the "yes" can be removed temporarily to avoid the model call until the input is finished. It can speed up also, when moving the visible pane away from many diagrams.

Additional information:

Sometimes, it can be useful to split the window via Menu → View → Window → Split and to open more windows via Menu → View → Window → New Window.

The worksheet can be renamed and copied within the Workbook without losing the connection to the model. The master worksheet, which was there first, must be kept in the workbook. Copying or moving the worksheet out of the file will disconnect it from the model.

In the case columns of the "Input" group, it is only possible to enter values. The cells cannot contain formulas, thus they cannot be referenced to other cells. Entered formulas will be overwritten with their values immediately, because of the model call.

Copying a column by selecting it and grabbing the small rectangle to draw it to the right will work well, if "Strg" is pressed at the same time. Otherwise the input data will count one up each column.

	A	B	C	D	E
1	Input				
2					
3	- In-between two double lines are pairs of choice-cells , of which one input cell can be chosen and must be filled. The other cell must be deleted, thus empty. - Special is the mass flow choice-cell . Only the manually setting cell must be filled or deleted. The automatically optimization cell will be deleted or filled automatically. - The column D can be copied into other columns of this sheet and the sheet can be copied within this workbook. Input data can be varied row-wise and results can be compared row-wise.				
4					
5					
6					
7					
8					
9					
10	Solar air collector				
31	System				
46	Climate				
47	Solar zenith angle (zenit = 0°, sun rise or sun set = 90°)	h_s	°	45	45
48	Solar azimuth angle (east = -90°, south = 0°, west = 90°)	γ_s	°	0	0
49	Global irradiation in direction of sun	G_{tot}	W/m ²	1000	1000
50	Ambient temperature	T_a	°C	10,0	10,0
51					
52	Field				
62	Mass flow				
66	Calculation support				
68					
69	Error check				
145	Do not insert, delete, or move rows above this row!				
146	Results for system design				
147					
148	Field dimensions				
149	Field length	$n_{Coll/Row}$	Coll	5,33	5,33
150	Field width	n_{Row}	Coll	1,50	1,50
151	Number of air collectors of field	$n_{Coll/Field}$	Coll	8,00	8,00
152	Thermal performance				
161	Fan design				
167	Cost effectiveness				
170					
171	Overview on results				
225	Detailed results				
434	Efficiency curve for ScenoCalc				
435					
436	Compiled parameter set for ScenoCalc (under consideration of thermo-hydraulic mass flow dependency and leakage)				
437	Conversion factor including leakage (use)	$\eta_{0,L}$	-	0,7769	0,7769
438	Linear heat loss coefficient	C_1	W/(m ² K)	7,772	7,772
439	Quadratic heat loss coefficient	C_2	W/(m ² K ²)	0,077723	0,077723

Figure 9: Grouped sections, some expanded groups, different frame colors for each main group, grey filled cells for individual colored highlighting, and copied column for second air collector operating case

4 Input (main group)

If you open the file, a warning about circular references may appear, which Excel cannot avoid, and which depends on the setting of previously opened Excel files. The warning can be ignored and closed.

For appropriate results, it is very important to enter a set of input data, which all go well together to describe a realistic system. Often, just changing a few input data without expertise on the whole system can lead to errors and unrealistic results.

There are pairs of input choice-cells, where it can be chosen which of two cells to fill. These can be recognized by an upper and a lower double frame line. The other cell must be deleted, thus left empty. If none or both cells are filled, an error cell will warn in the field "Error check". All other cells must be filled completely.

The input data are described in the following sub chapters.

Additional information:

If cell ranges are copied and pasted into several columns at once, all affected columns will be recalculated.

Only values can be entered in the "Input" group. If cells become referenced to other cells, the macro will overwrite these input cells with their value. It is advisable to copy and paste inputs, preferably with paste values to maintain the lay out.

After changing the input, redo will not be possible, since the execution of a macro generally causes the deletion of the memory.

4.1 Solar air collector

The sub group "Solar air collector" contains the collector coefficients of the models (1) and (5) to (7). The coefficients can be determined within AirCow under consideration of chapter 1.2. The coefficients and valid ranges must be copied by hand into this sub group.

Additional information

The input does not require constrains for the reduced temperature difference of the efficiency model (1) due to good experience with the efficiency curve model of liquid heating collectors. Extrapolation does not warn by an error cell. Nevertheless, an extrapolation is not without additional error and should be handled with precaution.

4.1.1 Area

The gross, aperture, or absorber area can be given. The coefficients of the efficiency map must be determined by consideration of the given area. Area specific results like thermal efficiency and specific mass flow are based on the given area.

4.1.2 Quadratic heat loss coefficient

For a linear efficiency map, this coefficient is zero. Otherwise, it is a quadratic efficiency map. A minus "-" will not be accepted.

4.1.3 Mass flow dependent heat loss coefficient

Additional information

If the coefficients of the efficiency map only without the coefficient c_m are available, which stand for one realistic mass flow, it is possible to set the coefficient c_m very high, e. g. one. Please check the influence of this chosen value. Then only this mass flow should be used as input. The mass flow cannot be optimized.

4.1.4 Linear ... and Quadratic pressure drop coefficient

Additional information

Without pressure drop coefficients of air collector and remaining system, the auxiliary demand cannot be calculated and the mass flow cannot be optimized. The pressure drop coefficients are necessary for the leakage calculation.

Without pressure drop coefficients, purely thermal calculations are possible. This includes the field length and width, but excludes hydraulic considerations.

4.1.5 Linear ... and Quadratic inward/outward leakage coefficient

Additional information

Without leakage coefficients, the leakage will not be considered. This is the case for entirely air-tight air collectors. For leaky air collectors, the ignored leakage will lead to the correspondent error.

4.1.6 Minimum ... and Maximum valid mass flow for efficiency, pressure drop

The mass flow constrains must not exceed the measured mass flow ranges of both the efficiency model (1) and the pressure drop model (6).

Additional information

If no pressure drop coefficients shall be entered, only the efficiency model depends on the mass flow range.

4.1.7 Minimum ... and Maximum valid pressure for leakage coefficients

The pressure constrains limit the range used for determining the leakage curves coefficients with model (7). The minimum comes from the curve for inward leakage and the maximum comes from the curve for outward leakage.

8	Solar air collector			
9	Manufacturer			Desert Wind
10	Name of air collector			Vitrine
11	Area	A_{coll}	m^2	2.222
12	Conversion factor	$\eta_{0,max}$	-	0.7777
13	Linear heat loss coefficient	$C_{1,max}$	$W/(m^2K)$	7.777
14	Quadratic heat loss coefficient	$C_{2,max}$	$W/(m^2K^2)$	0.007777
15	Mass flow dependent heat loss coefficient	C_m	h/kg	0.007777
16	Linear pressure drop coefficient	R_1	$Pa/(kg/h)$	1.111E-03
17	Quadratic pressure drop coefficient	R_2	$Pa/(kg/h)^2$	1.333E-05
18	Linear outward leakage coefficient	L_{e1}	$kg/(h*Pa)$	3.500E-02
19	Quadratic outward leakage coefficient	L_{e2}	$kg/(h*Pa^2)$	-7.000E-06
20	Linear inward leakage coefficient	L_{i1}	$kg/(h*Pa)$	3.500E-02
21	Quadratic inward leakage coefficient	L_{i2}	$kg/(h*Pa^2)$	7.000E-06
22	Minimum valid mass flow for efficiency, pressure drop	\dot{m}_{min}	kg/h	250
23	Maximum valid mass flow for efficiency, pressure drop	\dot{m}_{max}	kg/h	2500
24	Minimum valid pressure for leakage coefficients	p_{min}	Pa	-2500
25	Maximum valid pressure for leakage coefficients	p_{max}	Pa	2500
26	Ambrosetti parameter	r	-	
27	Incidence angle modifier for 50° of sun to normal of coll.	$K_{hem}(50^\circ)$	-	0.900
28				

Figure 10: Group "Input" – "Solar air collector"

Additional information

If no leakage coefficients shall be entered, the pressure range boundaries can be set to zero.

4.1.8 Ambrosetti parameter and Incidence angle modifier for 50° of sun to normal of coll.

Additional information

If no parameters for the choice-cells incidence angle modifier IAM are available, only calculations with a radiation normal to the collector surface are possible. For the radiation normal to the collector plane, the same angles must be given in the sub groups "Climate" and "Field". Then the value "total angle of sun to normal of collector plane" in the group "Overview on results" will be zero. The value of the Ambrosetti parameter or the IAM does not matter for a radiation normal to the collector surface.

4.2 Climate

4.2.1 Solar zenith/azimuth angle

The incidence angle of the sun and the orientation angle of the field will be calculated into the resulting "total angle of sun to normal of collector plane", which can be found in the group "Overview on results". If this value exceeds 90°, the "incidence angle modifier" and the "factor for projected field area" will be set to zero.

4.2.2 Global radiation in direction of sun

This is the sum of beam and diffuse radiation on a plane normal to the sun.

