ECOLOGICAL ASSESSMENT OF SOLAR THERMAL COOLING SYSTEMS

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1. Abstract

The environmental benefits of the use of renewable energy sources for cooling are widely known. As it is common practice this consideration usually only takes into account the driving energy source of the system. A complete and valid statement related to the environmental friendliness can only be obtained by taking into account the whole life cycle of the solar thermal cooling system. This paper presents a procedure to determine the assessment criteria amortisation time, yield ratio and savings on the basis of the global warming potential (GWP) and the cumulative primary energy demand (CED) of the system during its whole lifetime. As an example a typical solar thermal cooling system is compared to a conventional electrically and fossil fuel driven system by performing a life cycle assessment (LCA) on each of the systems. The obtained results and derived optimisation potential are discussed and recommendations for future work are given.

2. Introduction

The worldwide increasing demand for cooling leads to a growing consumption of fossil fuels and increasing environmental pollution. The use of solar thermal driven sorption chillers instead of conventional electrically driven compression chillers is one option to counteract this trend. Apart from simple solar thermal cooling systems thermal driven chillers are also used in combined solar thermal heating and cooling systems. These so called SolarCombiPlus systems are capable of providing space heating, domestic hot water preparation and space cooling. To support the still young but growing market of solar cooling technologies, standardized methods are necessary, that allow an assessment and comparison of different cooling systems based on energetic and ecological aspects. This requires both, standardized performance test methods as well as standardized procedures for the determination of the overall environmental impact. To develop the required testing and assessment procedures for solar thermal cooling systems including SolarCombiPlus systems with a cooling capacity of up to 20 kW_{th}, the project "SolTrans", which is financed by the German Ministry of Economy and Technology (BMWi), was initiated at ITW in 2008 (Frey, 2010). Streicher et al. (2004) developed a methodology to perform an overall environmental assessment of solar domestic hot water systems and solar combisystems. Within the project "SolTrans" this methodology has been taken up and developed further to perform an overall ecological assessment of solar thermal cooling systems and SolarCombiPlus systems which takes the savings of greenhouse gas emissions and primary energy savings of these systems into account.

3. Ecological assessment of solar thermal cooling systems

It is common sense that the use of renewable energy sources for heating and cooling has environmentally friendly effects, such as the reduction of CO_2-emissions and the protection of fossil fuel resources. In order to perform an overall ecological assessment not only energy or emission savings during operation of solar thermal cooling systems have to be taken into account. Also the energy consumption and greenhouse gas emissions caused by production, delivery and maintenance of the system play a decisive role related to the determination of the overall environmental impact. A complete examination has to cover the whole life cycle of the product from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave) according to EN ISO 14040 - 14043 (CEN, 2006). This can be performed by means of a life cycle assessment (LCA) which allows for a comparison of solar cooling systems with conventional systems providing the same comfort and an assessment of their environmental impact. The investigation is carried out in several steps by performing a life cycle inventory (LCI), which is then used for an assessment of the life cycle impact. The results of the life cycle impact assessment (LCIA) are used to determine comparative assessment criteria for solar thermal cooling systems.

3.1 Life cycle inventory analysis

In a first step a life cycle inventory (LCI) analysis is carried out to list all materials and processes needed during the life cycle of the system. For this the investigated system is split up into its main components. The main components are split up further into sub components until each component can be allocated to a dataset of a LCA database. The presented investigation is based on the ecoinvent database (Frischknecht and Rebitzer, 2005). To give an impression of the level of detail Tab. 2 shows the life cycle inventory regarding the production of a main component of solar thermal cooling systems – a solar thermal driven chiller. Materials and processes used in the production are accounted for for each component by quantity and unit. Structure and level of detail interact with the available datasets of the LCA database. Hence the generation of a life cycle inventory is an iterative process.

3.2 Life cycle impact assessment

On the basis of the life cycle inventory a life cycle impact assessment (LCIA) is carried out for different aspects such as primary energy consumption or contribution to global warming. This is performed by applying different impact assessment methods to the elaborated life cycle inventory. The goal of the life cycle assessment is e.g. a statement if it is energetically and ecologically worthwhile to use solar thermal driven cooling systems instead of conventional electrically driven cooling systems. In addition, information about the quantity of energetic and ecological advantages of solar thermal driven cooling systems can be gained. Investigations in this publication are based on two environmental impact categories, the cumulative energy demand (CED) and the global warming potential (GWP).

The cumulative energy demand (CED) accounts for the primary energy required to produce, deliver, operate and maintain the solar cooling system. Apart from the cumulative energy demand properties of the substances that are emitted to the environment during the life cycle of the system play an important role. The global warming potential (GWP) indicates the CO_2-equivalent of emitted greenhouse gases. The characteristic values for greenhouse gas emissions used in this publication are based on global warming potentials published in IPCC's Fourth Assessment Report (IPCC, 2007). The GWP can be determined for different time horizons. In this publication the GWP is determined for the common time horizon of 100 years (GWP 100a).

