Energy Payback Time – A Key Number for the Assessment of Thermal Solar Systems

E. Streicher, W. Heidemann, H. Müller-Steinhagen

University of Stuttgart, Institute for Thermodynamics and Thermal Engineering (ITW)
Pfaffenwaldring 6, D-70550 Stuttgart
Tel.: 0711 / 685-3536, Fax: 0711 / 685-3503
email: streicher@itw.uni-stuttgart.de

An important number for the assessment of thermal solar systems regarding environmental aspects is the energy payback time. This is 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.

The present paper outlines the methodology for determination of the energy payback time of thermal solar systems. It is explained how factors like pump operating hours or fractional energy savings influence the energy payback time. This will be demonstrated by calculating the energy payback time for a typical solar domestic hot water system (SDHW system).

Solar heating systems for combined domestic hot water preparation and space heating, so-called solar combisystems, are more complex in their structure than SDHW systems. As solar space heating can be realized with different system concepts, a uniform methodology is necessary for comparison of different solar combisystems. This uniform methodology is presented in the second part of this paper.

1. Determination of the Energy Payback Time

The energy payback time can be determined by comparing the primary energy embodied in the system (PEA_{in}) with the amount of primary energy that will be saved by the thermal solar system during its estimated lifetime (PEA_{sub}) according to equation 1.

$$PEA_{in}\ (t) = PEA_{sub}\ (t) \tag{1}$$

As can be seen from equation 2, the primary energy embodied in the system (PEA_{in}) comprises the cumulative energy demand for the production (KEA_p), for the operation (KEA_o) and for the maintenance (KEA_m).

$$PEA_{in}\ (t) = KEA_p + KEA_o \cdot t + KEA_m \cdot t \tag{2}$$

The cumulative energy demand for production (KEA_p) also includes transport, assembly and installation of the thermal solar system. It has to be taken into consideration that the cumulative energy demand for the operation and the maintenance are dependent on the lifetime of the thermal solar system.

The amount of primary energy saved by the thermal solar system (PEA_{sub}) is determined by the difference of $Q_{conv,tot}$ and the auxiliary energy ($Q_{aux,tot}$). $Q_{conv,tot}$ represents the total primary energy requirement of a conventional system that is necessary to meet the hot water and in case of a comibsystem also the space heating demand.

$$PEA_{sub}\ (t) = (Q_{conv,tot} - Q_{aux,tot}) \cdot t \tag{3}$$

The energy payback time AZ is calculated according to equation 4.

$$t = AZ = \frac{KEA_p}{Q_{conv,tot} - Q_{aux,tot} - KEA_o - KEA_m} \tag{4}$$

2. Energy Payback Time of Solar Domestic Hot Water Systems

In the following, the methodology of determining the energy payback time is explained by an example of two thermal solar systems. Both systems are domestic hot water systems (SDHW-systems) with the same design parameters: 5 m² collector area, 300 l total store volume including an auxiliary volume of 150 l. The two systems differ only in materials used for the collector and the supporting frame. The fractional energy savings are equal for both systems investigated.

2.1 Cumulative Energy Demand for Production

The cumulative energy demand (KEA_p) comprises the energy required for the production of the goods at all phases, including extraction, mining of raw materials, semi-manufactured products and the production process itself. For all following calculations the values are taken from an extensive database called “Ökoinventare für Energiesysteme” from Switzerland.

In order to determine the cumulative energy demand for production (KEA_p) it is suitable to divide the system into components (collectors, mounting frame, heat store, solar station and piping) and to identify the main materials used with their weight proportion. The cumulative energy demand is obtained by multiplication of the weight of the main materials with their respective primary energy demand values.

