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Does the use of Solar Home Systems (SHS) contribute to climate protection?

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Abstract

The paper addresses planners and decision-makers in the field of international development cooperation and also institutions concerned with the impacts of project- and technology promotion. The primary aim of the dissemination of Solar Home Systems (SHS) in off grid areas in developing countries is to improve the living conditions of the population in a cost-effective manner. A large-scale dissemination is essential both for significant contributions to development and for climate effectiveness. However, the contribution of SHS to climate protection is disputed. This analysis presents the most important parameters affecting the contribution of SHS to climate protection and quantifies the influence of those parameters. The case considered presupposes the commercial dissemination of SHS. Greenhouse gas (GHG) emissions are affected by the marketing decisions of the supplier of SHS. With regard to the impact on GHG emissions, a comparison is made between traditional lighting with petroleum lamps and the use of dry cell batteries to operate small devices (baseline case) on the one hand and SHSs on the other. The comparison shows GHG savings of around 9 tonnes of CO_2 equivalent GHG emissions within a 20-year period of use of one single 50 Wp SHS compared with the baseline case. The result is robust with respect to variations in GHG-affecting variables. Petroleum consumption and dry cell batteries dominate GHG emissions balances to such an extent that scarcely any importance can be attached to GHG emissions from the transportation and manufacture of SHS. Therefore, it is permissible to use simplified GHG inventories which ignore the GHG emissions arising from the transportation and manufacture of SHS. Therefore the conclusion is, if SHS are commercially disseminated and used cost efficiently to substitute kerosene and dry cell batteries they reduce GHG emissions effectively. In that case SHS can make a significant contribution to climate protection by the dissemination of large numbers.

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1. Introduction

In the rural areas of developing countries, around two billion people live without access to the electricity grid. The typical sources of light used in private households are petroleum pressure lamps and also candles or oil-wick lamps. Dry cell batteries power radios and cassette radios. In more affluent families, television sets are powered by car batteries, which are taken to the nearest town for recharging. From the energy viewpoint, these conventional practices are inefficient and expensive. However, owing to the low overall consumption of energy, such practices are affordable for households.

Photovoltaic (PV) systems, such as Solar Home Systems (SHS), are being promoted by international donor organizations as a cost-effective alternative for the basic electrification of rural households. SHS provide a large proportion of the rural population with access to modern services, such as electric lighting, information and entertainment through television and radio, and thus offer a new dimension of consumer choice in comparison with the typical methods of supply described above. SHS (50 Wp) can be shown to have a cost advantage for households which spend more than around $US 90 per year on the above described conventional energy services [1] [1]. However, broad income segments of the rural population in developing countries can only afford SHS with the help of a loan or on a rental basis. To date, SHS have been beyond the economic reach of the lowest income strata.

Worldwide strategies on climate protection call for the increased use of renewable energy sources in order to reduce greenhouse gas emissions and contribute to sustainable development. Apart from offering a cost-effective supply of energy, SHS are regarded also as a contribution to climate protection and are promoted by international donors, such as the GEF (Global Environment Facility, World Bank/UNDP). However, significant effects with regard to an improvement in the living conditions of the population as well as in climate protection through the use of SHS are only possible if these systems are disseminated in large numbers. According to estimates by GTZ and other institutions, over one million SHS have been installed worldwide, the majority in rural areas of Africa, Latin America and Asia [2]. However, it is not known how many of these systems are being operated properly. Monitoring costs as well as practical and methodological problems make it difficult to obtain reliable

[1] The annual costs of an SHS (50 Wp) including spare parts over a 20-year service life are on the order of $US 90/year. Assuming proper operation in sunny regions, the energy yield is 200-250 Wh/day. If the energy output is fully utilized, there results a theoretical electricity price of around $US 1/kWh (p. 53).

data on the effective service life of the installed SHS. Consequently, statistically insignificant surveys and diverging individual experiences leave much room for speculation.

Therefore, the actual contribution that SHS make, or are capable of making, to climate protection is disputed and is sometimes even called into question. Important arguments advanced in this regard are:

1. For various reasons, many SHS fail in practice to reach the period of use required to achieve energy savings.
2. The input required for manufacturing, transporting and maintaining the SHSs as well as the input required for spare parts are unduly ignored in simplified GHG inventories. For example, in GEF project applications, the greenhouse gas (GHG) emissions from the production of imported PV modules are not taken into account, nor do they consider the GHG emissions caused by international transportation.

The present paper takes up these arguments and estimates GHG emission balances in consideration of economic limits. For this purpose, use is made of project experiences gained with SHS in recent years and also of the now extensive data on GHG emissions in production and transport.

2. The comparison cases

The contribution SHS can make to climate protection is given as the GHG savings as compared with the baseline case. Depending on the local situation, the baseline case may vary, ranging from:

a) small electricity grids operated, for example, with diesel engines;
b) the energy mix in the national electricity grid; to
c) the case of petroleum lamps, dry cell batteries and car batteries (baseline case in the present paper).

The first two baseline cases are relevant to investment decisions by electric utilities which take account of the costs and climate effects of grid expansion versus the decentralized supply of households through SHS.