The total primary energy used for a system is the sum of the cumulative energy demand (CED) for production (index p), operation (index o) and maintenance (index m). The CED [kWh] for production occurs at the beginning of the life cycle of the system. Hence it is independent of time. For operation and maintenance the CED is time dependent [kWh a^{-1}] and therefore multiplied by the time t.

$$CED(t) = CED_p + CED_o \cdot t + CED_m \cdot t \qquad \text{(eq. 1)}$$

A similar equation can be defined for the GWP accounting for the greenhouse gas emissions caused by production (index p), operation (index o) and maintenance (index m). The GWP is given in kg CO_2-equivalents (kg CO_2-Eq.) respectively kg CO_2-Eq. a^{-1} for time dependent values of operation and production.

$$GWP(t) = GWP_p + GWP_o \cdot t + GWP_m \cdot t \qquad \text{(eq. 2)}$$

In the field of refrigeration technology it is common practice to use the TEWI (Total Equivalent Warming Impact) method described in EN 378-1 (CEN, 2010) to determine the total GWP of a system according to:

$$TEWI = GWP_e \cdot L \cdot t + GWP_e \cdot m \cdot (1 - \alpha_R) + t \cdot E_a \cdot \beta \qquad \text{(eq. 3)}$$

Where GWP_e is the global warming potential of the emitted refrigerant in kg CO_2-Eq. per kg refrigerant, L is the leakage rate in kg a^{-1}, t is the time in a, m is the mass of refrigerant filling in kg, α_R is the recovery factor that describes the fraction of refrigerant that can be recycled at the end of the system's life time compared to the total mass of refrigerant in the system. E_a is the annual electrical energy consumption of the system in kWh and β represents the CO_2-emissions caused by production of electricity in kg CO_2-Eq. per kWh. The three summands shown in eq. 3 are also accounted for within the presented life cycle impact assessment. Due to the fact that the first and the last summand are time dependent those two are part of the GWP of operation. The second summand of eq. 3 is considered within the GWP of production. Hence the presented method includes the determination of the complete GWP according to the TEWI method. Apart from the processes accounted for by the TEWI the presented life cycle impact assessment also considers the GWP of producing, operating and maintaining the whole system. This also includes e.g. the production of the refrigerant and initially filling the system as well as the greenhouse effect of refilling leakage losses during operation.

3.3 Comparative assessment criteria

To compare different systems, additional relative assessment criteria are derived from the CED and GWP. Streicher et al. (2004) introduced the energetic payback time of solar thermal systems, which is defined as the period the system has to be in operation in order to save the amount of primary energy that has been spent for production, operation and maintenance of the system. On this basis an amortisation time (AT) regarding the CED and the GWP is defined. The amortisation time (AT) specifies the time a solar thermal driven system (index sol) has to be in operation to save the primary energy consumption or greenhouse gas emissions that were caused by the additional expense of production, operation and maintenance compared to a conventional system (index conv). By comparing the total CED or GWP of the solar thermal cooling system with the total CED or GWP of the conventional system according to eq. 4 and eq. 5 the amortisation time for the CED and GWP can be determined according to eq. 6 and eq. 7.

$$CED(t)_{sol} = CED(t)_{conv} \quad \text{(eq. 4)}$$

$$GWP(t)_{sol} = GWP(t)_{conv} \quad \text{(eq. 5)}$$

$$AT_{CED} = \frac{CED_{p,sol} - CED_{p,conv}}{(CED_o + CED_m)_{conv} - (CED_o + CED_m)_{sol}} \quad \text{(eq. 6)}$$

$$AT_{GWP} = \frac{GWP_{p,sol} - GWP_{p,conv}}{(GWP_o + GWP_m)_{conv} - (GWP_o + GWP_m)_{sol}} \quad \text{(eq. 7)}$$

If a solar thermal cooling system has a lifetime longer than the specific amortisation time AT it is energetically and ecologically worthwhile to use it. Hence, based on this assessment criterion a statement can be made if the usage of a solar thermal cooling system is preferable, instead of e.g. using a conventional, electrically driven compression cooling system to provide the same comfort.

Beyond the amortisation time the system effectively saves primary energy and reduces the emissions of greenhouse gases. However the amortisation time AT does not give a conclusion about the quantity of saved energy and emissions. The absolute values of saved primary energy or avoided emissions of greenhouse gases (index sav) are time dependent and can easily be described by the difference between the total CED resp. GWP of the conventional system and the solar thermal driven system:

$$CED_{sav}(t) = CED_{conv}(t) - CED_{sol}(t) \quad \text{(eq. 8)}$$

$$GWP_{sav}(t) = GWP_{conv}(t) - GWP_{sol}(t) \quad \text{(eq. 9)}$$

In order to provide a comparable criterion that takes the quantity of saved energy and emissions into account a third assessment criterion is defined - the yield ratio (YR). This factor specifies how often a system saves during its lifetime t_{life} the amount of primary energy or greenhouse gases that was caused by the production compared to a conventional system. The yield ratio is an indicator of how effective a system is in saving energy or preventing the emission of greenhouse gases. The yield ratio is calculated by the fraction of the lifetime (t_{life}) and the specific amortisation time according to eq. 10 and eq. 11.

