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Broader Perspectives

Energy Payback Time of the High-concentration PV System FLATCON®

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The ecological benefit and sustainability of a new energy technology and its potential to reduce CO_2 emissions depend strongly on the amount of energy embodied in the materials and production processes. The energy payback time is a measure for the amount of time that a renewable energy system has to operate until the energy involved in its complete life-cycle is regenerated. In this paper, the energy payback time of the high-concentration photovoltaic system FLATCON® using III–V semiconductor multi-junction solar cells has been evaluated. Considering the energy demand for the system manufacturing, including transportation, balance of system and system losses, the energy payback time turns out to be as low as 8–10 months for a FLATCON® concentrator built in Germany and operated in Spain. The energy payback time rises slightly to 12 to 16 months for a system installed in Germany. The main energy demand in the production of such a high-concentration photovoltaic system was found to be the zinced steel for the tracking unit. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: energy payback time; high-concentration PV; FLATCON; III–V solar cells

INTRODUCTION

A new generation of photovoltaic (PV) systems working with III–V multijunction solar cells at high concentration levels greater than 500 suns, are a promising way to lower photovoltaic power generation costs in the future. Lenses focus the sunlight on a millimeter-size solar cell chip that has the advantage of an extremely high power conversion efficiency. Cell efficiencies of 36·9% have been validated,[1] values of more than 38% have been recently reported[2] and this development is still in an early stage. The III–V multijunction solar cells used in these PV modules have been originally developed for powering satellites in space. This technology was known to be far too expensive for terrestrial applications. But with the ability to reduce the size of the active solar cell area device by nearly an order of magnitude in a concentrator system, this technology now becomes attractive for terrestrial applications.

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The Fraunhofer ISE has been developing a unique all-glass concentrator FLATCON® (Fresnel-lens all-glass tandem-cell concentrator), using Fresnel lenses at a concentration level of 500 × together with III–V multijunction solar cells.[3,4] This development was carried out in collaboration with the Ioffe Institute in St Petersburg.[5] Besides the high system efficiencies, high-concentration PV also has the advantage of a low environmental impact. In general, high-concentration modules can be easily recycled[6] and have a potentially low energy payback time.

Energy payback time (EPBT) is the time a system for energy production needs to generate the input energy required during its whole life-cycle. This time indicates the energetic sustainability of a system. The EPBT is also closely connected to the CO_2 mitigation potential,[7] meaning a short EPBT indicates a high substitution of CO_2 emissions. Recycling of the FLATCON® concentrator is specifically easy as most of the material is steel for the tracking unit and glass for the modules. The solar cells are mounted on single copper heatspreaders which can also be removed after the lifetime of the system. Recycling of raw materials can have a major influence on the result of an EPBT calculation. In this paper the final stage of recycling and disposal could not be considered, due to the fact that there is currently not enough reliable data available.

EPBT for renewable energy systems vary between months and years. For example, the EPBT of a grid-connected multi-crystalline silicon PV rooftop system is about 3 yr (1·7 MWh/m^2/yr global average insolation) and about 4 years for a ground-mounted installation.[8] Wind energy turbines need only a few months to amortize energetically.[9]

Little is known about the EPBT of III–V solar cells due to the fact that their only present application is in space. Nevertheless, the EPBT of a mechanically stacked InGaP/mc-Si tandem-module has been calculated[10] to be approximately 5 yr. For solar thermal collectors an EPBT was published[11] in the range of 1–2 yr. It is important to bear in mind that these publications are based on different assumptions. Therefore, they cannot be directly compared.

This study focuses on the EPBT of the high concentration PV system FLATCON® using III–V multi-junction solar cells at a concentration level of 500 (Figure 1). The modules consist mainly of float-glass, with Fresnel lenses formed in a silicone rubber material. The lenses stick to the bottom of the front glass cover plate. This system uses state-of-the-art monolithic dual- or triple-junction solar cells, developed at Fraunhofer ISE for the specific prerequisites of the FLATCON® concentrator. These multi-junction solar cells consist of two or three active junctions of GaInP, GaInAs and Ge, the former two grown by metal–organic vapor phase epitaxy. The individual subcells are series-connected by interband tunneling diodes so that the actual device looks like a small conventional single-junction solar cell with an area of 3 mm^2.