COLLECTOR	SYSTEM 1					SYSTEM 2				
	Material	**Unit**	**Quan-tity**	**KEA [kWh/unit]**	**KEA [kWh]**	**Material**	**Unit**	**Quan-tity**	**KEA [kWh/unit]**	**KEA [kWh]**
Absorber	copper	[kg]	16	26.83	429	copper	[kg]	16	26.83	429
	coating sputtered	[m²]	5	5.30	27	galvanic coating (black chrome)	[m²]	5	12.37	62
Casing	fibre glass	[kg]	7	29.73	208	aluminium	[kg]	20	42.14	843
	acrylonitrile-butadiene-styrene	[kg]	13	31.67	412					
Cover	glass	[kg]	46	3.69	170	glass	[kg]	46	3.69	170
	glass hardening	[m²]	5	5.50	28	glass hardening	[m²]	5	5.50	28
Insulation	mineral wool	[kg]	10	4.97	50	mineral wool	[kg]	5	4.97	25
						polyurethane	[kg]	5	27.88	139
	silicone	[kg]	1	28.19	28	silicone	[kg]	1	28.19	28
	SUM				**1351**	**SUM**				**1724**
SUPPORTING FRAME	stainless steel	[kg]	16	26.82	429	aluminium	[kg]	16	42.14	674
	SUM				**429**	**SUM**				**674**

Table 1: Impact of different materials on the cumulative energy demand

Table 1 shows the impact of the use of different materials for the collector on the cumulative energy demand. The basis is system 1 with a collector that has a low cumulative energy demand. System 2 varies only in some collector materials used so that the impact on the energy payback time can be shown. The two systems only differ in absorber coating technique, the casing and insulation of the collector and in the material of the supporting frame. It can be seen that the absorber coating technique has only a minor influence on the cumulative energy demand of the whole system. Concerning the cumulative energy demand the relevant components of the collector are the absorber and the casing material.

The cumulative energy demand has to be determined for each component of the thermal solar system as shown in Table 2. It has to be considered that the store volume of the conventional heating system is reduced by using a thermal solar system. Therefore both systems are credited with the cumulative energy demand of a conventional hot water store of 135 litres (store credit in Table 2). The collector of system 1 is integrated in the roof, saving a large number of rooftiles. The cumulative energy demand for the saved rooftiles is therefore also credited to the thermal solar system.

	Unit	SYSTEM 1	SYSTEM 2
Collector	[kWh]	1351	1724
Rooftile credit for roof integrated mounting	[kWh]	-408	0
Supporting frame	[kWh]	429	674
Store	[kWh]	1521	1521
Store credit	[kWh]	-839	-839
Solar station	[kWh]	507	507
Piping	[kWh]	309	309
Sum	[kWh]	2871	3896
Transport	[kWh]	256	275
Transport credit for integrated mounting mode	[kWh]	-205	0
Sum materials and transport	[kWh]	2922	4171
Assembly and installation	[kWh]	292	417
CUMULATIVE ENERGY DEMAND FOR PRODUCTION KEA_p	**[kWh]**	**3214**	**4588**

Table 2: Determination of the cumulative energy demand for production

In addition the cumulative energy demand of the transport of the thermal solar system from the manufacturer to the place of installation has to be considered. It was assumed that a distance of 300 km from the manufacturer to the wholesale dealer is covered with a truck and that a distance of 100 km from the wholesale dealer to the place of installation is covered by a delivery van. The cumulative energy demand for transportation is directly coupled with the total weight of the thermal solar system (including package).

With respect to the integrated mounting mode a credit for the rooftile transport has to be granted. With a general approach that the average transport distance is 400 km and that the transport is carried out by truck, the transport credit amounts to 205 kWh.

Concerning assembly and installation of the thermal solar system no general data base is available. Since the effort of installation varies depending on the kind of thermal solar system, it is calculated with a general approach of 10% of the cumulative energy demand for production of the materials and for the transport.

Table 3 shows the impact on the energy payback time. It can be seen that both systems only differ in the cumulative energy demand for the production that comprises materials used, transport, assembly and installation of the system. All other influences on the energy payback time such as cumulative energy demand for operation and for maintenance and the primary energy saved by the solar system are equal for both systems investigated.

System 1 with a minor cumulative energy demand for production has an energy payback time of 1.4 years. The cumulative energy demand for production of system 2 is 43 % above the value of system 1. This results in an increase of the energy payback time to 2.1 years.