$$YR_{CED} = \frac{(CED_o(t_{life}) + CED_m(t_{life}))_{conv} - (CED_o(t_{life}) + CED_m(t_{life}))_{sol}}{CED_{p,sol} - CED_{p,conv}} = \frac{t_{life}}{AT_{CED}} \quad \text{(eq. 10)}$$

$$YR_{GWP} = \frac{(GWP_o(t_{life}) + GWP_m(t_{life}))_{conv} - (GWP_o(t_{life}) + GWP_m(t_{life}))_{sol}}{GWP_{p,sol} - GWP_{p,conv}} = \frac{t_{life}}{AT_{GWP}} \quad \text{(eq. 11)}$$

Due to the fact that solar thermal cooling systems are a very young technology there is so far no reliable information on the lifetime of these systems. The lifetime of solar combisystems is in the range of 20 years. Hence, in the following a lifetime of 20 years is estimated for the whole solar thermal cooling system. This value may be adapted with available long term data of solar thermal cooling systems.

4. Description of the investigated solar cooling system and the reference system

As already mentioned the life cycle assessment is performed by comparing a solar thermal cooling system, in this case a SolarCombiPlus system, to a conventional heating and cooling system using an electrically driven chiller and an oil fired boiler providing the same comfort. As an example, in the following a fictive typical SolarCombiPlus system is opposed to a generic conventional heating and cooling system.

4.1 Solar thermal cooling system: SolarCombiPlus system

The operated thermal driven chiller is an absorption chiller using lithium bromide as sorbent and water as refrigerant. It is driven by thermal energy provided by eleven evacuated tubular collectors with a total aperture area of 38.5 m^2. The working fluid of all circuits is water. At nominal operation the absorption chiller provides a chilling capacity of 10 kW_{th}. To temporarily bridge a lack related to the availability of thermal driving energy a heat store with a total volume of 2.000 l is used. The absorption chiller provides chilled water to the cold distribution system consisting of four convectors with an electricity consumption of 56 W each. Full cooling capacity and high efficiency of thermal driven chillers can only be reached when operating the chiller at relative high chilling temperatures (14 – 18 °C chilled water temperature). Due to this fact the convectors are sized very large in comparison to the convectors of conventional cooling systems providing space cooling at convector inlet flow temperatures of 14 °C. Waste heat of the solar cooling system is rejected by a hybrid heat rejection unit with a nominal electricity consumption of the fans of 280 W. In times of high outdoor temperatures and high cooling loads the evaporative cooling is used by spraying water onto the ambient air heat exchanger. Fig. 1 shows the investigated SolarCombiPlus system. The dotted line indicates the boundary used for LCA. Boiler, domestic hot water distribution system, space heating distribution system as well as the pumps in the boiler circuit and the heating circuit are outside the boundary due to the fact that they are identical for both the SolarCombiPlus system and the conventional reference system. The four circulation pumps inside the boundary are grouped in a hydraulic station. A central controller with a nominal power of 1.5 W is used to control the whole system and the room temperatures. The fractional energy savings of the system regarding the heat demand are considered to be 45 %. The rest is covered by the boiler.

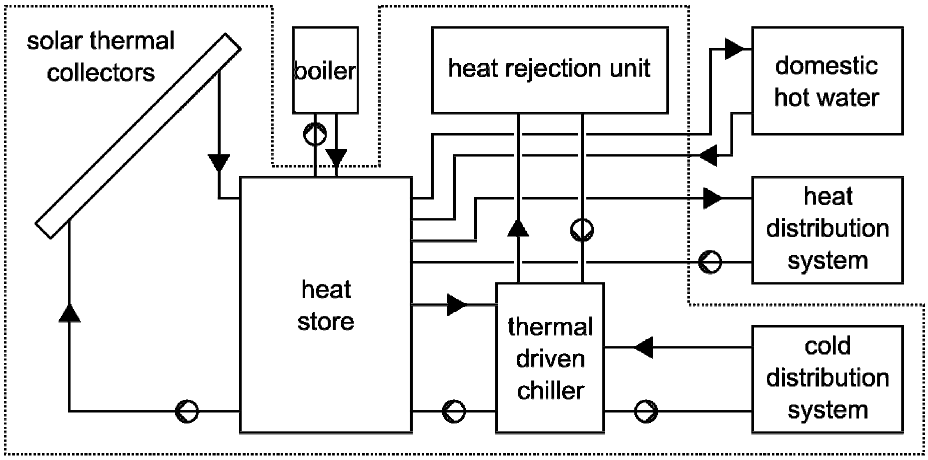

Fig. 1: Hydraulic scheme of the SolarCombiPlus system

4.2 Conventional reference heating and cooling system

The European market for individual air conditioning systems is dominated by single split units with 78 % market share (Grignon-Masse et al.). Hence, as reference cooling system a conventional electrically driven compression cooling system is used. A system consisting in total of four split units with a cooling capacity of 2.5 kW_{th} each is assumed. The energy efficiency of an electrically driven cooling unit is characterised by the Energy Efficiency Ratio (EER). According to eq. 12 it is defined as the ratio between cooling capacity $\dot{Q}_{cool}$ and electric power input P_{el}.