Additional information

In science, the solar radiation on a horizontal surface is mostly given. This value changes stronger during a day than the radiation on a plane normal to the sun. Therefore, in this calculation, the radiation on a surface normal to the sun is used. This can be used for a big angle range or day time span, as long as the air mass does not change too much. If the radiation in direction of sun is once known, it will be easier for the user to just change the angle for different day times or seasons.

The albedo is not considered here, which would come from another direction.

29	Climate			
30	Solar zenith angle (zenit = 0°, sun rise or sun set = 90°)	θ_s	°	45
31	Solar azimuth angle (east = -90°, south = 0°, west = 90°)	γ_s	°	0
32	Global radiation in direction of sun	$G_{o,d}$	W/m ²	1000
33	Ambient temperature	ϑ_a	°C	10.0
34				

Figure 11: Group "Input" – "Climate"

4.3 Field

4.3.1 Solar tilt/azimuth angle

See chapter 4.2.1.

4.3.2 Temperature rise and Field length (number of air collectors per row)

The temperature rise depends strongly on the row length. Because of this correlation, the model allows to give either value of the choice-cells.

For air collectors, which are typically not connected in series, the field length should be given with the value of one.

If the mass flow is intended to be optimized, either the temperature rise and the power of the following choice-cell or the field length and width must be given.

4.3.3 Power (at field outlet or at load) and Field width (number of rows of field)

The "Power (at field outlet or at load)" is scaled by the width of the field. Therefore, either value of the choice-cells can be given. For the field with overpressure in the closed loop, the load leakage will be considered for the given power, depending on the selection (chapter 4.4.2). If the field width is given, the system mass flow depends on the mass flow per row, and therefore, the flow resistance of the remaining system influences the mass flow optimization.

4.3.4 Inlet fluid temperature of field and Mean fluid temperature of field

If a system configuration with over- or with underpressure in the field is chosen (not with over- and underpressure), and if an open loop is intended, the inlet temperature must equal the ambient temperature.

The mean temperature (4) is the mean value of the field inlet and outlet temperature. This input was introduced, since it is an input of the simulation file ScenoCalc too. Either value of the choice-cells can be given.

35	Field			
36	Tilt angle (horizontal collector surface = 0°, vertical = 90°; β_{coll})	°		45
37	Azimuth angle (east = -90°, south = 0°, west = 90°)	γ_{coll}	°	0
38	Temperature rise	ΔT_{rise}	K	25.0
39	Field length (number of air collectors per row)	$n_{coll/row}$	coll	
40	Power (at field outlet or at load)	Q_e	W	10000.0
41	Field width (number of rows of field)	n_{row}	coll	
42	Inlet fluid temperature of field	ϑ_i	°C	20.0
43	Mean fluid temperature of field	ϑ_m	°C	
44				

Figure 12: Group "Input" – "Field"

4.4 Air heating system

4.4.1 Hydraulic system configuration

1 - Field with overpressure

If the system is an open loop, it has a pressing fan before the field (e. g. ventilation pre heating, drying system). If the system is a closed loop, the load is leaking and the fan is after the load and before the field (e. g. recirculating air heating with un-tight building).

2 - Field with underpressure

If the system is an open loop, it has a soaking fan after the field (e. g. ventilation pre heating, drying system). If the system is a closed loop, the load is leaking and the fan is after the field and before the load (e. g. recirculating air heating with un-tight building).

3 - Field with over- and underpressure

The system is a closed loop with air-tight load and air-tight channels. Only the field can be leaky. The fan position does not matter (e. g. air-water heat exchanger, recirculating air heating with air-tight building).

For choosing between an open and a closed loop, see chapter 4.3.4.

4.4.2 Field with overpressure

This cell is relevant for fields with overpressure only. Otherwise, it has no relevance.

For an open loop chose 1 and make sure, the inlet temperature equals the ambient temperature.

In the closed loop with a field with overpressure, the same leakage air flow rate, which leaves the field, must enter into the load, to keep the air volume stable in the system. The load soaks this air in at ambient temperature, which cools the load. This is considered in the model.

The selection of 2 will neither consider the load leakage losses for the given "power (at field outlet or at load)" in sub group "Field" nor for mass flow optimization. The power is given at the field outlet, if not the "field width (number of rows of field)" is given instead.

The selection of 3 will consider the load leakage losses for the given power, if it is given, and for mass flow optimization. If the power is given instead of the field width, the power is given at the load. The selection of 3 will further consider the load leakage losses for the model compilation to the thermal efficiency curve model of liquid heating collectors for use in ScenoCalc.

Some results will show "Not for this syst.!" instead of values, if not 2 or 3 is selected for the field with overpressure.

4.4.3 Field with over- , underpressure (considered for fan mass flow)

For the calculation of the fan volume flow, the fan position must be known. This is relevant only for the field with over- and underpressure. For the fields with over- or underpressure, the fan position is already known from the field pressure.

4.4.4 Flow resistance before/after air collector field

Together with the field pressure drop and the dynamic pressure loss, the pressure drop of the remaining system influences the auxiliary demand and subsequent the mass flow optimization. The pressure drop of the remaining system influences the pressure in the field, and therefore the field leakage enthalpy loss too.

For closed loops with over- or with underpressure in the field, a strongly leaking load is considered, which has ambient pressure, e. g. an un-tight building. In these loops, before the field is in-between load and field and after the field is in-between field and load. For a closed loop with over- and underpressure in the field, an air-tight load is considered. In this loop, the pressure drops before and after the field will be summed up, because these represent the remaining system from field outlet to inlet. For open loops with over- or with underpressure, it should be self-explanatory.

4.4.5 Blowing air into how many large volumes in series ...

If the air heating system blows the heated air into a large volume like a building for space heating, the dynamic pressure gets lost. Additionally to the pressure drop of the total system, the fan must generate this dynamic pressure resulting in an additional auxiliary demand. In the results, the dynamic pressure loss is accounted for the auxiliary demand of the remaining system and not of the field. Eventually, it will be considered in the cost function for the mass flow optimization.

It is possible that the system consists of more than one large volume. For example, the air can be blown into a building, then into the next room, and eventually out of the building into the ambience. In

this case the velocity gets lost three times, and "3" must be entered. For all channel outlets into large volumes, the same cross-sectional area (see chapter 4.4.6) and the field outlet temperature is considered.

At least one large volume must be chosen for all open loops, since the air will leave at the end of these systems. If it is a closed loop with a large volume like a building it must be chosen too. This is for all hydraulic system configurations: overpressure, underpressure, as well as over- and underpressure.

Differing temperatures and channel cross-sectional areas

For the calculation of the dynamic pressure loss, the temperature at the field outlet is considered for the density. This is for the case that the heated air is blown into the load like a building. If the air is blown with a lower temperature into the next room or into the ambience, the field outlet temperature is considered again, which does over predict the dynamic pressure loss. If the temperature is 30 °C lower, the dynamic pressure loss is about 10 % over predicted. For such cases, it is possible to enter real numbers for the number of large volumes, like "1.9".

For all considered channel outlets into large volumes, the same channel cross-sectional area is considered, given in chapter 4.4.6 as channel diameter or side length. If it is necessary to adapt the number of volumes for different cross-sections at several large volumes, it must be considered, that the dynamic pressure loss (10) considers the square of the cross-sectional area. This is the exponent four of the given channel diameter or side length.

45	Air heating system			
	Hydraulic system configuration: Enter: 1 - field with overpressure; 2 - field with underpressure; 3 - field with over-, underpressure			2
46				
	Field with overpressure (considered for given power): Enter: 1 - open loop; 2 - closed loop without leakage of load; 3 - closed loop with leakage of load			1
47				
	Field with over- and underpressure (considered for fan volume flow): Enter: 1 - fan after load and before field; 2 - fan after field and before load			1
48				
49	Fan efficiency (electric -> mechanic -> hydraulic)	η_{fan}	%	57.2
50	Flow resistance before air collector field	$R_{sys,before}$	Pa/(m ³ /h) ²	4.00E-05
51	Flow resistance after air collector field	$R_{sys,after}$	Pa/(m ³ /h) ²	4.00E-05
	Blowing air into how many large volumes in series (e.g. building; for dynamic pressure losses and velocity): Enter: 0 - no; 1 - one; 2 - two large vol.; 3 - etc.			1
52				
	Channel diameter of circular cross-section before large volumes, if present (for consideration of dynamic pressure losses at mass flow opt. and for velocity)	$d_{chan,circ,vol}$	m	0.300
53				
	Channel side length of square cross-section before large volumes, if present (for consideration of dynamic pressure losses at mass flow opt. and for velocity)	$a_{chan,square,vol}$	m	
54				
	Diameter of circular cross-section of regular channel (only for velocity calculation)	$d_{chan,circ,reg}$	m	0.300
55				
	Side length of square cross-section of regular channel (only for velocity calculation)	$a_{chan,square,reg}$	m	
56				
57				

Figure 13: Group "Input" – "Air heating system"

4.4.6 Channel diameter ..., channel side length ...

One of the choice-cells "channel diameter ..." or "channel side length ..." must be filled. If a large volume of chapter 4.4.4 is chosen, the dynamic pressure loss will be calculated from this, which influences the mass flow optimization. The diameter or side length of a circular or square channel cross-section is the

one at the end of the channel at the outlet. If a diffuser is applied, these are the largest dimensions at the very end.