	Symbol	Unit	SYSTEM 1	SYSTEM 2
PRIMARY ENERGY EMBEDDED IN THE SYSTEM				
Materials		[kWh]	2871	3896
Transport		[kWh]	51	275
Assembly and installation		[kWh]	292	417
Cumulative energy demand for production	KEA_p	[kWh]	**3214**	**4588**
Cumulative energy demand for operation	KEA_o	[kWh/a]	**312**	**312**
Cumulative energy demand for maintenance	KEA_m	[kWh/a]	**41**	**41**
PRIMARY ENERGY SAVED				
Yearly primary energy demand of a conventional system	$Q_{conv,tot}$	[kWh/a]	4687	4687
Auxiliary heating demand	$Q_{aux,tot}$	[kWh/a]	2109	2109
Primary energy saved	PEA_{sub}	[kWh/a]	**2578**	**2578**
ENERGY PAYBACK TIME	**AZ**	**[a]**	**1.4**	**2.1**

Table 3: Determination of the energy payback time

2.2 Cumulative Energy Demand for Operation

The cumulative energy demand for operation includes the electrical power consumption of the solar loop pump and the electrical power consumption of the controller. The power consumption in [W] is multiplied by the respective operating hours of the pump and the controller. For the determination of the cumulative energy demand the resulting electrical power consumption has to be multiplied by the primary energy equivalent for electrical power.

	System 1 + System 2			
	Power Consumption [W]	**Operating Hours [h/a]**	**Primary Energy Equivalent [$kWh_{primär}$/kWh]**	**Cumulative Energy Demand [kWh/a]**
Pump	43	1500	3.80	245
Controller	2	8760	3.80	67
Total	**Cumulative Energy Demand for Operation**			**312**

Table 4: Determination of the cumulative energy demand of operation

2.3 Cumulative Energy Demand for Maintenance

Previous experiences show that service and maintenance mainly consist of general revision tasks like checking the concentration of the heat transfer fluid, control of the impermeability of the system, primary pressure of the expansion vessel, control of the system operation pressure etc. In general replacement of certain components is not necessary. These revision tasks mainly cause labor costs. Therefore for the calculation of the cumulative energy demand for maintenance only the driving distance of 30 km (one-way) with a passenger car is considered. Furthermore it is assumed that the inspection is done once a year.

2.4 Primary Energy Saved

The amount of primary energy saved by the thermal solar system PEA_{sub} is determined by the difference between $Q_{conv,tot}$ and the auxiliary primary energy demand required by the thermal solar system $Q_{aux,tot}$. Here, $Q_{conv,tot}$ represents the total primary energy requirement of a conventional reference system that is necessary to meet the hot water and in case of a combisystem also the space heating demand.

The energy demand of a conventional domestic hot water system as well as the heat losses of the domestic hot water store are based on the European draft standard prEN 12977-2 which specifies a unique European reference system. The yearly heat demand for domestic hot water preparation (including heat losses of the store) is 3589 kWh.

For the determination of the yearly energy demand of the reference system (in the form of oil or gas) Q_{conv}, the efficiency of the boiler (η = 85 %) of the conventional (non-solar) reference system has to be considered. Taking into account the primary energy value of gas of 1,11 $kWh_{primär}$/kWh, the yearly primary energy demand of the conventional reference system $Q_{conv,tot}$ amounts to 4687 kWh/a.

The auxiliary primary energy demand required by the thermal solar system can be calculated based on the fractional energy savings. For the calculation of the fractional energy savings the energy saved by the thermal solar system is compared with the energy demand of a conventional (none solar) system. System 1 and system 2 both have fractional energy savings of 55%, which lead to an auxiliary primary energy demand $Q_{aux,tot}$ of 2109 kWh per year.

3. Other Influences on the Energy Payback Time

The yearly energy demand for the operation represents another important influence criterion on the energy payback time. Analysis showed that pump capacities and pump operating hours differ considerably between different thermal solar systems. A comparison of system 2 with a system that differs only in the pump and controller capacity and in the pump operating hours is made in Tables 5 and 6. The fractional energy savings are equal for both systems investigated. Table 6 shows the reduction of the energy payback time.