Baseline case (c) represents the benchmark for the present paper. It is appropriate if in those areas that are remote from the grid, SHS actually displace conventional energy sources (petroleum pressure lamp, dry cell batteries, etc.).

Baseline case (c) is defined in the following for two different energy demand levels or income segments of the rural population. The essential difference lies in the additional use of a TV set operated by car batteries. The key data of the comparison cases (baseline case/alternative) are given in Table 1; further details are described in Appendix A.

Table 1
Energy services of the comparison cases

Comparison case 1: Low energy demand	**Baseline case 1 Traditional supply**	**Alternative 1 (small SHS) (15 Wp)**
Lighting: 4 h/day	Petroleum pressure lamp with kerosene	Compact fluorescent lamps with lead battery (car battery), recharging on site by SHS
Radio/cassette recorder: 2 h/day	Dry cell batteries	
Comparison case 2: Medium energy demand	Baseline case 2 Traditional supply	Alternative 2 (medium SHS) (50 Wp)
Lighting: 5 h/day	Petroleum pressure lamp with kerosene	Compact fluorescent lamps with lead battery (car battery), recharging on site by SHS
Radio/cassette recorder: 2 h/day	Dry cell batteries	
TV set: 4 h/day	Lead battery (car battery), transported to nearest town for recharging	

2.1. Supplier of SHS and the marketing area

A supplier sells SHS on a commercial basis to that part of the population which is able to pay (i.e. for which it is affordable and economically advantageous). This presupposes a cost-covering and profitable supply and maintenance structure [2].

This requirement is important because it is the only way of guaranteeing the sustainable dissemination of SHS. On the other hand, it means that the sales costs incurred by suppliers (advice, delivery, installation, maintenance) must be covered by price mark-ups. The area to which SHS can be supplied-the marketing areas geographically limited, because this is the only way of implementing cost-covering services with acceptable mark-ups on the cost price of SHS. The case of suppliers serving geographically remote customers with small individual systems is excluded.

In order to calculate the costs of the services rendered by the supplier in delivering and maintaining the SHS as well as the associated GHG emissions, the following assumptions are made:

- The supplier has its principal place of business in a district centre (regional centre) with transport links to a port (100 km away) for importation of the SHS.

[2] To date, this requirement is met only in a few cases. Nevertheless, the commercial dissemination of SHSs is an objective which is being promoted by technical cooperation projects, because a high degree of public subsidy could not be financed for large quantities of SHSs.

- The supplier has three regional agencies in the supply area (10,000 km2) each with an action radius of 50 km. To handle its SHS business, the supplier has two permanent employees and uses the personnel of the regional agencies as required. The supplier runs a small truck (pick-up) for transporting the goods to the supply area.
- The supply area is home to 50,000 families, of which around 10,000 households (20%) have typical energy consumption as in baseline case 1 or baseline case 2.
- For these households/income segments the supplier offers small SHS (15 Wp) for low energy consumption as in baseline case 1 or standard SHS (50 Wp) for medium-level energy consumption as in baseline case 2.
- The supplier sells 400 SHS every year (250 small 15 Wp SHS and 150 standard 50 Wp SHS).
- According to marketing studies, the supplier expects market saturation to be reached when 8000 SHS have been sold.

Examples from Technical Cooperation projects and isolated private-sector SHS sales structures show that the costs of selling (marketing, delivery and maintenance) are high. These costs must be covered out of the product margins. Consideration is given to the following reference variables in Table 2.

The supplier's selling price covers the following services:

- delivery and installation of the SHS
- 5-year maintenance guarantee including passing on of manufacturer's guarantees (20 years on PV modules; 6 months on batteries; 1 year on charge controller; etc.).
- After expiry of the manufacturer's guarantees, customers must purchase the spare parts.

Maintenance after expiry of the 5-year maintenance guarantee is offered to customers on a paying basis and is not included in the margin. Through its business activity the supplier generates a pre-tax profit of around $US 8600 per year. Appendix A.4 presents the main elements of the supplier's statement of costs and revenues.

Regarding the GHG inventories, it is of significance that the margin imposes a limit on the costs of selling-and therefore also on the use of energy by transport services for delivery and maintenance in the marketing area. Overall, assuming a

Table 2
Costs of selling a SHS

	Cost price, (cif port) ($US)	Selling price ($US)	Gross margin ($US)
Comparison case 1: 15 Wp SHS	150	200	50
Comparison case 2: 50 Wp standard SHS	350	500	150

20-year period of use of the SHS, there is the following transportation requirement as given in Table 3.

2.2. Results of comparison cases and questions for sensitivity analysis

The results of the comparison cases are presented in the following two charts in Fig. 1 with regard to GHG emissions. The results are described in greater detail in Appendix A.

Comparison case 1: The GHG emissions from a 15 Wp SHS including transportation, replacement investments and maintenance amount to around 160 kg CO2 equivalent over a 20-year period of use.

This corresponds to 2.7% of the GHG emissions of the baseline case and means savings of around 6 tonnes CO_2 equivalent, which is credited predominantly to the avoided consumption of petroleum.

Comparison case 2: The GHG emissions from a 50 Wp SHS including transportation, replacement investments and maintenance amount to around 650 kg CO_2 equivalent over a 20-year period of use.