It is important to remember that these channel dimensions have no influence on the system flow resistance within this model.

Different cross-section shapes

If the used channel cross-section is not circular or square, a substitution value can be found. The cross-sectional area of the used channel must be calculated. This area can be considered as circular or square, and the diameter or side length can be calculated and entered. For example, the channel cross-section is rectangular with 0.1x0.2 m²; the area is 0.02 m². The root gives 0.1414 m side length of a square channel, which can be entered. It is possible to enter the equation " $=0.1*0.2$ " directly. The macro will change the equation to its value 0.1414.

4.4.7 Diameter or circular/side length of square cross-section of regular channel ...

Only the velocity in channels is calculated from these dimensions. It has no influence on any other calculation. One of the choice-cells must be filled.

If the cross-section shapes are not circular or square, see chapter 4.4.6 and find a substitution value.

4.5 Global system for mass flow optimization

4.5.1 Kind of optimization: 1 - primary energetic; 2 - monetary; ...

By this value the optimization basis of the mass flow will be determined.

1 – primary energetic

Both primary energetic factors and the thermal efficiency of the heating system of the thermal energy to replace are considered.

2 – monetary

Both energy prices and the thermal efficiency of the heating system of the thermal energy to replace are considered.

3 – site energetic

The heating system of the thermal energy to replace is considered.

4 – system energetic

The thermal power at the field outlet and the electrical power for the fan are considered.

58	Global system for mass flow optimization			
59	Kind of optimization: 1 - primary energetic; 2 - monetary; 3 - site energetic; 4 - system energetic			1
60	Primary energy factor of electrical energy for fan	$f_{p, fan}$	-	3.0
61	Primary en. factor for heating energy carrier to replace	$f_{p, sys, repl}$	-	1.1
62	Price per unit electrical energy for fan	C_{fan}	cent/(kWh)	30.000
63	Price per unit heating energy carrier to replace	$C_{sys, repl}$	cent/(kWh)	11.000
64	Efficiency of heating sys. to repl. (chemical -> thermal)	$\eta_{sys, repl}$	%	90
65				

Figure 14: Group "Input" – "Global system for mass flow optimization"

4.5.2 Efficiency of heating sys. to repl. (chemical -> thermal)

In case, the solar air heating system replaces the conventional heating system completely, the efficiency of the conventional system without distribution of the thermal power can be used. The distribution losses of the solar heated air are not considered also.

If the solar air heating system just supports a conventional system partly, the efficiency of the conventional energy converter without the steady heat losses of a hot water storage because of burner modulation can be used. The heat losses of the storage would occur anyway.

Large dimensioned systems

If a solar air heating system provides more power, than the demand is, and if the heat cannot be stored, the MMP can be taken as upper limit, and the mass flow can be reduced until the demand is matched.

Combined air systems

If the solar air heating system is separate of possible other air systems of the load, it is clear, which system flow resistance is to consider for the mass flow optimization.

If the solar air heating system is attached to an air system, questions arise, which part of system flow resistance must be considered. The answers may be different, if the system switches between the non-solar and the solar operation, or if it runs with mixed mass flows. This discussion will not be covered by this manual.

Solar air heating systems without external auxiliary demand

If the solar air heating system includes a PV panel, which drives the fan, the system is independent of external auxiliary demand. The mass flows of these systems cannot be optimized with this workbook, since it is necessary to consider the monetary or primary energetic effort for providing the panel. This effort must be distributed on the period of amortization, which makes annual simulations necessary.

In this workbook, it can be tried to estimate and consider the effort for the panel per time (cost for buying or primary energy for producing the panel divided by power of the panel, period of amortization, and running hours per year to get $f_{p, fan}$ or C_{fan} of Figure 14) to get an idea about the MMP and the PV panel dimensions. Then, the panel size can be chosen to meet the auxiliary demand, and the mass flow can be varied to equal the auxiliary demand to the panel power, while the thermal performance should remain acceptable. Because of lack of experience, the sensitivity of the results can be tested for ranges of the estimated input values.

Solar air heating systems, which do not replace a conventional system

If a solar drying system does not replace conventional heating but traditional direct sun drying, the advantage of a higher quality and less scrap of a preferably high amount of drying goods should be reduced for the auxiliary demand. This difference is the cost function to maximize for finding the MMP. The mass flow optimization of this workbook does not contain this cost function but is able to give an MMP as upper mass flow limit, which should not be exceeded. Otherwise an additional conventional heating system would be preferable. An individual cost function can be defined and entered below the group "Error check". The cost function can be optimized by changing the mass flow (and other variables) manually.

If an otherwise unheated weekend cottage is ventilated or heated by an air heating system with auxiliary from the mains supply, the advantage of less moldy air and a higher temperature for occasional cottage visits should be reduced for the auxiliary demand. This difference is the cost function to maximize for finding the MMP. The MMP determined by this workbook should not be exceeded like for the drying system above. If the cottage was unheated before, and an electrical heater was determined as too power consuming, a lower mass flow than the MMP should be chosen. It must be repeated, that not the COP or the reciprocal of it must be considered for this decision, but that the optimization leads to a working point, where a decrease or increase of the mass flow leads to a decrease or increase of the auxiliary power and the thermal power, both by the same quantity. If the MMP_{cost} was found, it would be similar. In one example the MMP_{cost} was reduced to a mass flow 23 % lower, while the auxiliary demand was halved and the thermal power lost 4 %.

4.6 Mass flow

4.6.1 Manually set outlet mass flow per row (enter or delete) and Autom. optimized outlet mass flow per row (do not enter)

If optimized, the outlet mass flow per row (Figure 15) is a characteristic parameter describing the relation of heat transfer and flow resistance of air collectors. Multiplied by the number of rows, it gives the "outlet mass flow of field", which often is a requirement of the load or can be regulated by a controller to follow a set temperature.

-	66	Mass flow			
·	67	Manually set outlet mass flow per row (enter or delete)	$\dot{m}_{e,row}$	kg/h	
·	68	Autom. optimized outlet mass flow p. row (do not enter)	MMP	kg/h	747.6
·	69				

Figure 15: Group "Input" – "Mass flow"

Different to other choice-cells, here only the upper cell must be either filled with a mass flow of the user's choice or deleted. If the upper cell becomes deleted, the mass flow will be optimized and entered in the cell below automatically. If a mass flow will be given by the user again, it must be entered into the upper cell. The lower cell will be deleted automatically. Thus, the lower cell never must be changed. Only fill or delete the upper cell.

For mass flow optimization, either the temperature rise and the field power or the field length and width must be given in the subgroup "Field". The optimization methods are not examined yet for the specification of either the temperature rise and the field width or the field length and the power. For these specifications an error notice is implemented.

Additional information:

An energetic and an economic optimization method are used. These methods do not consider the special behavior of all possible loads like drying, heat pump, or cooling in the interaction with the field. Simple heating applications are best represented with the implemented optimization methods.

The optimization does maximize the net primary power, the net site power, the net system power, or the net cost saving per time by power, which are related on the field area. The maximization basis depends on your choice above (see chapter 4.5.1). Depending on the maximization goal, the resulting characteristic mass flow, MMP, is defined in chapter 1.2.5. The value to maximize can be followed in the row "cost function" of the group "Overview on results" - "Mass flow optimization". Right above are all possible cost functions to find with its units.

If the field length and width are given, the flow resistance of the remaining system is considered for the optimization. If the temperature rise and power are given, the flow resistance of the remaining system cannot be considered. This is, because, if the mass flow per row is increased in the optimization process, the field length will increase too to hold the given temperature rise. If the field length increases, the field width will decrease to hold the given power. Therefore the mass flow per row and the field width are inversely proportional. Since the system mass flow is the product of the mass flow per row by the field width, the system mass flow will remain constant. Then the auxiliary demand of the remaining system remains constant too and has no influence on the optimization.

If the field length and width are given together with the inlet temperature, the MMP will turn out very high. This is, because then the temperature rise and the mean temperature are low and the temperature dependent losses are kept small. This behavior is especially for small flow resistances of the remaining system. For higher flow resistances the MMP does come down. This cannot occur for the other cases, since either the mean temperature is given directly or is fix, because of given inlet temperature and temperature rise.

4.6.2 Connection to model, only if "yes"

This cell can be left unchanged.

Additional information:

This cell will be checked by macro after each input entry. If the cell contains "yes" (exact word, lowercase), the column will be calculated. If "yes" is deleted or changed, the column will not be calculated. Columns, which are empty or used for other purposes, will be detected and omitted that way. Therefore, feel free to use other columns in-between or behind model connected columns individually.