$$EER = \frac{\dot{Q}_{cool}}{P_{el}} \qquad \text{(eq. 12)}$$

Riviere et al. (2009) identified an average Energy Efficiency Ratio (EER) of single split units for cooling of 2.9. Taking this into account a total average electrical power consumption of 3,448 W is needed to provide a chilling capacity of 10 kW_{th}. Fig. 2 shows the conventional heating and cooling system used as reference system. The boundary is given by the dotted line. It includes the split air conditioners and a 135 l heat store. The volume of the heat store was chosen in accordance with the reference system used by Streicher et al. (2004).

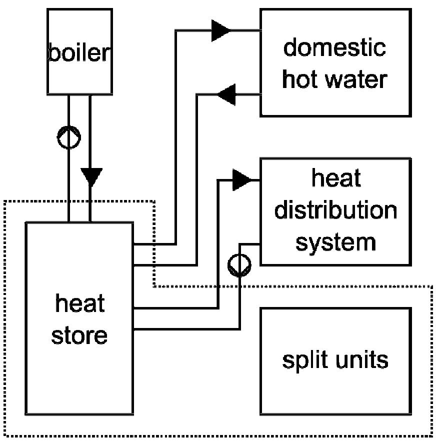

Fig. 2: Hydraulic scheme of the conventional reference system

5. Impact assessment of the investigated cooling systems

In order to determine the cumulative energy demand and the global warming potential for each system the CED and GWP for production, maintenance, and operation have to be determined. Disposal or recycling of the systems apart from the recovery of the refrigerant is not accounted for in this investigation due to the insufficient data base regarding disposal. All specific values for CED and GWP are taken from the ecoinvent database v2.2, which represents the situation in Germany in 2010. Direct emissions of R134a to the environment are accounted for with a GWP of 1,430 according to IPCC (2007).

5.1 Impact of production

The CED for production includes the primary energy needed for all production processes beginning with the mining of raw materials, conversion to semi finished products, manufacturing of the final product, transport and installation of the system. The GWP of production includes all emissions of greenhouse gases during this phase of the life cycle. Following this procedure the cumulative energy demand and the global warming potential are determined for all main components of the SolarCombiPlus system and the conventional heating and cooling system as shown in Tab. 1.

Tab. 1: Determination of the cumulative energy demand and the global warming potential for production

Main component	SolarCombiPlus system			Reference system		
	Weight [kg]	CED [kWh]	GWP [kg CO_2-Eq.]	Weight [kg]	CED [kWh]	GWP [kg CO_2-Eq.]
Absorption chiller	380.0	7,157.0	1,623.2	-	-	-
Piping	151.0	2,303.2	410.9	-	-	-
Store	268.0	3,634.0	720.5	90.0	920.0	187.0
Extension vessel	7.6	185.2	37.7	-	-	-
Hydraulic station	45.5	557.1	117.5	-	-	-
Solar collectors	634.2	26,248.3	3,717.5	-	-	-
Collector field periphery	88.7	3,209.3	722.3	-	-	-
Heat rejection unit	166.0	3,579.8	1,059.1	-	-	-
Convectors	244.4	7,856.9	1,844.4	-	-	-
Split unit	-	-	-	185.2	3,970.8	2,260.4
Sum materials and processes	1,985.3	54,730.9	10,253.2	275.2	4,890.8	2,447.4
Transport (incl. 10 wt% packing)	2,183.9	3,123.0	633.4	302.7	644.7	130.1
Assembly and installation	-	5,785.4	1,088.7	-	553.6	257.8
Sum production	2,183.9	63,639.3	11,975.3	302.7	6,089.1	2,835.3

To determine the values of GWP and CED for production the main components are divided into smaller sub-components until a suitable level of detail is reached to be able to use the given component properties (e.g. mass, material) in combination with the corresponding data of the ecoinvent database. The absolute values (CED [kWh], GWP [kg CO_2-Eq.]) are obtained by multiplication of the specific quantity with the respective unit-specific value (CED [kWh $unit^{-1}$], GWP [kg CO_2-Eq. $unit^{-1}$]) from the ecoinvent database. As an example of main components the life cycle inventory and assessment for the thermal driven chiller is given in Tab. 2. The life cycle inventory and assessment of the other main components of the SolarCombiPlus system and the reference system are not listed but where performed with the same level of detail.