This corresponds to around 6.8% of the GHG emissions of the baseline case and means savings of around 8.9 tonnes CO_2 equivalent, which is credited predominantly to the avoided consumption of petroleum.

Consequently, both comparison cases demonstrate significant GHG savings through the use of SHS.

After market saturation has been reached in the supply area with a total of 5000 small (15 Wp) SHS and 3000 standard (50 Wp) SHS, there are annual GHG savings of around 2800 tonnes of CO_2 equivalent.

On the basis of the comparison cases, both of which show high GHG savings for SHS, the following questions remain:

1. How sensitive is the result to changes in key parameters?
2. In what borderline cases do SHS or their ways of dissemination lead to additional GHG emissions?

Table 3
Limits for transportation requirements during 20-year period

Transportation requirement for SHS	Case Small 15 Wp SHS (km)	Case Standard 50 Wp SHS (km)
Marine freight	10,000	10,000
Truck to target area	100	100
Delivery and maintenance by small truck (pick-up)	150	500

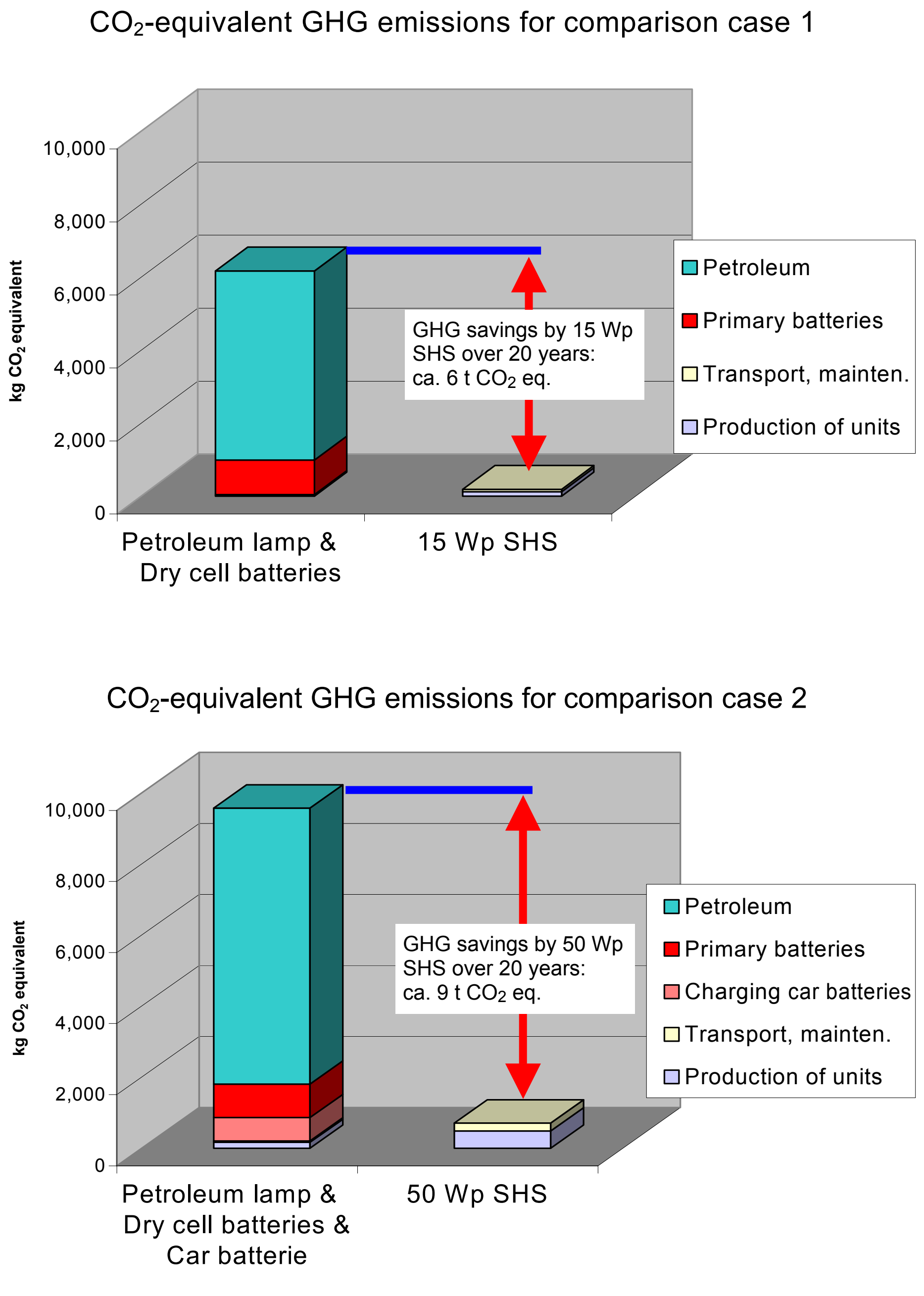

Fig. 1. Results of GHG comparison cases for small and medium SHS.