61	Calculation support			
62	Connection to model, only if "yes"			yes
63				

Figure 16: Group "Input" – "Calculation support"

5 Error check (main group)

This chapter covers the error handling on the sheet "SAHC Calc.+Opt.". It does not cover the previous sheets for fitting the coefficients.

For appropriate results, it is very important to enter a set of input data, which all go well together to describe a realistic system. Often, just changing a few input data without respect for the whole system can lead to unrealistic results and errors.

The cells in the main group "Error check" turn red, if errors occur. The last row summarizes the error cells above and shows an error, if at least one error occurs. Then it turns from green to red. It is recommended to leave the sub group "Summary" expanded and visible.

Though, it was tried to detect as most as possible of unrealistic and non-calculable cases in the group "Error check", there is no guaranty for detecting all possible unrealistic systems. Finally, the user is responsible for appropriate input data.

The following sub chapters describe the reasons of occurring errors and possible solutions.

Common way of finding error causes:

If one error reason causes several errors, it can be difficult to find the reason. If the errors cannot be cleared out, the values in the group "Overview on results" should be checked thoroughly. Values can be out of realistic ranges or can have a wrong algebraic sign. Then it needs to be thought backwards.

For example, a given small temperature rise causes a short row length, which causes a high number of rows to cover a given power, which causes a high system mass flow (product of mass flow per row and number of rows), which causes a high pressure drop in the remaining system, which causes a high field pressure, which causes the leakage calculation outside the valid pressure range, which can lead to negative algebraic signs for leakage. The results show all these values within suspect ranges. It must be thought of, what causes what, and what stands in the beginning of the reaction chain. In this case it would help to enter a higher temperature rise.

Fortunately, the reaction chain must not always be that long. Figure 20 and Figure 21 in Appendix A show flow charts of the model in a simplified form. These may be of valuable help to understand what causes what and to localize the problem.

At this place can be mentioned, that giving a field length and width reduces the risk of errors significantly. On the other hand, the appropriate field dimensions may not be known in the beginning. If these shall be determined by giving a temperature rise and a power, the other input data like temperatures, orientation, and climate should cause a not too low thermal efficiency. A low efficiency can cause an unrealistic high field length and may violate e.g. the given valid pressure range of the leakage curves. Then the mass flow can be optimized. The resulting field length and width should be used for further case columns.

5.1 Choice-cells

5.1.1 Fill out only one cell of ...

These error cells warn, if in the group "Input" pairs of choice-cells, of which only one cell must be filled, both or none of both cells are filled. The empty cell must be empty, not just zero.

5.2 Mass flow optimization

These error cells become active, only if the mass flow was to be optimized by deleting the upper choice-cell in the group "Input" – "Mass flow".

Before inducing the optimization, errors of other error cells should be solved. If there is doubt about error-free optimization, different mass flows from low to high can be entered manually, and no error should appear.

5.2.1 Give either ...

The error cell “give either temperature rise and power or field length and width. Do not give other parameter combinations.” warns, if either temperature rise and field width or field length and power are given, while the mass flow is to optimize. This is because the optimization method is not examined for these specifications.

5.2.2 Optimization of mass flow ...

The error cell “optimization of mass flow is not possible with negative power” warns that the optimization cannot lead to reliable results, if the power is negative. Nevertheless the calculations can be valid without mass flow optimization.

5.2.3 Auxiliary demand is higher ...

The error cell “auxiliary demand is higher than thermal power (cost function is negative and has no maximum)” indicates that the cost function is negative for two checked key mass flows. It is quiet probable, that the cost function is all over negative and has no maximum to find. Therefore, the mass flow optimization may result in a negative mass flow.

The mass flow optimization will be tried anyway, since there is a very small chance to find a maximum, if the auxiliary demand is nearly as high as the thermal power. If this result will be used, the error can be neglected, but the considered system may be unrealistic.

If the cost function has no maximum and is negative, the input data characterize an inefficient system. The cost function considers the difference of the thermal power output minus the auxiliary power demand, both in relation to the field area. For the primary energetic and the economic optimization the powers are multiplied by the primary energy factors or the energy prices respectively (see chapter 1.2.5). The negative cost function indicates that the auxiliary demand is higher than the thermal power. The system has no practical relevance. Either the thermal power must be increased or the auxiliary demand decreased.

The thermal power can be increased by the efficiency map coefficients, the IAM, the orientation of field and sun, the climate, and the inlet or mean fluid temperature.

The auxiliary demand can be decreased by the pressure drop coefficients of air collector and remaining system and the power or the field width.

The temperature rise and the field length influence both, the thermal power and the auxiliary demand.

5.2.4 Mass flow optimization ...

The error cell “mass flow optimization could not be performed” warns that the optimization algorithm could not deal with the results coming from the model. A large range of mass flows per row is considered for the optimization. If the model returns Excel calculation errors (#Div/0!, #Num!, ...) or unrealistic results due to diverging circular references for certain mass flows, the optimization procedure will interrupt and return no optimal mass flow.

The optimization algorithm considers the cost function values of three mass flows and determines the maximum of the quadratic curve fitting the cost function values. In the next step, the range will be reduced and centered on the predicted maximum. This procedure will be repeated until a certain precision. The algorithm allows finding the MMP outside the initially considered mass flow range too.

The initially considered mass flow range is determined by use of the first term in square brackets of (1) which is the mass flow dependent factor $Factor_{F0,max}$ of the collector efficiency factor at infinite mass

flow. This factor is rearranged to the mass flow in (18), and the factor of 0.8 and 0.999 is used to calculate the mass flow boundaries.

$$\dot{m}_{row} = - \frac{\ln(1 - Factor_{F'_{o,max}})}{c_m} \quad (18)$$

For example, for a mass flow dependent heat loss coefficient c_m of 0.005 h/kg the mass flow range is from 322 kg/h to 1382 kg/h, for 0.010 h/kg it is from 161 kg/h to 691 kg/h, and for 0.015 h/kg it is from 107 kg/h to 461 kg/h.

It can be tried with a few entered realistic mass flows, to find the maximum manually. It is possible also to set up about ten case columns, to vary the manually given mass flow per row, and to draw a diagram with the cost function over the mass flow. If appropriate, other values can be watched over the mass flow then.

5.2.5 Relative range around ... and MMP was not found ...

The error cell "MMP was not found within a relative range of ± 0.1 % of the real MMP" will be triggered, if the "relative range around the real MMP in which the MMP was found" is greater than ± 0.1 %.

The procedure to check this tries, whether the cost function for mass flows 10 % more or less of the found MMP is bigger than the cost function for the found MMP. Next it tries this for ± 1 %, then for ± 0.1 % and so on. The minimal range in which the MMP has a higher cost function is displayed in the upper cell. If the mass flow was tried to optimize and no value is shown, the macro procedure was interrupted, what is indicated by the error cell described in chapter 5.2.4.

If the relative mass flow range still is ± 1 % or ± 10 %, and if this can be tolerated, this error can be neglected. If the relative mass flow range is too high, it can be checked, if the input parameters characterize a realistic system. To better understand the situation, a few case columns can be set up, to vary the manually given mass flow per row, and to draw a diagram with the cost function over the mass flow.

The optimization procedure was positive tested under various conditions in the development phase. If there still realistic conditions will be found, at which the optimization causes problems, the developer is always interested in information about it.

5.3 Iterative calculation

5.3.1 Number of iterations ... and Set max. iterations ...

The error "set max. iterations of circ. references is hit (divergency) -> efficiency is too low or do input field length and width" will be triggered, if the iterative model calculation diverges and the "number of iterations of circular references" reaches 100. This error does not occur, if both the field length and the field width are given.

These divergent calculations often trigger error warnings in other error cells. Solving this problem often clears the other error warnings. Depending on how unstable the calculations under the actual conditions are, the calculations show sometimes apparent realistic and sometimes very unrealistic unstable results. In the first case, the other error warnings may help to find the problem, in the latter case, they can be confusing.

If one or both are given, the "temperature rise" and/or the "power (at field outlet or at load)", the convergence often cannot be reached, if the inner efficiency of gained heat (regarding the transferred heat from absorber to air, before leakage occurs) is a small two-digit value around the zero efficiency. For

these working points, the field length and width cannot be determined. The field length would be unrealistic high. The input data must be changed.

Another reason can be unrealistic leakage coefficients for the field with over- and underpressure. The curves can be checked in a leakage mass flow diagram over the air collector pressure.

This error can be indicated also, if the input parameters are correct, but if another instance of this workbook is open, and if its last use (model call) caused this error. Then, close the other workbook.

5.4 Valid model ranges

5.4.1 Mass flow is out of set ...

The error cell "mass flow is out of set valid mass flow range of efficiency and pressure drop coefficients" indicates, that the "outlet mass flow per row" is out of the set mass flow range in group "Input" – "Solar air collector". A mass flow within the valid range must be given. If the mass flow is to be optimized, the input data should be changed to another working point leading to an MMP within the valid range. Widening the mass flow range for extrapolating the model is on own risk of increasing model error.