Due to the fact that there is no dataset available for lithium bromide the dataset of a similar material (lithium chloride) was used. In the conventional system each air conditioning unit contains 1 kg of the widely used R134a as refrigerant. Based on the overview on refrigerant leakages of common cooling systems given by Frischknecht (1999) the leakages are assumed to be 3 % during initial filling of the system and 15 % at the end of the lifetime (α_R = 0.85). These recovery losses at the end of the system's life are accounted for within the impact of production to reach conformity with the TEWI method.

Tab. 2: Life Cycle Inventory and Assessment of the investigated absorption chiller

Component	Material / Process	Unit	Quantity	CED		GWP	
				[kWh unit^{-1}]	[kWh]	[kg CO_2-Eq. unit^{-1}]	[kg CO_2-Eq.]
Vessels, tube bundle heat exchangers and plate heat exchangers (generator, condenser, evaporator, absorber, solvent heat exchanger, reservoirs)	chromium steel	[kg]	150.0	21.3	3195.0	4.5	675.0
	chromium steel sheet rolling	[kg]	125.0	3.0	375.0	0.6	75.0
	drawing of chromium steel pipe	[kg]	25.0	1.2	30.0	4.5	112.5
	steel welding using gas	[m]	5.0	0.6	3.0	0.2	1.0
Valves (hand valves and actuated control valves)	chromium steel	[kg]	5.0	21.3	106.5	4.5	22.5
	chromium steel product MFG	[kg]	5.0	11.8	59.0	2.4	12.0
	brass	[kg]	5.0	11.9	59.5	2.5	12.5
	brass product MFG	[kg]	5.0	9.1	45.5	1.9	9.5
	polypropylene handle	[kg]	0.5	20.9	10.5	2.0	1.0
	plastic injection moulding	[kg]	0.5	8.0	4.0	1.3	0.7
	controller	[kg]	1.5	128.4	192.6	26.0	39.0
Pumps	pumps (3 x 2,5 kg)	[pcs.]	3.0	32.9	98.7	7.0	21.0
Thermal insulation	thermal insulation	[kg]	2.5	35.1	87.8	4.5	11.3
Screw connections of the piping	chromium steel	[kg]	5.0	21.3	106.5	4.5	22.5
	chromium steel product MFG	[kg]	5.0	11.8	59.0	2.4	12.0
Refrigerant (lithium bromide)	production	[kg]	10.0	17.8	178.0	4.6	46.0
Frame structure	low-alloyed steel	[kg]	40.0	7.7	308.0	1.8	72.0
	steel sheet rolling	[kg]	40.0	1.8	72.0	0.4	16.0
Base tub	chromium steel	[kg]	25.0	21.3	532.5	4.5	112.5
	chromium steel sheet rolling	[kg]	25.0	3.0	75.0	0.6	15.0
Sheet metal covering	low-alloyed steel	[kg]	100.0	7.7	770.0	1.8	180.0
	steel sheet rolling	[kg]	100.0	1.8	180.0	0.4	40.0
Welding seam of the casing	steel welding	[m]	1.0	0.6	0.6	0.2	0.2
Paint	alkyd paint	[kg]	2.0	23.1	46.2	2.9	5.8
Chromium steel piping	chromium steel	[kg]	10.0	21.3	213.0	4.5	45.0
	chromium steel sheet rolling	[kg]	10.0	3.0	30.0	0.6	6.0
Copper piping	copper	[kg]	15.0	9.4	141.0	1.9	28.5
	copper sheet rolling	[kg]	15.0	1.8	27.0	0.4	6.0
Welding seam of piping	steel welding of piping	[m]	20.0	0.6	12.0	0.2	4.0
Thermal insulation of the piping	thermal insulation of tubes	[kg]	1.0	35.1	35.1	4.5	4.5
Metal working factory	metal working factory	[kg]	340.0	0.3	102.0	0.0	13.2
Plastics processing factory	plastics processing factory	[kg]	0.5	0.9	0.5	0.2	0.0
Pump factory	pump factory	[pcs.]	3.0	0.5	1.5	0.1	1.0
Sum	**-**	**[kg]**	**380.0**	**-**	**7157.0**	**-**	**1623.2**

After manufacturing (MFG) the system has to be transported to the place of installation. As obvious and also shown in Tab. 3 the cumulative energy demand and the global warming potential depend on the distance and the total weight of the system. For transportation packaging of the system is necessary. The weight of the packaging is assumed to be 10 % of the weight of the system. Hence the total weight for transportation including packaging is 110 % of the system weight. In conformance with Streicher et al. (2004) it was assumed that the systems are transported by truck from the manufacturing plant to the wholesaler over a distance of 300 km. From the wholesaler to the place of installation the system is transported by delivery van over a distance of 100 km. Split air conditioner units are usually produced in Asia. Hence an additional transport effort from Osaka harbour to Hamburg harbour is considered for the split units.