A variation of parameters directed at changes in GHG emissions usually also has cost impacts, as is demonstrated by the following example:

If the costs of selling and maintenance are increased as a result of widening the marketing area to include remote regions, then the GHG emissions rise along with the transportation requirements. At the same time, the greater distances and increased costs of transportation to customers result in the need for higher margins on the part of the supplier. However, an increase in costs cannot be passed on to customers and the consequence is that fewer customers find SHS attractive. In the case of significant cost increases, sales remain small, i.e. a large-scale dissemination is not achieved and the GHG impact likewise is marginal.

The GHG-relevant variables cannot be varied beyond certain limits if the intention is to avoid GHG parameter variations whose economic impact *would* jeopardize the large-scale dissemination of SHS. To date, there are no reliable data on the price elasticity of demand for SHS in rural areas of developing countries. Therefore, the present study limits the GHG-relevant variables in that the associated additional costs are allowed to rise by no more than $US 50 for the small 15 Wp SHS and $US 150 for the 50 Wp SHS. It is *assumed* that within these limits the additional costs (price mark-ups) passed on to customers do not have a significantly adverse effect on the demand for SHS.

Proceeding from the above results of the comparison cases, the following questions are now addressed:

What is the effect on the GHG balance if

1. Neither the manufacture of SHS nor their international transportation is taken into account? This calculation follows a national inventory of GHG emissions, assuming that all the components of the SHS are imported.
2. Neither international nor local transportation emissions are taken into account? Both for the reference case and also for the SHS alternative, this simplified assumption completely ignores the GHG emissions arising from transportation (including maintenance), which are in some cases complex and can often not be clearly determined. How great, therefore, is the error caused in the present case by this simplified assumption?
3. Airfreight is used instead of marine freight for the long-distance transportation of the entire SHS? Research shows that airfreight is more expensive than marine freight by a factor of approximately 20. This option is economically disadvantageous and will, in practice, be relevant only in exceptional cases. On international routes with a low volume of freight, the additional costs for air freight of the entire SHS (including spare parts) would even increase the costs by *more than* $US 50 *or* $US 150 respectively and would thus - according to the above-defined limits - jeopardize the large scale dissemination. This case is nevertheless examined here, because it represents an extreme value with regard to GHG emissions.
4. The distances of local transport (delivery and maintenance) have to be doubled?

This case is perfectly realistic if the supplier extends the marketing area or if there is a rise in maintenance costs owing to technical shortcomings. It results in additional costs which can be compensated for by the supplier through an approximately 60% higher margin.

5. Monocrystalline instead of multicrystalline PV modules are used? Compared with multicrystalline PV modules, monocrystalline PV modules require a 25% higher input of energy in manufacture.
6. The period of use of the SHS drops to 10 years? This considers the case that the technical service life of the PV modules-which is, in the final analysis, also assured by the usual guarantee periods of the PV manufacturers-cannot be achieved. The reasons for this may be many and varied and will not be discussed in detail here. Initially, a reduced period of use of the SHS has virtually no adverse effect on the marketing concept and cost structure of the supplier. However, the economic benefits for purchasers of SHS will no longer be achievable in the case of a 10-year period of use.
7. Zinc-carbon dry cell batteries are used instead of alkaline-manganese batteries as the baseline case? Experience shows that in developing countries the use of zinc-carbon batteries is more widespread than that of alkaline-manganese batteries. Consequently, zinc-carbon batteries would be more likely to represent the baseline case than alkaline-manganese batteries. Owing to the more reliable data, however, alkaline-manganese batteries were chosen as the baseline case.

3. Results of parameter variations

Table 4 shows the result of the parameter variations.

Overall, it becomes clear that the SHS-related reductions in GHG emissions are very robust in the face of variations in variables affecting the GHG balance. Even a reduced period of SHS use of only 10 years would still result in significant GHG reductions attributable to SHS.

The results show only a low sensitivity to changes in the local and international transportation requirements (questions 2 and 4). However, this finding should not hide the fact that, in particular, an increase in maintenance costs may quickly drive up the overall costs of SHS, thus making the product too expensive for the target group.[3] Therefore, economic forces that work in-the first place (cost-efficiency, profitability) tend to prevent the GHG benefits of SHS from being considerably diminished.

[3] This result is made plausible by the following consideration: 100 km distance driven with a small truck (diesel-powered pick-up) causes, with personnel, costs of around $US 20 and additionally 43 kg CO_2 equivalent GHG emissions. The costs of a 50 Wp standard SHS ($US 500) would, therefore, rise by 4%, while'the GHG savings would, owing to emissions in transportation, be reduced by 0.5% (with reference to around 9000 kg CO_2 equivalent). Expressed in more general terms: With additional transportation costs, the limit at which an SHS becomes uneconomic is reached 10-times faster than the GHG emissions limit.

Table 4
Results of parameter variations

	Reduction in GHG emissions through SHS assuming a 20-year period of use (tonnes CO_2 equivalent)	
	15 Wp SHS	50 Wp SHS
Results of comparison cases	**6.0**	**8.9**
Question 1 Comparison cases without taking account of • manufacture of SHS • international transportation of SHS	6.1	9.2
Question 2 Comparison cases without taking account of transportation emissions from delivery and maintenance	6.0	9.1
Question 3 Air freight instead of marine freight for SHS	5.7	6.0
Question 4 Doubling of local delivery and maintenance distances	5.9	8.6
Question 5 Use of monocrystalline instead of multicrystalline PV modules (higher GHG emissions in manufacture)	6.0	8.8
Question 6 Halving of period of use of SHS to 10 years	2.9	4.2
Question 7 Use of zinc-carbon dry cell batteries in the baseline case	6.9	9.9

As long as the dissemination of SHS is commercially organized, this result also justifies the simplification in GHG accounting that the GEF accepts by ignoring the emissions caused by transportation.