At the Fraunhofer ISE, FLATCON® outdoor module operating efficiencies[4] of 22·7% were reached by using dual-junction cells (2 mm diameter) with an efficiency of 30% under 500 × and AM1·5d. Using >36% triple-junction solar cells, system efficiencies of 28% at a temperature of 25°C seem to be achievable for the FLATCON® concentrator system. Considering operating temperatures, the module efficiency is assumed to be 26% with >36% cells.

High-concentration PV systems have to follow the sun to keep the lens focused on the active solar cell area, which is done by a so called tracker on which FLATCON® modules are mounted. The ensemble of tracker, concentrator modules and balance of system elements defines one FLATCON® system having an output power of about 6 kW_p.

All embodied energy of the system components presented in this paper are converted into an equivalent primary energy demand. Therefore, according to other authors[8,10,12] electrical input or output energy of the system is multiplied by an 'electrical conversion factor' in order to get the primary energy equivalent. This factor depends on the country supplying the electric energy. In Germany, for example, the factor is 2·9 whereas in Spain[13] the factor is only 2·5. This means that in Germany an average of 2·9 MJ of primary energy are used to produce 1 MJ of electrical energy. In this study two scenarios are evaluated: Fabrication of the FLATCON® concentrator in Germany and subsequent installation in Spain as well as installation in Germany. The country where the system is installed has an influence on the primary energy equivalent of the electricity generated by the PV system and therefore, influences the EPBT.

The energy demand for the production process and the raw materials involved are carefully calculated and will be described later in the text. In the utilization phase the energy demand of the tracking engines is

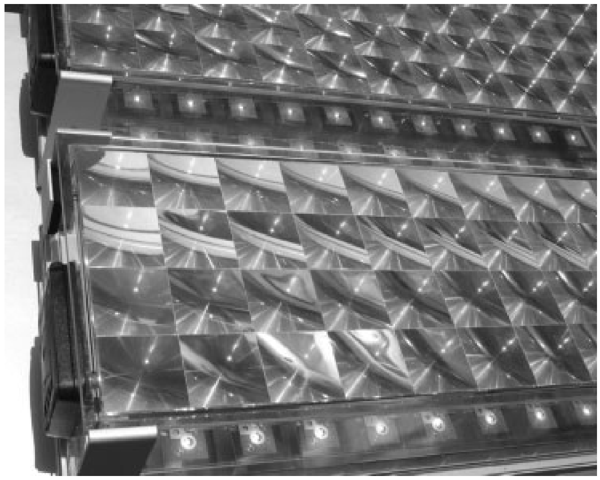

Figure 1. FLATCON® prototype modules

considered. Due to the lack of reliable data concerning the energy required to build up new production facilities for FLATCON® systems, the embodied energy of the equipment as well as the energy used by employees travelling to the workplace, these parameters are excluded from this investigation.

METHODOLOGY

This study is based on current state-of-the-art prototypes of the FLATCON® concentrator as they are built by the Fraunhofer ISE. For the calculation of the embodied energy, the system manufacturing process was split up into six main components. These are the production of III–V multi-junction solar cells, the cell packaging, the module and tracker production, the balance-of-system (e.g. inverter) elements and the transportation. The pre-products (e.g., wires, sensors or steel pipes) and the processes necessary for the main components were identified. For information about the embodied energy of the input materials and pre-products the term cumulated energy demand (CED) is used. The CED is part of the life-cycle assessment and is gained by analyzing the energy chains and cycles of a specific product.[14] It states the entire demand, valued as primary energy, which arises in connection with the production, use and disposal of an economic good (product or service) or which may be attributed respectively to it in a casual relation.[14] There is various literature available about the CED of products or the CED/mass of materials, which was obtained by following the VDI 4600 guideline.[14] In this report, data from the ProBas database[13] of the German Federal Environmental Agency and the GABIE study[15–17] of the Research Institute for Energetic Economy in Munich is primarily used.