For assembly and installation there is no general database available. The effort of installation varies depending on the installation place and the system. Following Streicher et al. (2004) a general approach of 10 % of the CED resp. GWP of the production of materials and transport is used to calculate the impact of assembly and installation. Taking manufacturing, transport and installation into account a total sum of CED resp. GWP can be obtained as shown in Tab. 1.

Tab. 3: Determination of cumulative energy demand and global warming potential for transport

SolarCombiPlus system			CED		GWP	
Vehicle	**Distance [km]**	**Weight [kg]**	**[kWh t^{-1} km^{-1}]**	**[kWh]**	**[kg CO_2-Eq. t^{-1} km^{-1}]**	**[kg CO_2-Eq.]**
Lorry	300	2,183.9	1.6	1,048.3	0.3	196.6
Delivery van	100	2,183.9	9.5	2,074.7	2.0	436.8
Sum	-	-	-	**3,123.0**	-	**633.4**

Reference system			CED		GWP	
Vehicle	**Distance [km]**	**Weight [kg]**	**[kWh t^{-1} km^{-1}]**	**[kWh]**	**[kg CO_2-Eq. t^{-1} km^{-1}]**	**[kg CO_2-Eq.]**
Transoceanic freight ship	20,800	203.7	0.05	211.8	0.01	42.4
Lorry	300	302.7	1.6	145.3	0.3	27.2
Delivery van	100	302.7	9.5	287.6	2.0	60.5
Sum	-	-	-	**644.7**	-	**130.1**

5.2 Impact of Operation

The energetic and ecological impact of operation is primarily caused by the consumption of fossil fuel and electrical power. The GWP_o is additionally influenced by the leakage of refrigerant from the conventional cooling system. The annual CED caused by electrical components is obtained by multiplication of the power consumption, the operating hours and the primary energy factor for electricity. The CED caused by the boiler firing is obtained by division of the annual thermal energy demand for space heating and domestic hot water preparation by the boiler efficiency and multiplication with the primary energy factor of oil. For the annual GWP the specific values of greenhouse gas emissions are used instead of the primary energy factors.

Tab. 4: Determination of the cumulative energy demand and the global warming potential for operation

SolarCombiPlus system			CED		GWP	
Electricity consumer	**Power consumption [W]**	**Operating hours [h a^{-1}]**	**[kWh kWh_{el}^{-1}]**	**[kWh a^{-1}]**	**[kg CO_2-Eq. kWh_{el}^{-1}]**	**[kg CO_2-Eq. a^{-1}]**
Cold distribution pump	40	500	3.5	70.0	0.7	14.0
Chiller pump station	120	500	3.5	210.0	0.7	42.0
Solar pumps	120	1,500	3.5	630.0	0.7	126.0
Chiller	150	500	3.5	262.5	0.7	52.5
Heat rejection unit	280	500	3.5	490.0	0.7	98.0
Controller	1.5	8,760	3.5	46.0	0.7	9.2
Convectors	224	500	3.5	392.0	0.7	78.4
Fuel consumer	**Energy demand [kWh_{th} a^{-1}]**	**boiler efficiency [-]**	**[kWh kWh_{th}^{-1}]**	**[kWh $^{-1}$]**	**[kg CO_2-Eq. kWh_{th}^{-1}]**	**[kg CO_2-Eq. a^{-1}]**
Oil fired boiler	6,973.5	0.85	1.3	10,665.4	0.3	2,461.2
Sum	-	-	-	**12,765.9**	-	**2,881.3**

Reference system			CED		GWP	
Electricity consumer	**Power consumption [W]**	**Operating hours [h a^{-1}]**	**[kWh kWh_{el}^{-1}]**	**[kWh a^{-1}]**	**[kg CO_2-Eq. kWh_{el}^{-1}]**	**[kg CO_2-Eq. a^{-1}]**
Split Unit	3,448.3	500	3.5	6,034.5	0.7	1,206.9
Controller	6.0	8,760	3.5	184.0	0.7	36.8
Leakage of refrigerant [kg a^{-1}]			**[kWh kg^{-1}]**	**[kWh a^{-1}]**	**[kg CO_2-Eq. kg^{-1}]**	**[kg CO_2-Eq. a^{-1}]**
0.3			0.0	0.0	1,430.0	429.0
Fuel consumer	**Energy demand [kWh_{th} a^{-1}]**	**boiler efficiency [-]**	**[kWh kWh_{th}^{-1}]**	**[kWh a^{-1}]**	**[kg CO_2-Eq. kWh_{th}^{-1}]**	**[kg CO_2-Eq. a^{-1}]**
Oil fired boiler	12,679.0	0.85	1.3	19,391.4	0.3	4,474.9
Sum	-	-	**-**	**25,609.9**	**-**	**6,147.6**

The total annual thermal energy demand for space heating and domestic hot water preparation is considered to be 12,679 kWh_{th}. According to EN-12977-2 this value consists of 9,090 kWh_{th} for space heating, 2,945 kWh_{th} for domestic hot water preparation and 644 kWh_{th} thermal losses of the heat store. Chiller operation is assumed to be 500 h a^{-1} according to the guideline 2002/31/EG (EG, 2002) of the European commission regarding energy labelling of room air conditioners. As shown in Tab. 4, for the reference system no pumps are considered. Nevertheless the annual consumption of electrical energy of the reference system is nearly three times as high as the electrical energy consumption of the solar thermal driven system due to the operation of compressors in the split units. According to Frischknecht (1999) the leakages during operation are assumed to be 7.5 % per year (L = 0.3 kg a^{-1} for four units).