4. Conclusion

SHS that are commercially disseminated and used cost efficiently to substitute kerosene and dry cell batteries reduce GHG emissions effectively. In that case SHS can make a significant contribution to climate protection by the dissemination of large numbers.

Appendix A. Characterization of the comparison cases

A.1 System components of comparison cases 1 and 2

In the system analysis two realistic comparison cases for the supply of energy services are examined with reference to the thereby occurring GHG emissions.

The focus is on the computation of GHG emissions arising

- in the manufacture of the products,
- in the transportation of the products to the target area and
- during a period of use of 20 years.

It has been assumed that the energy services provided in the comparison cases are comparable (see Table 1).

A.1.1. Manufacture and operation of a petroleum pressure lamp

The luminous flux from a petroleum pressure lamp (PPL) is, depending on consumption, between 220 and 1300 lm and includes the operating range of fluorescent tubes. To establish comparability between PPL and fluorescent tubes, further calculations are based on a luminous flux of 500 lm for baseline case 1 (600 lm for baseline case 2) for the PPL.

During the 20 years of operation the lamp is assumed to be replaced five times, because a 4-year service life is assumed in the case of daily use. A PPL consists predominantly of sheet steel and glass. The corresponding value is: 1.753 kg CO_z equivalent/kg PPL.

The summary of data for petroleum pressure lamps are presented in Tables Al and A2.

A.1.2. Dry cell batteries (DCBs) for small electrical devices

Small electrical devices are usually powered by DCBs of different sizes. Usually, mignon cells (IEC designation LR6; ANSI designation `AA') are used in small transistor radios. Usually, mono cells (IEC designation LR20; ANSI designation 'D')

Table A1
Summary of data on petroleum pressure lamp (PPL)

		Unit	Source
Weight of PPL	1.5	kg	[6]
Specific CO_2 equivalent of GHG emissions for manufacture	1.753	kg $C0_2$/kg PPL	[6, p. 63]
Service life of PPL	4	Years	
Fuel conversion coefficient	0.8	lm/W	[7]
Calorific value of petroleum	44.75	MJ/kg	[10]
Specific CO_2 equivalent	3.216	kg $C0_2$/kg petroleum	[10]

Table A2
Fuel consumption and CO_2 equivalents of GHG emissions for PPL operation

Baseline case 1: 4-h operation/day at 500 lm; Specific fuel consumption at 500 lm: 0.0503 kg/h			
Petroleum	0.20 kg/day	73 kg/year	1468 kg/20 years
CO_2 equivalent of GHG emissions	0.64 kg/day	235 kg/year	4722 kg/20 years
Baseline case 2: 5-h operation/day at 600 lm; Specific fuel consumption at 600 lm: 0.066 kg/h			
Petroleum	0.30 kg/day	110 kg/year	2202 kg/20 years
CO_2 equivalent of GHG emissions	0.97 kg/day	354 kg/year	7082 kg/20 years

are used to power radio/cassette recorders. The same is assumed for the baseline cases 1 and 2 of the present study.

The energy contained in DCBs is not normally indicated on the product by the manufacturer and is determined not only by the size but also by the combination of materials (Table A3).

The value of the alkaline-manganese monocell 20 Wh with a weight of 134 g is used for the further calculations of the baseline cases. The market prices of the various PBs by and large correspond the capacities/energy content (approx. 50 to 100 $US/kWh).

It is difficult to calculate the GHG emissions arising from the manufacture of alkaline-manganese DCBs, because, to date, hardly any GHG studies have been published on the processes involved. Use was made in this case of data that are presently being prepared by Öko-Institut (Institute for Applied Ecology) for the GEMIS database [5](Table A4)[4].

Table A3
Energy contained in monocells according to various sources

	Zinc-carbon	Zinc-chloride	Alkaline-manganese
Monocells, LR 20[a]	2 Wh [4]	6 Wh [4]	13.5 Wh [4]
Monocells, LR 20[b]	11 Wh [12]	12 Wh [3]	about 25 Wh [3,12]

[a] [4]World Bank, 2000, p. 24 (original source: Batteries International, 1993). To calculate the energy content, the capacity was multiplied by an average discharge voltage of 1.5 V.

[b] Manufacturers` data as well as data from independent studies [5] and [12] show, in some cases, considerably higher amounts of energy contained in comparison with [4]. For example ([3] VARTA, 2001), a typical capacity of 16.5 Ah is given for the alkaline-manganese mono cell, this corresponding, at a discharge voltage of 1.5 V, to an energy content of almost 25 Wh. For the zinc-chloride mono cell VARTA states a typical capacity of 8 Ah, corresponding to an energy content of 12 Wh.

[4] The data are based on a mignon cell and exhibit the following key values:

1. At an average discharge voltage of 1.5 V; the specific storage density is 0.166 kWh/kg.
2. GHG emissions are 29.10 kg (CO_2 equivalent)/kWh (output dry cell battery) or 4.83 kg (CO_2 equivalent)/kg (dry cell battery).