The process energies are all electrical in nature and have to be multiplied by the country-specific conversion factor to achieve the primary energy equivalent. To calculate the total CED of the system, all energy contributions (CED of input materials and process energies) are added. Finally, the EPBT (in years) is given by

$$\mathrm{EPBT} = \frac{\mathrm{CED}_{\mathrm{system}}}{(E_{\mathrm{el}} - E_{\mathrm{tracking}})\mathrm{R}_{\mathrm{prim}}}$$

where $\mathrm{CED}_{\mathrm{system}}$ is the total CED [J] of the system, E_{el} (J/s) is the electrical energy of the system produced in one year, E_{tracking} (J/s) is the electrical energy consumption of the tracking motor per year and R_{prim} is the conversion factor between electricity and primary energy, which depends on the country where the system is installed. While electric energy multiplied by R_{prim} gives the primary energy.

At first, the scenario in which the FLATCON® system is manufactured in Germany and installed in the south of Spain is considered. It is assumed that the FLATCON® system will be operating in Tabernas. This is because Plattaforma Solar de Almeria, the largest center for research, development and testing of concentrating solar technologies in Europe, is located in Tabernas and the direct annual insolation is well known[18] to be about 1900 kW h/m^2 for this location. Southern Spain offers good meteorological conditions for high-concentration PV and it is representative of locations where this technology will be realized in the future.[18] Then the second scenario where the FLATCON® system is build and installed in Freiburg, Germany is evaluated for comparison.

Production chain and system description

Four-inch (10 cm) germanium wafers are used as substrates for the growth of the III–V multi-junction solar cells. One wafer requires about 100 MJ (1 MJ = 10^6 J) electrical energy in production (W. Geens, personal communication, March 2003). This number was given by Umicore, one of the largest germanium manufacturers in the world. These wafers are used as substrates for the metal–organic vapor phase epitaxy (MOVPE) process of the compound semiconductor materials. During the MOVPE process, hydrogen carrier gas as well as hydride and metalorganic precursors for As, P, Ga, In, . . . are used. All source materials and consumables as well as the electricity demand for the equipment are calculated on the basis of measured data of an AIX2600G3 MOVPE reactor with a capacity of 8×4-inch substrates. This reactor is also used for the current production of space solar cells.

Further steps in the processing of the wafers to solar cells include wet-chemical etching of surfaces, photolithography, evaporation and annealing of metal contacts and deposition of anti-reflection coatings.

A 4-inch wafer covers 1150 concentrator solar cells, each 2 mm in diameter. A yield of 85% is considered, based on experience at Fraunhofer ISE. The solar cells are separated by sawing and soldered to 3×3 cm copper heatspreaders. The copper heatspreader is necessary for the passive cooling of the cell and serves also as the back contact. The ensemble of the packaged solar cell on the copper heatspreader is called a cell-chip. For the cell-chip production an automated leadframe process is assumed. A material loss of 10% during the processing of the copper heatspreaders is taken into account.

The Fresnel lenses are formed in silicone by a stamp process. The cell-chips are adjusted in the focal point of the lenses. The interconnection of the modules is made with a high-voltage interconnection board. All sidewalls of the FLATCON® module are made from float-glass sealed with silicone. Glass losses of 5% due to breakage in the module production as well as a silicone loss of 50% in the stamp process are considered.

A FLATCON® system consists of 333 individual modules mounted on one tracking unit and supplies about 6 kW_p output power. The tracker follows the sun by a motor which is electronically controlled through a sunlight sensor. The FLATCON® system is mounted on a concrete foundation which is also taken into account for the calculation of the EPBT, as well as the inverter and the cables for the grid connection.

RESULTS

In Tabernas a FLATCON® system with an optical aperture area of 25·6 m^2 and an assumed operation module efficiency of 26% generates 11 888 kW h of electrical energy per year,[19] when considering system losses (due to cables and inverter) of 6%. For the tracking motor an average working time of 12 h at 50 W is estimated, resulting in 219 kW h of consumed electrical energy per year. Consequently the net electrical energy output of the FLATCON® system operated in the south of Spain is 11 669 kW h per year, equivalent to a primary energy of 105 017 MJ.