5.4.2 Pressure is out of set ...

The error cell "pressure is out of set valid pressure range of leakage coefficients" indicates a too high positive or negative pressure in the field. It is important to know, that the quadratic leakage model curve can turn its trend with an increasing pressure to decreasing leakage losses after the maximum or minimum of the curves. This can even lead to turning the algebraic sign of the leakage losses, causing unrealistic leakage gains. Therefore, far extrapolation should be strongly avoided.

5.4.3 Leakage mass flows ...

The error cell "leakage mass flows have wrong algebraic sign -> check correct diagram quadrants for leakage curves" warns, if one or both leakage curves are not mainly within the first or third diagram quadrant with the considered pressure range. The curves can be checked in a leakage mass flow diagram over the air collector pressure.

If inward leakage mass flows become positive and outward leakage mass flows become negative, the model continues the calculation with values around zero (± 0.000001 kg/h). These manipulated values will be shown as results too.

5.5 Low thermal efficiency

5.5.1 Calculation with negative efficiency ...

The error cell "calculation with negative efficiency only with given field length and width or negative temp. rise and field power" indicates that a positive "temperature rise" and/or a positive "power (at field outlet or at load)" are given and that the other given boundary conditions lead to a negative thermal efficiency. In this case, for the temperature rise and/or power, whichever is given, negative values must be given.

This error does not occur, if both the field length and the field width are given, which are always considered to be positive.

5.5.2 Outlet temperature is above ...

The error cell "outlet temperature is above maximum possible mean temperature" warns, if the calculated field outlet temperature is above the theoretic mean fluid temperature, which would occur at zero efficiency, while the inlet temperature is below the outlet temperature.

This can occur, because the mass flow dependent efficiency map model considers the mean temperature (4). For detecting this situation, this model is solved for the mean fluid temperature at zero efficiency, and this theoretic temperature is compared with the outlet temperature for error detection. The “mean fluid temperature at zero efficiency (before leak.)” can be viewed very down in the group “Overview on results”.

The error can occur, if a rather high temperature rise or row length is given and a rather high mean fluid temperature or rather high (with given temperature rise) or low (with given row length) inlet fluid temperature is given.

The chance of this error increases, if the “global radiation in direction of sun” decreases or the “total angle of sun to normal of collector plane” increases.

Another reason can be, that input data are given resulting in a mean temperature above the theoretic mean fluid temperature at zero efficiency with a given positive temperature rise. In this case the temperature rise must be negative.

If the inlet temperature is above the theoretic mean fluid temperature at zero efficiency, and if the outlet temperature is in-between, this error cell will indicate no error.

5.6 Summary

The error cell “summary of error notices” summarizes all error cells above and shows an error, if at least one error occurs. Without an error it will stay green, and it will turn red with errors. It is recommended to leave the sub group “Summary” expanded and visible. It is also possible to reference this cell into the used result table and format it green and red by Conditional Formatting in the menu Home.

6 System planning

6.1 Results for system design (main group)

The group “Results for system design” concentrates some key values for system planning, like length and width of the field, power, efficiency, flow rate, and temperature at field outlet, the temperature rise of the field, the pressure drop of the field and the remaining system, the dynamic pressure loss, and the volume flow rate of the fan. With this, the field dimensions and performance are determined and an appropriate fan can be chosen from the market.

Further, the share of electric auxiliary power is given as the ratio of electric fan power to flow through the whole system per thermal power at the field outlet. The electric power does source from the socket, here no primary power factor or energy price is considered.

The share of money for auxiliary is given too as the ratio of the costs for electric energy for the fan to flow through the whole system per saved costs of the replaced thermal energy. The energy prices and the thermal efficiency of the replaced system are considered here.

Additional information:

In this group only the power at field outlet is displayed and not the power after leakage into the load, to keep the group simple. For further information see chapter 4.4.2. The power after leakage into the load can be viewed in the groups “Overview on results” and “Detailed results”.

The “instantaneous efficiency at field outlet” may help to evaluate how efficient the air collectors are used. This cannot be done with the power, if the field length or width is varied.

6.2 Instructions

- 1) First, the group “Input” must be filled out regarding chapters 1.2 and 4. In the sub group “Field” a “temperature rise” and a “power (...)” of the desired field performance should be given.
- 2) Then the cell of “manually set outlet mass flow per row (...)” must be deleted for optimizing the mass flow. If this cell was already empty, the mass flow is already optimized. The optimal mass flow per row, MMP, realizes the maximum net power or net profit for each square meter of the field.
- 3) The group “Error check” should be opened. If errors were detected, it is necessary to go back to step 1) to eliminate the errors regarding chapter 5.
- 4) Without errors, in the group “Results for system design” – “Field dimensions”, the “field length” and the “field width” can be seen. The optimization led to a characteristic field length and mass flow per row, MMP, for the given temperature rise. The field width results from the given power. The collector numbers are given in real numbers, whereas usually only integer collector numbers can be implemented in real systems. Therefore, an additional calculation is necessary. The whole case column must be copied into an empty column (Figure 17).
 - a) Now, in the group “Input” – “Field”, the just obtained values of field length and width must be rounded and given as integer, while the temperature rise and power has to be deleted.
 - b) The optimal mass flow of the first column in the group “Input” – “Mass flow” must be given as manually set outlet mass flow. Subsequently, the results can be viewed in the group “Results for system design” already.
- 5) Several case columns can be copied for rounding up and down the integer collector numbers of the field dimensions of the first column to compare their performances. Onsite requirements or the header complexity to connect parallel rows can be considered for the choice of the number of rows and other input data can be changed too.
 - a) The field length, the mass flow per row, and the temperature rise form a trinity ($m_{d_{Row}} * T_{rise} \sim n_{Coll/Row}$), which proportionality has a small imbalance from the temperature and

mass flow dependent efficiency and the leakage. That means, if the field length is changed, the mass flow can be adapted to get back to an acceptable temperature rise.

- b) As the field length, the field width, and the field power form another trinity ($n_{\text{Coll/Row}} * n_{\text{Row}} \sim Q_{\text{dField}}$), in the next step, the field width can be adapted to get back to an acceptable power.
- 6) Additional to the variations with manually set mass flow, the mass flow can be optimized for the given integer field length and width. This will lead to a lower MMP with a higher temperature rise, while the net power or net profit of the given field area is at its maximum. It must be checked, if the temperature rise still is acceptable.
 - 7) The “total pressure rise of total system” and the “fan volume flow” in the group “Results for system design” – “Fan design” is the working point of the fan to choose from the market. For the fan volume flow, the density is considered with the field inlet or outlet temperature regarding the fan position. If the calculated working point differs from the fan performance map, input values can be adapted, which include the fan efficiency.
 - 8) If the field was the first design step, now the remaining system can be designed. If the flow resistance of the designed remaining system has changed from the initial values, it should be checked, if the field performance is still optimal.
 - 9) Before using the final results, the correspondent column should be checked for errors in the group “Error check” again.

Additional information

The group “Results for system design” – “Air velocity in channels ...” gives flow velocities, which are calculated from the volume flow and the diameter or side length of a circular or square channel cross-section. These have no connection with the flow resistance of the remaining system. Additionally to the auxiliary demand of the remaining system and the field, only the velocity into large load volumes is considered for the auxiliary demand and the mass flow optimization.

35	Field				
36	Tilt angle (horizontal collector surface = 0°, vertical = 90°)	h_{Coll}	°	45	45
37	Azimuth angle (east = -90°, south = 0°, west = 90°)	γ_{Coll}	°	0	0
38	Temperature rise	ΔT_{rise}	K	25.0	
39	Field length (number of air collectors per row)	$n_{Coll/Row}$	Coll		4.0
40	Power (at field outlet or at load)	Qd_e	W	10000.0	
41	Field width (number of rows of field)	n_{Row}	Coll		2.0
42	Inlet fluid temperature of field	T_i	°C	20.0	20.0
43	Mean fluid temperature of field	T_m	°C		
44					
45	Air heating system				
58	Global system for mass flow optimization				
66	Mass flow				
67	Manually set outlet mass flow per row (enter or delete)	$md_{e,Row}$	kg/h		743.9
68	Autom. optimized outlet mass flow p. row (do not enter)	MMP	kg/h	743.9	
69					
70	Calculation support				
72					
73	Error check				
74					
75	Details				
104	Summary				
105	Summary of error notices			No errors found	No errors found
106					
173	Do not insert, delete, or move rows above this row!				
174	Results for system design				
175					
176	Field dimensions				
177	Field length	$n_{Coll/Row}$	Coll	3.95	4.00
178	Field width	n_{Row}	Coll	1.92	2.00
179	Number of air collectors of field	$n_{Coll/Field}$	Coll	7.59	8.00
180	Thermal performance				
181	Power at field outlet	Qd_e	W	10000.0	10511.2
182	Instantaneous efficiency at field outlet	η_{Use}	%	59.3	59.1
183	Outlet volume flow of field	Vd_e	m³/h	1306.0	1359.6
184	Outlet mass flow of field	md_e	kg/h	1430.3	1487.8
185	Inlet temperature	T_i	°C	20.0	20.0
186	Outlet temperature	T_e	°C	45.0	45.3
187	Temperature rise	ΔT_{rise}	K	25.0	25.3
188	Mean fluid temperature of field	T_m	°C	32.5	32.6
189	Fan design				
190	Pressure drop of field	Δp_{Field}	Pa	32.8	33.3
191	Pressure drop of remaining system	Δp_{Sys}	Pa	127.9	138.7
192	Dynamic pressure losses into large load volumes (sum)	$p_{dyn,Sum,Sys}$	Pa	14.4	15.6
193	Total pressure rise of total system	$p_{Sys,tot}$	Pa	175.2	187.7
194	Fan volume flow	Vd_{Fan}	m³/h	1221.9	1272.7
195	Fan mass flow	md_{Fan}	kg/h	1452.4	1512.7
196	Air velocity in channels (no consideration of flow resistance here)				
197	Velocity before large load volumes (for dynamic pressure)	$U_{Chan,Vol}$	m/s	5.1	5.3
198	Velocity in cold regular channel	$U_{Chan,reg,cold}$	m/s	4.8	5.0
199	Velocity in hot regular channel	$U_{Chan,reg,hot}$	m/s	5.1	5.3
200	Cost effectiveness				
201	Share of electric power for auxiliary	$1/COP_{syst}$	%	1.04	1.10
202	Share of money for auxiliary	$1/COP_{cost}$	%	2.55	2.71
203					