Table A4
Summary of data on dry cell batteries (DCBs), mono cell, alkaline-manganese

		Source
Weight of a DCB	0.134 kg	[3]
Specific CO_2 equivalent of GHG emissions in manufacture of a DCB	4.83 kg CO_2/kg PB	[10][a]
Energy contained in a DCB	20 Wh	Average value, see above

[a] Data on dry cell batteries are not yet contained in the Internet version of GEMIS 4.

A.1.2.1. DCB consumption and $C0_2$ equivalents of GHG emissions

The energy demand and the concomitant demand for DCBs (mono cells, alkaline-manganese) results from a 2-h period of operation per day of the radio/cassette radio with an average consumption of 2 W. (Table A5)

A.1.3. Manufacture and operation of car batteries (lead batteries) for operation of television sets (baseline case 2)

A 2-year service life is assumed because, in practice, batteries are subjected to extremely heavy loading [4, p. 24] [5]:

1. Frequent deep discharging
2. Mechanical stress as a result of transportation to the charging station
3. Frequent fast charging at the charging stations and poor chargers.

(Table A6)

A.1.3.1. Consumption of car batteries and CO_2 equivalents of GHG emissions

The energy demand and the concomitant demand for car batteries results from the operating period of the television set with an average power consumption of 20 W. (Table A7)

For charging, the car battery is taken by public transport to a nearby town. For charging, the electricity is supplied from the grid with a specific CO_2 equivalent of 0.9 kg CO_2/kWh. The losses during charging of the car battery and through self-discharge amount to 20%. (Table A8)

Table A5
Summary of data on consumption of dry cell batteries (DCBs)

Energy supplied by DCB	4 Wh/day	1.46 kWh/year	29.2 kWh/20 years
DCB consumption (quantity)	0.20 units/day	73 units/year	1460 units/20 years
DCB consumption (weight)	0.03 kg/day	9.8 kg/year	195 kg/20 years
CO_2 equivalent of GHG emissions		47 kg $C0_2$/year	945 kg CO_2/20 years

[5] This gives an upper value of 50 cycles as an empirical value.

Table A6
Summary of data on car batteries

		Unit	Source
Weight of a car battery (12 V)	12	kg	
Energy contained in a car battery with 100% depth of discharge	0.5	kWh	
Service life of a car battery (approx. 100 cycles with 80% depth of discharge)	2	years	Empirical value
Energy supplied during service life	44	kWh/battery	
Specific CO_2 equivalent of GHG emissions in manufacture	1.26	kg $C0_2$/kg battery	[6][a]

[a] Ref [6 footnote 1, p. 59]. According to information made available by the Hagen company, a lead battery consists of 76% lead, 17.3% water and sulphuric acid, 6.2% plastic and 0.4% tin, it being assumed that the lead consists 48% of secondary lead. Using the specific GHG emissions factors of the processes from the GEMIS database [9] there results a value of 1.264 kg CO_2 equivalent/kg lead battery.

Table A7
Baseline case 2 with 4 h of operation/day

	kWh/day	kWh/year	kWh/20 years
TV set, 12V, 20 W average power consumption	0.080	29	584
		units/year	units/20 years
Consumption of batteries (quantity)		0.5	10
		kg/year	kg/20 years
Consumption of batteries (weight)		6	120
CO_2 equivalent of GHG emissions		7.58	151.7

Table A8
Charge energy and GHG for car battery

	Charges/year	Charges/20 years
Charging operations (quantity)	58	1168
	KWh/year	kWh/20 years
Charge energy	36.5	730
CO_2 equivalent of GHG emissions for battery charging	32.9	657

A.2. Alternatives to the baseline cases

The alternatives to the baseline cases are SHS of different power rating with the following components (Table A9).

The electrical energy supplied by the 15 Wp SHS amounts for clear days (global

Table A9
GHG emissions of a small SHS. Alternative case 1: 15 Wp SHS

Components	Service life (years)	Power	Weights of one (kg)	all components (kg)	Specific GHG emissions (kg $C0_2$ eq./kg)	GHG emissions (kg $C0_2$ eq.)	Source
PV module, multicrystal-line	20	15 Wp	1.96	1.96		98.90	(8)[a]
Lead battery (car battery)	4	10 Ah	2	10	1.264	12.64	Similar to [6]
Lamp housing	10		0.2	0.4	4.795	1.92	[61
Lamp	2	2x6W 42 lm/W	0.1	1.0	1.106	1.11	(6,7)
Copper cable, 2m	20		0.03	0.08	5.98	0.16	(12)
Charge controller	10		0.2	0.4	5.98	2.39	Similar to [6]
Totals				13.7		117.1	

[a] The specific value per Wp results from the following data of the study:

- Assuming a module area of 0.52 m2, an efficiency of 9.66% with reference to the module area and an irradiation in the module plane of 2000 kWh/m^2 x year, a 50 Wp PV module will generate 3000 kWh of electricity in a 30-year period of use.
- Assuming a 30-year period of use and a harvest factor of 6.1, the necessary energy for the manufacture of a multicrystalline 50 Wp module is calculated at just under 500 kWh.
- The energy for the production process is supplied virtually entirely by the electricity grid. Assuming the German grid generation mix with 0.667 kg C02 equivalent per kWh, the manufacture of a multicrystalline 50 Wp module causes GHG emissions of around 330 kg C02 equivalent with a specific value of around 6.6 kg C02 equivalent/Wp.