SYSTEM 2					VARIATION SYSTEM 2				
	Capa-city [W]	Opera-ting Hours [h/a]	Primary Energy Equivalent [kWh_{prim}/kWh]	KEA [kWh/a]		Capa-city [W]	Opera-ting Hours [h/a]	Primary Energy Equivalent [kWh_{prim}/kWh]	KEA [kWh/a]
Pump	43	1500	3.80	245	Pump	25	742	3.80	70
Controller	2	8760	3.80	67	Controller	1.4	8760	3.80	47
KEA_o				**312**	**KEA_o**				**117**

Table 5: Influence of lower capacity and pump operating hours on the cumulative energy demand of operation

	Symbol	Unit	SYSTEM 2	VARIATION SYSTEM 2
PRIMARY ENERGY EMBEDDED IN THE SYSTEM				
Cumulative energy demand for production	KEA_p	[kWh]	**4588**	**4588**
Cumulative energy demand for operation	KEA_o	[kWh/a]	**312**	**117**
Cumulative energy demand for maintenance	KEA_m	[kWh/a]	**41**	**41**
PRIMARY ENERGY SAVED				
Yearly primary energy demand of a conventional system	$Q_{conv,tot}$	[kWh/a]	4687	4687
Auxiliary heating demand	$Q_{aux,tot}$	[kWh/a]	2109	2109
Primary energy saved	PEA_{sub}	[kWh/a]	**2578**	**2578**
ENERGY PAYBACK TIME	**AZ**	**[a]**	**2.1**	**1.9**

Table 6: Influence of cumulative energy demand of operation on the energy payback time

The reduction of the energy payback time of 0.2 years might seem to be very small regarding the lifetime of a thermal solar system of about 20 years. However one should consider that this corresponds to the influence of an increase or decrease of the fractional energy savings of 5% on the energy payback time, as shown in Table 7.

	Symbol	Unit	VARIATION FRACTIONAL ENERGY SAVINGS		
			55%	60%	50%
PRIMARY ENERGY EMBEDDED IN THE SYSTEM					
Cumulative energy demand for production	KEA_p	[kWh]	**4588**	**4588**	**4588**
Cumulative energy demand for operation	KEAo	[kWh/a]	**312**	**312**	**312**
Cumulative energy demand for maintenance	KEAm	[kWh/a]	**41**	**41**	**41**
PRIMARY ENERGY SAVED					
Yearly primary energy demand of a conventional system	$Q_{conv,tot}$	[kWh/a]	4687	4687	4687
Auxiliary heating demand	$Q_{aux,tot}$	[kWh/a]	2109	1875	2343
Primary energy saved	PEA_{sub}	[kWh/a]	**2578**	**2812**	**2344**
ENERGY PAYBACK TIME	**AZ**	**[a]**	**2.1**	**1.9**	**2.3**

Table 7: Influence of different fractional energy savings on the energy payback time

4. Energy Payback Time of Solar Combi-Systems

The general methodology for the determination of the energy payback time of solar combisystems is the same as explained above. The particularities that arise from various different system concepts for the realization of solar space heating will be explained in the following. This will be demonstrated by calculating the energy payback time for four solar combisystems – two combisystems without integrated burner and two combisystems with integrated burner.

4.1 System Boundaries

In order to be able to compare the energy payback time of solar combisystems with different system concepts, system boundaries have to be defined.

The system boundary for solar **combisystems without integrated burner**, i.e. where the boiler is a separate component, is directly at the store. The auxiliary heating loop with boiler and hydraulic station is not taken into consideration as these components do not represent specific solar components. They are also necessary for a "conventional" heating system without using solar energy. The same applies to the hot water loop. Components that are situated beyond the system boundary are not considered.

Solar **combisystems with integrated burner** are thermal solar systems where a gas or oil burner is integrated in the store. As for combisystems without integrated burner, the system boundary is directly at the store. But in this case the balance comprises the integrated burner and the hydraulic station. As flue pipes are situated outside of the system boundary, they are not taken into account.

4.2 Credits

In order to be able to compare solar combisystems with integrated burner with solar combisystems without integrated burner, standardized components are defined that can later be credited to solar combisystems with integrated burner. This will be done by special credits, as already described above with the store credit for the hot water preparation. Depending on the system concept these credits comprise burner, hydraulic station and controller of the heating loop. The single components are balanced with the average values indicated below.

The **reference hydraulic station** consists of a 3-way valve, a mixer, a pump, 3 m copper tubing with insulation and an expansion vessel of 35 l for the heating loop. The cumulative energy demand for the production of this reference hydraulic station amounts to 247 kWh.