Figure 17: Mass flow optimized first column with real numbers for field dimension and second column with given integer for field dimension and manually given mass flow per row

7 Scientific studies

Displayed areas are related the same as the given collector area in the group “Input” – “Solar air collector”, e.g. gross, aperture, or absorber area.

If result cells show the text “Not for this syst.!", which means ‘Not for this system configuration!’, these values are not determined for the chosen system configuration. These values are shown only, if the field with overpressure in a closed loop is chosen.

The values of the maximization functions can be used as evaluation criterions besides of thermal efficiency, auxiliary power and coefficient of performance.

7.1 Overview on results (main group)

The values displayed in the group “Overview on results” are mainly based on the whole field with some exceptions. Power, power loss by leakage, and leakage mass flows are given in absolute and relative values. In contrary to the group “Detailed results”, the results are based on different aspects.

7.1.1 Reduction of efficiency of ... and Instantaneous efficiency of ...

The “usable efficiency (after leakage, at field outlet)” is the most interesting value, which occurs at the field outlet. For further description of the other values, please see chapter 7.3.

7.1.2 Leakage mass flow (outward/inward) as fraction of inlet mass flow

The fractions are calculated by the quotient of the leakage mass flow and the inlet mass flow.

7.1.3 Leakage power loss (outward/inward/into load) as fraction of power

The fractions are calculated by the quotient of the leakage power loss and the power, which would occur without leakage. The power without leakage is the sum of the outward and the inward leakage power loss of the field and the power at the field outlet.

7.1.4 Velocity ...

The velocities are calculated from the volume flow and the diameter or side length of a circular or square channel cross-section. No flow resistance is considered here. The velocity into large load volumes is considered for the auxiliary demand and the mass flow optimization.

7.1.5 Mean fluid temperature at zero efficiency (before leak.)

The additional value “mean fluid temperature at zero efficiency (before leak.)” may be interesting. It is important to know, that this value does not occur in the evaluated working point. It is the maximum temperature the field can provide at its outlet with the set boundary conditions, while neglecting the set inlet or mean fluid temperature and the leakage.

7.2 Detailed results (main group) – Values of total system

The group “Detailed results” is divided into sub groups, which contain the results based on different aspects like total system, remaining system without field, field, row, collector, and square meter.

7.2.1 Coefficient of ...

The sub groups “Performance, ...” in “Values of total system” show different coefficients of performance, COP. A COP is the relation of the gained useful solar power or the saved conventional

power to the expended power, whereas powers can be replaced by costs. Figure 18 shows, at which places within the global system the COP are determined.

The system energetic COP considers the thermal power at the field outlet and the electric power demand of the fan to flow through the whole air heating system. This approach is frequently used, e. g. for heat pumps. The other three COP consider the thermal efficiency of the conventional energy converter, which thermal power is to replace. The primary energetic and the monetary COP consider additionally the primary energy factors or the energy prices respectively. The calculation is similar to the right sides of (14) to (17), if the minus is replaced by a fraction stroke, while the field area can be canceled.

All of the four COP variations are additionally calculated including the leakage losses of the load, if the field with overpressure is chosen in a closed loop. The reciprocal of the COP, labeled as "Share of ...", are shown right under each COP.

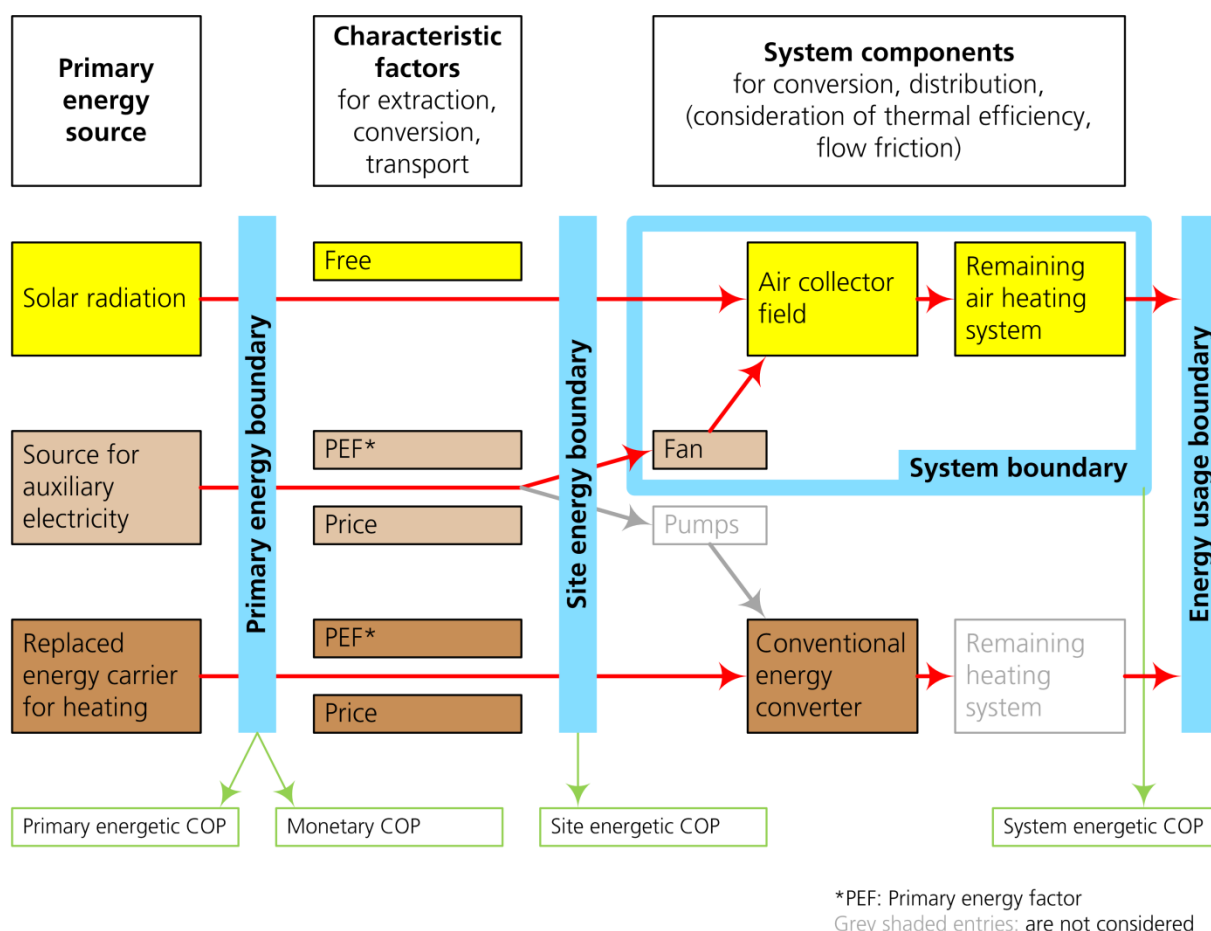


Figure 18: Coefficient of performance determination for air collector fields within the global system context

7.3 Detailed results (main group) – Relative ... and Absolute efficiency reduction at operating point

These values should help to get an idea about the origin of losses specific for air collectors. For this, different theoretic and practical efficiencies and their ratios and differences are shown.

7.3.1 Reduced temperature difference

This value is the main variable of an efficiency curve of liquid heating collectors and the mass flow dependent efficiency map of air collectors. It can also be called as working point. It is drawn on the axis of abscissae for plotted efficiency curves and maps. The axis of ordinates will be labeled with the efficiency.