Another study on the subject [13] calculates, for frameless multicrystalline PV modules, the energy required for manufacture at between 35 MJ/Wp and 96 MJ/Wp. If one applies the GHG emissions of the German grid generation mix (0.667 kg C02 equivalent/kWh), specific GHG emissions between 6.5 and 17.8 kg C02 equivalent/Wp result. The same study gives reason to expect that, by 2007, the specific values for multicrystalline PV modules may drop to 1.9 kg C02 equivalent/Wp.

radiation in the plane of the module 5.5 kWh/m^2 x-day) to 82.5 Wh/day. In order to calculate the net energy supplied, a system efficiency (line losses and storage losses) of 80% and a utilization rate of 80% are assumed. On average, approximately 53 Wh/day are available for electric loads. Consequently, it is possible to operate 2 x 6 W lamp for 4 h (48 Wh/day) as well as a radio or cassette radio for 2 h (4 Wh/day). (Tables A 10 and A 11)

The electrical energy supplied by the 50 Wp SHS amounts for clear days (global radiation in the plane of the module 5.5 kWh/m^2 x day) to 275 Wh/day. In order to calculate the net energy supplied, a system efficiency (line losses and storage losses) of 80% and a utilization rate of 80% are assumed. On average, approximately 176 Wh/day are available for the electric loads. Consequently, it is possible to operate

Table A10
Power generation and consumption of a small SHS

	Wh/day	kWh/year	kWh/20 years
Gross power generation of PV module (global radiation 5.5 kWh/M^2 x day)	82.5	30	602
Net power supplied for electric loads	53	19	385
Consumption by electric loads	52	19	377

Table A11
GHG emission of a medium SHS. Alternative case 2:5 WP SHS

Components	Service life (years)	Power	Weights of one (kg)	all components (kg)	Specific GHG emissions (kg CO_2 eq./kg)	GHG emissions (kg CO_2 eq.)	Source
PV module, multicrystalline	20	50 Wp	6.53	6.53		329.55	See altern.1
Steel fabrication for attachment of module	20		10	10	1.59	15.87	[11]
Lead battery (car battery)	4	80 Ah	20	100	1.264	126.4	Similar to [6]
Lamp housing	10		0.2	0.4	4.795	1.92	[61
Lamp	2	2x8W 421m/ W	0.1	1.0	1.106	1.11	[6,7]
Copper cable, 25m	20		0.8	0.8	5.98	4.78	[11]
Charge controller	2		0.2	0.4	5.98	2.39	Similar to [6]
Totals				119.4		483.9	

2 x 8 W lamp for 5 h (72 Wh/day), a radio or cassette radio for 2 h (4 Wh/day), and a television set for 4 h (80 Wh/day). (Table A12)

In contrast to baseline case 2, for the SHS alternative the average service life of car batteries is assumed to be 4 years. The reasons are:

Table A12
Power generation and consumption of a medium SHS

	Wh/day	kWh/year	kWh/20 years
Gross power generation of PV module (global radiation 5.5 kWh/m^2∗day)	275	100.4	2007
Net power supplied for electric loads	176	64.2	1284
Consumption by electric loads	155	57	1135

1. A more sparing operation thanks to the low average depth of discharge of around 20% (baseline case 80%).
2. A sparing stationary operation (baseline case 2 requires approximately weekly transportation to the charging station).

A.3. Transportation costs of the comparison cases

Petroleum and diesel oil are imported. GHG emissions in the upstream production chain for both fuels are taken into account as follows:

- In the case of petroleum, the figure is 0.31 kg C02 equivalent per kg petroleum.
- In the case of diesel, the value is contained in the specific GHG emissions of the means of transport.

A.3.1. Transportation costs for the components of the baseline cases

Petroleum pressure lamps, dry cell batteries and car batteries for the baseline cases are produced locally. Assumed is an average local transportation requirement for delivery of 100 km using a truck. For charging, the car battery is regularly taken to a nearby town by public transport. The GHG emissions arising from transportation by means of public transport are ignored.

A.3.2. Transportation costs for the components of the SHS

With regard to the components of the SHS, it is assumed that they are manufactured in an industrialized country. They are shipped over 10,000 km by marine freight to the target country, where they are then taken a further 100 km by truck to the marketing area of the supplier.