For the **reference controller of the heating loop** a controller with a weight of 1.25 kg (including temperature sensors) is defined. The cumulative energy demand for the production of this reference controller amounts to 89 kWh. The nominal power of the reference controller is specified with 3 W. This results in an annual energy consumption of 26 kWh. With the primary energy equivalent for electric power (3.8 kWh_{prim}/kWh) the cumulative energy demand for the operation of this reference controller amounts to 100 kWh per year.

As **reference burner** a standard burner for oil or gas with a weight of 45 kg is specified. It is composed of different materials like mild steel, stainless steel, aluminium, copper and polypropylene. The cumulative energy demand for the production of this burner amounts to 972 kWh.

The application of the credits will be demonstrated with the help of the calculation of the cumulative energy demand for the production of four different solar combisystems.

System Component	Without Integrated Burner		With Integrated Burner	
	System 3	**System 4**	**System 5**	**System 6**
	KEA [kWh]	KEA [kWh]	KEA [kWh]	KEA [kWh]
Collector	4332	3877	2060	4118
Supporting Frame	900	1465	737	697
Store (Store Credit included)	1859	1609	3206	2256
Solar Station	792	716	1347	1943
Piping	305	301	309	309
Credits				
Burner			-972	-972
Hydraulic Station			-247	-247
Controller	-89		-89	
KEA Materials	**8099**	**7968**	**6351**	**8104**

Table 8: Cumulative energy demand of the materials used in solar combisystems with and without integrated burner

As shown in Table 8, a solar combi-system with integrated burner can be credited with a maximum cumulative energy demand of 1308 kWh (system 5). In the case that the controller of the combisystem also includes the control algorithm for the heating loop, credits for the controller are also applicable for solar combisystems without integrated burner, as can be seen in system 3.

As the operation of the controller consumes electrical power, the amount of power consumption has to be credited too. Therefore the cumulative energy demand of the operation will be reduced by a credit of 100 kWh that represents the cumulative energy demand of the reference controller of the heating loop.

4.3 Example

Table 9 contains the calculated results for the four solar combisystems. The determination of the primary energy that will be saved by the thermal solar system during its lifetime will be explained below.

The yearly primary energy demand of the conventional system includes the primary energy demand for hot water preparation as well as the primary energy demand for space heating. According to the European draft standard prEN 12977-2 an amount of 2945 kWh is assumed for the hot water consumption and an amount of 644 kWh is considered for heat losses of the store. The space heating demand of a single family house with low energy consumption standard and approximately 130 m² heated area is 9090 kWh. This results in a total energy consumption of 12679 kWh per year. Taking into account the efficiency of the boiler of $\eta = 85\%$ and the primary energy equivalent of oil or gas with 1.11 $kWh_{primär}/kWh$ yields to the primary energy demand of the reference system $Q_{conv,tot}$. Finally the primary energy saved is calculated by subtraction of the auxiliary heat demand from the primary energy demand of the reference system.

	Symbol	Unit	Without Integrated Burner		With Integrated Burner	
			System 3	System 4	System 5	System 6
PRIMARY ENERGY EMBODIED IN THE SYSTEM						
Production	KEAp	[kWh]	**9448**	**9420**	**7596**	**9531**
Operation	KEAo	[kWh/a]	**282**	**542**	**443**	**207**
Maintenance	KEAm	[kWh/a]	**83**	**83**	**83**	**83**
PRIMARY ENERGY SAVED						
Primary Energy Demand of the Reference System	$Q_{conv,tot}$	[kWh/a]	16557	16557	16557	16557
Auxiliary Heating Demand	$Q_{aux,tot}$	[kWh/a]	12584	12915	14074	11921
Primary Energy Saved	PEA_{sub}	[kWh/a]	**3973**	**3642**	**2483**	**4636**
ENERGY PAYBACK TIME	**AZ**	**[a]**	**2.6**	**3.1**	**3.9**	**2.2**

Table 9: Energy Payback Time of Solar Combi-Systems with and without integrated burner

5. Conclusion

The energy payback time is a suitable method for the integral assessment of thermal solar systems. Solar domestic hot water systems have energy payback times between 1.3 to 2.3 years. For solar combisystems typical energy payback times are slightly higher, from 2.0 to 4.3 years. Taking into consideration that thermal solar systems have a minimum lifetime of 20 years or more, the substantial potential for saving of primary energy has hence been demonstrated.