7.3.2 Theor. effic. for gaining heat (extrapol. infinite mass flow)

The field would reach the theoretic inner efficiency for gaining heat with an infinite mass flow and with no leakage losses at the field and at the load. The absorber temperature would come down to the air temperature, and the thermal losses would be reduced. For this consideration, the mass flow dependent efficiency map (η) is very far extrapolated. Therefore, this value must be handled with precaution. The prefixed adjective 'inner' is described in the next chapter.

7.3.3 Inner efficiency (average mass flow, before leakage)

The inner efficiency is the power gained by the air stream from the absorber and before leakage losses occur, in relation to the irradiance on the collector surface. It is calculated by (η) with the real mass flow. The field would have this efficiency, if it had no leakage.

7.3.4 Usable efficiency (after leakage, at field outlet)

The usable efficiency at the field outlet is the power at the field outlet in relation to the irradiance on the collector field surface. Thermal and leakage losses of the collector are already considered. It is calculated by the enthalpy balance. This efficiency can be named also as outer efficiency.

7.3.5 Usable efficiency (after leakage into load)

For the usable efficiency after leakage into the load, the power gain at the load is related to the irradiation on the collector field surface. In comparison to the efficiency of chapter 7.3.4, the load leakage is considered additionally.

This efficiency can be determined only, if the field with overpressure is chosen, and if the inlet temperature is different to the ambient temperature, what represents a closed loop (see chapter 4.4.2 and 4.4.3). Otherwise, it will show the text "Not for this syst.!".

7.3.6 Ratio of ...

In-between the efficiencies are given ratios of the efficiencies to evaluate the relative influence of mass flow, field leakage, and load leakage. All these ratios are related to the "inner efficiency (average mass flow, before leakage)", the efficiency after the heat transfer absorber-air neglecting leakage. The ratio considering field leakage was used by [7].

7.3.7 Efficiency reduction by ...

In-between the efficiencies are given differences of the efficiencies to evaluate the absolute influence of mass flow, field leakage, and load leakage. The differences are taken from one loss cause to the next, which are mass flow, field leakage, and if applicable load leakage.

The efficiency difference caused by mass flow is subdivided into the cause of infinite to fan mass flow and the cause of fan mass flow to average mass flow. The first efficiency reduction increases with decreasing mass flow. E.g., it can become nearly double-digit percentage point values, if a temperature guided fan control must set a low mass flow to provide a high temperature at a low irradiance. The latter efficiency reduction is usually very small.

The last cell of this sub-group shows the sum of the four efficiency reductions above.

8 Efficiency curve for ScenoCalc (main group)

8.1 Efficiency curve considering one working point

In the group “Efficiency curve for ScenoCalc”, the air collector coefficients, i.e. mass flow dependent efficiency, pressure drop, and leakage coefficients, become converted into the three coefficients of the efficiency curve model of liquid heating collectors (19), which is considered by ScenoCalc. Similarly, this converted coefficient set can be used in other simulation software considering (19).

For the coefficient compilation, one operating point is considered. Since one operating point cannot represent the trend of the leakage behavior over the reduced temperature difference, for a more precise compilation, three operating points can be considered (see chapter 8.2).

The present model (1) considers the mass flow dependent efficiency map of air collectors. For the determination of the three coefficients wanted, one set of boundary conditions for the field, the remaining system, and the climate is applied, which will be given in the “Input” group. The outlet mass flow per row is considered, which can be optimized optionally. The optimization takes the flow resistance and the dynamic pressure loss of the total system into account. The resulting average mass flow per row, which differs to the outlet mass flow per row because of leakage, will be used in (1), so that (1) can be further solved. This results in an anticlockwise rotation of the efficiency curve around the point of zero efficiency (bracketed term with e-function in equation (20) and blue arrow in Figure 19).

$$\eta(\Delta T/G) = \eta_0 - c_1 \cdot T^* - c_2 \cdot G \cdot T^{*2} \quad (19)$$

Additionally, the conversion factor η_0 will be further reduced by subtraction of the efficiency reduction caused by the leakage enthalpy loss at the field and if applicable at the load. The load leakage will be considered for fields with overpressure, if the cell “Field with overpressure” in the group “Input” – “System” is set to 3. This approach results in a parallel down shift of the efficiency curve (second bracketed term in equation (20) and green arrows in Figure 19).

$$\begin{aligned} \eta_0 &= \eta_{0_{max}} \cdot \left(1 - e^{-c_m \cdot \bar{m}_{row}}\right) - \left(\Delta\eta_{L_{field}} + \Delta\eta_{L_{load}}\right) \\ c_1 &= c_{1_{max}} \cdot \left(1 - e^{-c_m \cdot \bar{m}_{row}}\right) \\ c_2 &= c_{2_{max}} \cdot \left(1 - e^{-c_m \cdot \bar{m}_{row}}\right) \end{aligned} \quad (20)$$

For fair and repetitious comparison of air collectors, the mass flow must be optimized to consider the air collectors individual mass flow MMP.

The resulting three coefficients (20) of (19) are shown in the sub group “Converted coefficient set for ScenoCalc (under consideration of thermo-hydraulic mass flow dependency and leakage)” and are ready for annual output simulations in ScenoCalc.

Specialty for Solar KEYMARK

After choosing the feature “A. SK Certificate Pre-Calculation”, the button “Perform Calculation” will perform the calculations including the mass flow optimization automatically.

The input data visible after choosing the feature “B. System Planning, Scientific Studies” will be used as boundary conditions for the Solar KEYMARK pre-calculation with the following exception. The air collector coefficients and their validity boundaries will be copied from the sheet “SK efficiency curve” into the group “Input” – “Solar air collector”. The mass flow of the group “Input” – “Mass flow” will be optimized.

If difficulties are faced to perform the optimization from the sheet “SK efficiency curve”, the feature “B. System Planning, Scientific Studies” can be used with its existing input setting but with the own air collector coefficients to solve the problem.

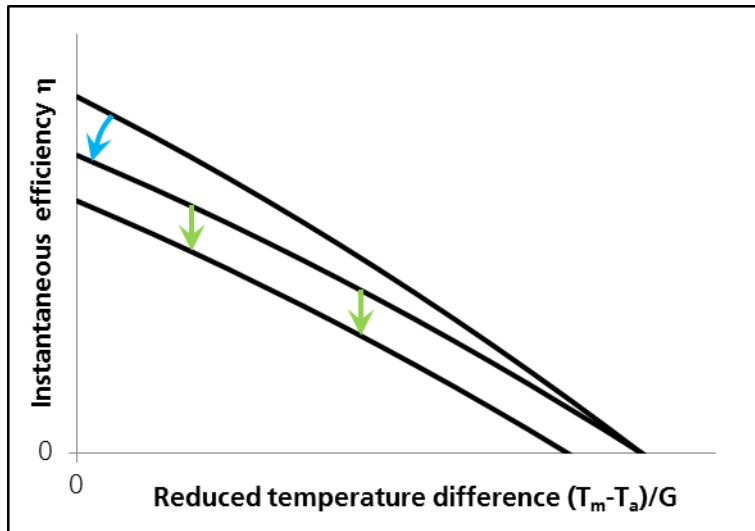


Figure 19: Steps for compilation of air collector model coefficients to liquid heating collector model coefficients (blue arrow for mass flow and flow resistance consideration, green arrows for leakage consideration)

8.2 Efficiency curve considering three working points

An examination showed that the efficiency reduction caused by the leakage enthalpy loss usually is not a parallel downshift of the efficiency curve as used in chapter 8.1. Different system configurations showed different behaviors, listed in Table 1. The leakage enthalpy losses range from zero to rather high and the trend over the reduced temperature difference can increase and decrease. At this point, an average behavior was chosen for the coefficient compilation.

Table 1: Considered influences on the coefficient of performance, COP

System configuration	Field pressure	Leakage enthalpy losses and trend with increasing reduced temperature difference
Open loop	Underpressure	No leakage losses
Open loop	Overpressure	Rather high leakage losses, no trend (just one working point)
Closed loop, leaking load	Underpressure	Rather high leakage losses, increasing trend
Closed loop, without consideration of leaking load	Overpressure	Rather high leakage losses, decreasing trend
Closed loop, with consideration of leaking load	Overpressure	Rather high leakage losses, increasing trend
Closed loop, air-tight load	Over-, underpressure	Rather small leakage losses, increasing trend

To accomplish a coefficient compilation over a range of reduced temperature differences three working points must be considered, which cover that range. For linear efficiency curves, two working points are sufficient. Unfortunately, this is not implemented yet in this Excel workbook. The converted coefficients can be red out from the displayed equation of a trendline in a diagram, which shows the efficiencies of the three working points over the reduced temperature difference. From advanced users, the Excel array formula `LINEST()` can be used to transform the three efficiencies into the wanted

coefficients, which allows a higher grade of automation. The function name may be different in set Excel languages other than English.