5.3 Impact of Maintenance

Maintenance and service for the SolarCombiPlus system are considered to consist of revision effort like inspection of the primary pressure of the expansion vessel and system pressure every year. Inspection mainly causes expenditure of human labour which is not taken into account in the assessment with regard to CED and GWP. For the reference system an annual inspection is required according to EN 378-4. Within this inspection the refrigerant leakage is being compensated by refilling the lost amount of refrigerant. Apart from this for both systems the energetic and ecological impact of driving to the place of installation has to be taken into account. The bi-directional journey is considered to be 2 x 30 km = 60 km in a passenger car. Hence a yearly value of 60 km in a passenger car is accounted for for both systems. The unit pkm refers to passenger-kilometre. The impact of maintenance is summarized in Tab. 5.

Tab. 5: Summary of the cumulative energy demand and the global warming potential for maintenance

SolarCombiPlus system			CED		GWP	
Maintenance	**Unit**	**Quantity**	**[kWh a^{-1} $unit^{-1}$]**	**[kWh a^{-1}]**	**[kg CO_2-Eq. a^{-1} $unit^{-1}$]**	**[kg CO_2-Eq. a^{-1}]**
Passenger car	[pkm]	60	1.4	84.0	0.2	12.0
Sum	**-**	**-**	**-**	**84.0**	**-**	**12.0**

Reference system			CED		GWP	
Maintenance	**Unit**	**Quantity**	**[kWh a^{-1} $unit^{-1}$]**	**[kWh a^{-1}]**	**[kg CO_2-Eq. a^{-1} $unit^{-1}$]**	**[kg CO_2-Eq. a^{-1}]**
Passenger car	[pkm]	60	1.4	84.0	0.2	12.0
Refilling refrigerant	[kg]	0.3	44.6	13.4	103.3	31.0
Sum	**-**	**-**	**-**	**97.4**	**-**	**43.0**

By this CED and GWP for production, operation and maintenance are determined and listed in Tab. 6. A total sum cannot be provided due to the fact that the values for operation and maintenance are time dependent. On the basis of these values the comparative assessment criteria introduced in chapter 3.3 are determined and listed in Tab. 7.

Tab. 6: Summary of the CED and GWP potential for production, operation and maintenance

	CED			GWP		
	Unit	SolarCombiPlus system	Reference system	Unit	SolarCombiPlus system	Reference system
Production	kWh	63,639.3	6089.1	kg CO_2-Eq.	11,975.3	2,835.3
Operation	kWh a^{-1}	12,765.9	25,609.9	kg CO_2-Eq. a^{-1}	2,881.3	6,147.6
Maintenance	kWh a^{-1}	84.0	97.4	kg CO_2-Eq. a^{-1}	12.0	43.0

Tab. 7: Amortisation time, yield ratio and achieved savings during lifetime regarding CED and GWP

CED			GWP		
AT	YR	savings	AT	YR	savings
[a]	[-]	[kWh]	[a]	[-]	[kg CO_2-Eq.]
4.5	**4.5**	**199,597.8**	**2.8**	**7.2**	**56,806.0**

After 4.5 years of operation the investigated SolarCombiPlus system effectively saves primary energy. Due to the fact that thermal driven chillers only use harmless working fluids with regard to global warming, the amortisation time related to the GWP is only 2.8 years. After this period of operation the SolarCombiPlus system effectively contributes to decreasing the greenhouse effect. In a lifetime of 20 years the investigated SolarCombiPlus system is capable of saving nearly 57 tons of CO_2 which is about five times as much as the amount of greenhouse gases that have been emitted during production. Solar thermal cooling systems and especially SolarCombiPlus systems can very effectively contribute to the reduction of global warming and the protection of non renewable energy sources.

6. Ecological Assessment of cooling systems

Life cycle assessment according to the presented procedure not only provides a final statement on the ecological and energetic profitability of solar thermal cooling systems. It also allows the comparison of different system configurations and the determination of optimisation potential.

A SolarCombiPlus system gives the opportunity of using one distribution both for heat distribution and cold distribution for example in a floor heating system. Hence it is possible to save the CED and GWP caused by the convectors of the investigated SolarCombiPlus system. Apart from these savings the efficiency of the thermal driven chiller can be increased using a floor cooling due to the higher cooling temperatures that are possible. A case study for the combined use of the distribution system for space heating and cooling has been carried out. All other system characteristics including operation characteristics of the chiller are estimated to be the same.