A.3.3. Sale, installation, maintenance using small truck

SHS incur costs of selling which are required for the marketing, sale, installation and operation of the systems in remote areas. Transportation is by means of a small (1.5 tonne) diesel-powered truck (pick-up). It is assumed that a distance driven of 500 km is required per 50 Wp SHS for installation and maintenance during the period of use. For a 15 Wp solar lamp, a smaller value of 150 km is assumed during the period of use owing to the higher density of systems in the marketing area. (Table A13)

A.4. Model of quantities and costs of supplier

(Table A14)

Appendix B Data for parameter variations

B.1. GHG emissions with regard to monocrystalline PV modules

The data source is, Ref. [8]. The specific value per Wp results from the following data of the study:

Table A13
Summary of data used for GHG transportation emissions, taken from GEMIS 4 database [10][a]

Method of transportation	Data allocation according to GEMIS 4	Specific GHG emissions
Marine freight	Ocean-going ship	7.41 g CO_2, eq. /t*km
Land transportation, truck	Truck, 1980s, medium-size	165.37 g CO_2, eq. /t*km
Land transportation, small truck	Truck, 1980s, small	0.31 kg CO_2, eq. /km [b]

[a] The data on specific GHG emissions contain both the GHG emissions for the manufacture of the means of transport, the consumption of fuels and also the GHG emissions released by the upstream chain of fuel supply.

[b] Since the supplier's own small truck is used predominantly for maintenance-i.e. since, despite the low payload, the entire vehicle is moved-the full GHG emission per km driven are applied irrespective of payload.

- Assuming a module area of 0.43 m^2, an efficiency of 11.5% with reference to the module area and an irradiation in the module plane of 2000 kWh/M^2*year, a 50 Wp PV module will generate 3000 kWh of electricity during a period of use of 30 years.
- Assuming a 30-year period of use and a harvest factor of 4.8, the necessary energy for producing a monocrystalline 50 Wp module is calculated at around 620 kWh.
- The energy for the production process is supplied virtually entirely by the electricity grid. Assuming the German grid generation mix with 0.667 kg CO_2 equivalent per kWh, the production of a monocrystalline 50 Wp module will cause GHG emissions of around 412 kg CO_2 equivalent.
- The specific value amounts to 8.25 kg CO2 equivalent/Wp[6].

B.2. GHG emissions with regard to air freight

The data on GHG emissions with regard to air freight originate from the GEMIS 4 database [9]. (Table B1)

B.3. GHG emissions in the manufacture of zinc-carbon monocells

The data were taken from [12][7] for R20 round cell: Zinc-carbon, 1.5V round cell, weight 95 g; Energy contained in a DCB 0.041 MJ (11.4 Wh); Energy for manufacture 3.99 MJ (1.1 kWh); Assuming the German grid generation mix with 0.667 kg

[6] Another study on the subject [13] calculates, for frameless monocrystalline PV modules, the energy required for manufacture at between 47 MJ/Wp and 109 MJ/Wp. If one applies the GHG emissions of the German grid generation mix (0.667 kg CO_2, equivalent/kWh), specific GHG emissions between 8.7 and 20.2 kg CO_2 equivalent/Wp result. The same study gives reason to expect that, by 2007, the specific values for monocrystalline PV modules may drop to 2.6 kg CO_2 equivalent/Wp.

[7] Stiftung Praktischer Umweltschutz Schweiz (Pusch) 1998; product tables for brochure.

Table A 14
Economic model of supplier

Turnover related variables [a]	Qty./year	Cost price $US	Sale price $US	Margin $US
Sale of small 15 Wp SHSs	250	150	200	50
Sale of medium-size 50 Wp SHSs	150	350	500	150
Total turnover		125.000	$US/year	
Margin		*35,000*	*$US/year*	
Transport weight (incl. spare parts)		21 t/year		
Distance driven by supplier's own small truck:				
1. For installation, 5-year guarantee and maintenance, covered out of margin	km/year per system	km/year for all systems		
Small 15 Wp SHSs	75	18,750		
Medium-size 50 Wp SHSs	250	37,500		
2. For maintenance in 15 years after guarantee on paying basis	km/year per system	km/year for all systems		
Small 15 Wp SHSs	75	18,750		
Medium-size 50 Wp SHSs	250	37,500		
Total average distance driven each year		112,500		
of which on a paying basis		56,250		
Costs of small truck (pick-up) diesel				
Purchase		18,000 $US		
Total distance driven during service life		250,000 km		
Annual costs of repair, maintenance, insurance		5000 $US/year		
Annual distance driven		112,500 km/year		
Diesel consumption		15.50 1/100 km		13.33 kg/100 km
Fuel costs		0.30 $US/1		
Annual fuel costs		5231 $US/year		
Specific costs (including depreciation, maintenance, fuel, insurance)		0.163 $US/km		
Costs				
Personnel costs		10,000 $US/year		
Business premises, other fixed costs		3000 $US/year		
Costs of average capital input (6% on $US 80,000 capital required for running business)		4200 $US/year		
Small truck (56,250 km at 0.163 $US/km)		9166 $US/year		
Pre-tax profit		*8634 $US/year*		

[a] The costs and revenues pertaining to maintenance contracts after expiry of the guarantee period are not included, because they are on a paying basis and have no effect on the supplier's profit. With regard to calculation of the costs of the small truck, however, the maintenance contracts are of significance, because the apportioning of the fixed costs reduces the specific costs.

Table B 1
Specific GHG emissions of air freight

	Data allocation according to GEMIS 4	Specific GHG emissions
Air freight	Aircraft, foreign country	2405 g CO_2 eq./t*km

CO_2 equivalent /kWh, the manufacture of zinc-carbon monocells causes 7.78 kg CO_2 equivalent /kg.

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