9 Afterword

Suggestions, complains, and advice on errors are highly welcome. Please, get back to Christian Welz, Michael Hermann, Korbinian Kramer, or Christoph Thoma (christian.welz@ise.fraunhofer.de, michael.hermann@ise.fraunhofer.de, korbinian.kramer@ise.fraunhofer.de, or christoph.thoma@ise.fraunhofer.de).

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Appendix A: Overview on the calculations of the model

Figure 20 and Figure 21 show the calculation procedure of the model in a simplified form for a given field length and width and a given temperature rise and power respectively. Only some important input data were considered to keep it understandable. The small fractions of the purely thermal or hydraulic model parts show that the calculations are mainly on thermo-hydraulic dependence.

The efficiency map coefficients and the leakage curves coefficients are summarized under the quantities efficiency map and leakage curves. The boxes framed by double lines are parameters to enter in choice-cells in the Excel workbook. Arrows leading to one box are of the same color. The dashed line from the leakage power loss per row is relevant only for the closed loop with a field with overpressure and if the load leakage losses are considered. Arrows going backwards indicate the iterative calculation, which is from the temperature rise to the mean temperature and from the leakage mass flow per row to the field length. The arrow going back from the cost function to the mass flow per row indicates the mass flow optimization algorithm.

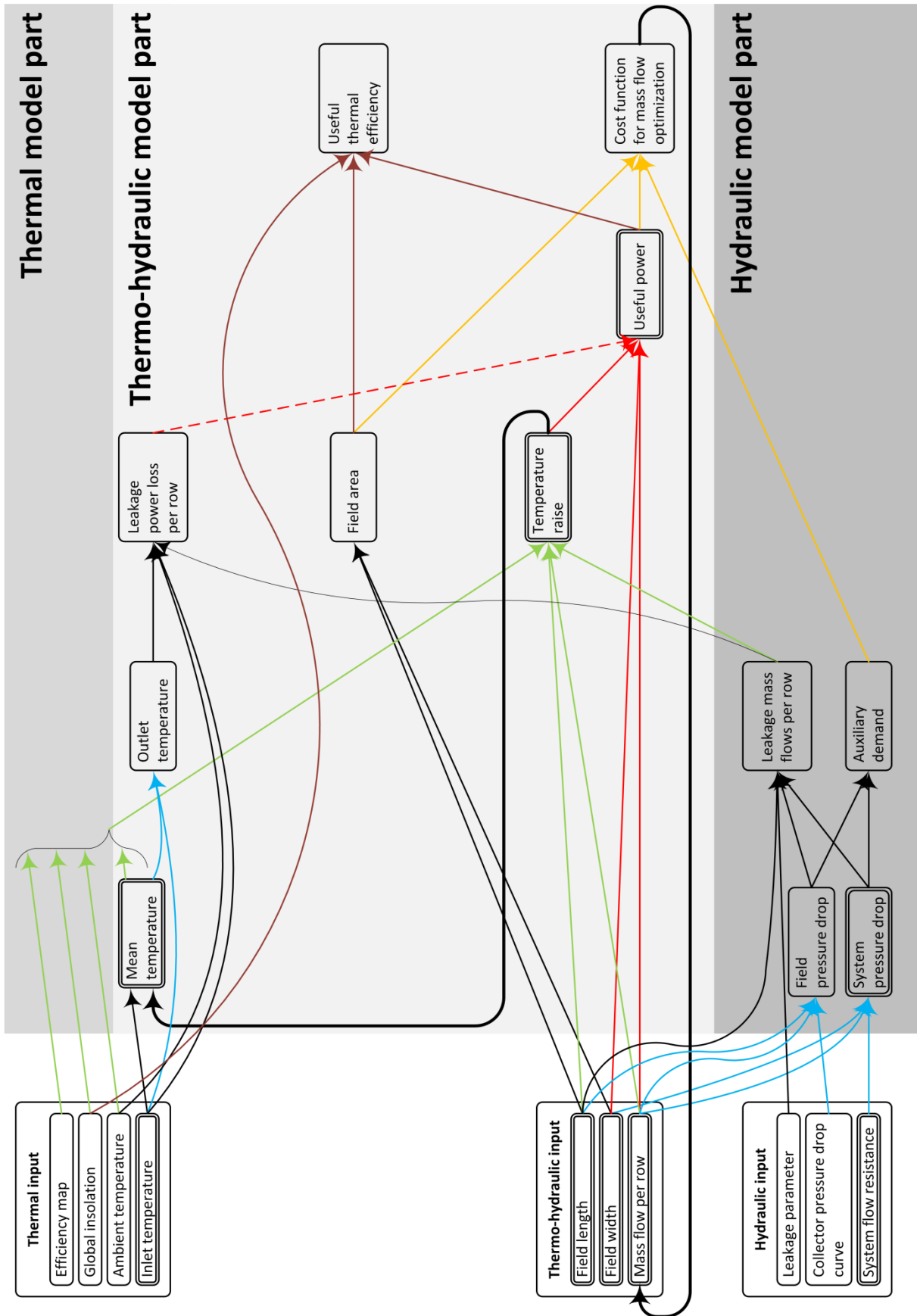


Figure 20: Flow chart of calculations in a simplified form for given field length and width

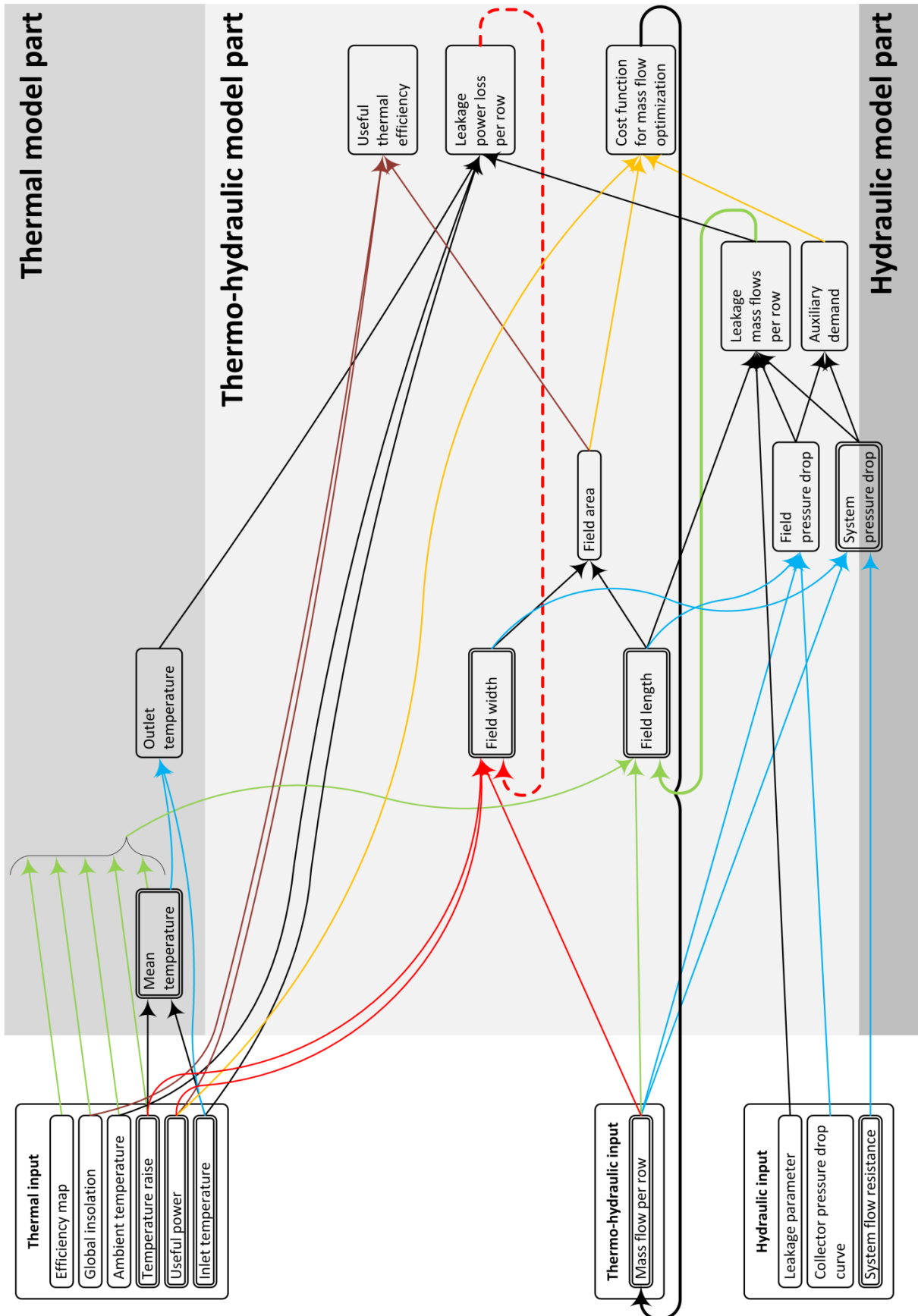


Figure 21: Flow chart of calculations in a simplified form for given temperature rise and thermal power