Tab. 8: Summary of the CED and GWP potential for production, operation and maintenance

	CED			GWP		
	Unit	SolarCombiPlus system	Reference system	Unit	SolarCombiPlus system	Reference system
Production	kWh	54,531.6	5,849.4	kg CO_2-Eq.	9,873.7	2,790.8
Operation	kWh a^{-1}	12,373.9	25,609.9	kg CO_2-Eq. a^{-1}	2,802.9	6.147.6
Maintenance	kWh a^{-1}	84.0	95.6	kg CO_2-Eq. a^{-1}	12.0	43.0

Tab. 8 shows the GWP and CED for production, operation and maintenance of the new system configuration with a combined heating and cooling distribution system. Both the effort for production and the effort for operation of the SolarCombiPlus system have been reduced.

As Tab. 9 shows the amortisation time can be decreased tremendously by 0.7 to 0.8 years when using a combined heat and cold distribution system instead of convectors. The yield ratio is increased and remarkable savings are achieved. The combined use of the distribution system results in an increase of the savings of 6.4 % regarding greenhouse gas emissions and 8.4 % regarding primary energy during 20 years of operation.

Tab. 9: Amortisation time, yield ratio and achieved savings during lifetime regarding CED and GWP

CED			**GWP**		
AT	**YR**	**savings**	**AT**	**YR**	**savings**
[a]	**[-]**	**[kWh]**	**[a]**	**[-]**	**[kg CO_2-Eq.]**
3.7	**5.4**	**216,269.8**	**2.1**	**9.5**	**60,430.9**

7. Conclusion

An energetic and ecological assessment based on life cycle assessment (LCA) of solar thermal cooling systems was presented. The energetic amortisation time (AT) introduced for solar domestic hot water systems and solar combisystems by Streicher et al. (2004) was used and extended by an assessment method related to the Global Warming Potential (GWP) of solar thermal cooling systems including SolarCombiPlus systems. As additional assessment criteria the yield ratio (YR) and the absolute savings where introduced. An exemplary assessment of a typical SolarCombiPlus system showed the applicability of this method for solar thermal cooling systems. On the basis of a life cycle impact assessment (LCIA) possibilities for improvement of SolarCombiPlus systems have been identified and evaluated. Hence the described method enables the determination of an overall environmental assessment of solar thermal cooling systems and may additionally be used as optimisation tool.

8. Outlook

Regarding the final values of AT, YR and savings of primary energy and greenhouse gas emissions it has to be taken into account that the compared systems are on the one side an emerging and young technology using small scale thermal solar thermal driven chillers and on the other side a well established technology that has already passed through decades of optimisation. Especially for the thermal driven chiller there is a great potential of reduction of the impact of production and operation e.g. by reducing the material content or weight of the system respectively as well as by decreasing the electrical power consumption. With the beginning commercialization of these systems the ongoing cost reduction will lead to optimisation of production processes and a decrease in the system weight. This will have direct positive effect on the CED and GWP of production. Hence it can be expected that the environmental benefits resulting from the use of solar thermal cooling systems will further increase.

9. Acknowledgements

The work described in this paper is part of the project “Solar thermal heat transformers” (SolTrans) funded by the German BMWi (Bundesministerium für Wirtschaft und Technologie / Federal Ministry of Economics and Technology) under the grant number 0327454A and managed by PtJ (Projektträger Jülich / Project Management Jülich). The authors gratefully acknowledge this support. The sole responsibility for the content of this document lies with the authors.

10. Nomenclature

Quantity	Symbol	Unit
Cumulative energy demand	CED	kWh or kWh a^{-1}
Global warming potential	GWP	kg CO_2-Eq. or kg CO_2-Eq. a^{-1}
Time	t	a
Total Equivalent Warming Impact	TEWI	kg CO_2-Eq.
Leakage rate	L	kg a^{-1}
Recovery factor	α_R	
Global warming potential of electrical energy	β	kg CO_2-Eq. kWh_{el}^{-1}
Yield ratio	YR	
Power	P	W
Amortisation time	AT	a
Energy efficiency ratio	EER	
Annual electricity consumption	E_a	kWh_{el}
Cooling capacity	$\dot{Q}_{cool}$	kW_{th}

Quantity	Subscript
Production	p
Operation	o
Maintenance	m
Emissions	e
Savings	sav
Electrical	el
Thermal	th
Solar	sol
Conventional	conv
Lifetime	life

Name	Abbreviation
Life cycle assessment	LCA
Life cycle inventory	LCI
Life cycle impact assessment	LCIA
German Ministry of Economy and Technology	BMWi
Institute of Thermodynamics and Thermal Engineering	ITW
Research and Testing Centre for Thermal Solar Systems	TZS
Manufacturing	MFG
Pieces	pcs.
Equivalent	Eq.
Project Management Jülich	PtJ

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