Figure 2 shows the contribution of the six main components to the CED of the FLATCON® system. The largest contribution to the CED is covered by the tracker production. This is not surprising as nearly one ton of steel elements are needed for the tracker. Zinced steel parts, which have an embodied energy[16] of about 29 MJ/kg, are by far the most important energy factor of the FLATCON® system. It is assumed that the lifetime of the tracker is the same as for the modules and solar cells. Also important in terms of mass and CED is the

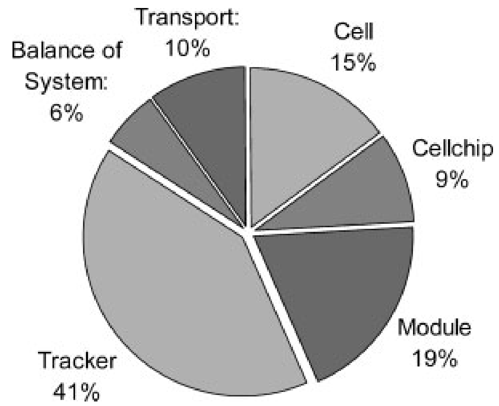

Figure 2. Contribution of the main process steps and components to the energy payback time of the FLATCON® system. Percentage share of the FLATCON® energy main components

float-glass housing. With a total input mass of 800 kg and an average primary energy equivalent of 13 MJ/kg,[13,15] it is the second biggest single CED component. The CED for the transportation of the concentrator system from the manufacturing site to its operating destination is influenced by the distance, the transported weight and the type of transportation. For this study it is estimated that the whole system, with a weight of 2 tons, is delivered over 2000 km by a mixture of truck and rail with a CED contribution[16] of 2 MJ/(km*t*). Only the transportation from the manufacturing location to the installation site is considered. Other minor transportation efforts e.g., for, raw materials or engineers are neglected due to the large uncertainties. Figure 3 shows a ranking of the 10 largest single CED components that have been identified in this study.

In Table I all CED components that have been taken into account are listed with their CED, the percentage of their contribution to the EPBT of the FLATCON® system and the reference taken for the calculation of the CED. 'Measured' means that the actual energy demand of existing equipment at the Fraunhofer ISE laboratory was taken and 'estimated from X' means that the CED value was estimated from data of similar materials and products given in reference X.

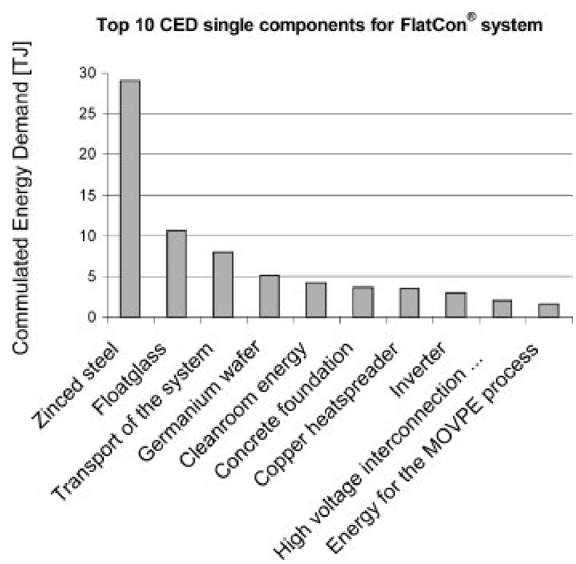

Figure 3. Contribution of the 10 largest single components to the cumulated energy demand of the FLATCON® concentrator system

Table I. Cumulated energy demand for the different components of the FLATCON® concentrator system. The percentage of the contribution of each component to the CED is also given together with the origin of the CED value

System component	CED (MJ)	Contribution%	Data source
Germanium wafer	5110	6·4	Umicore
Hydrogen	40	0·1	[13]
Hydride gases	45	0·1	Estimated from[13]
Metalorganics	2	0·002	Estimated from[13]
Energy for the MOVPE process	1700	2·1	Measured
Energy for the cleanroom	4170	5·2	Measured
Solvents	140	0·2	Estimated from[13]
Acids	9	0·01	[13]
Materials for photolithography	160	0·2	Estimated from[17]
Noble metals for evaporation	1140	1·4	[13]
Energy for cell technology	520	0·6	Measured
Copper heatspreader	3500	4·4	[16]
Materials for chip packaging	1600	2·0	[16]
Energy for chip packaging	1300	1·6	Measured/estimated
Float-glass	10 580	13·2	[13,15]
Silicone sealing material	800	1·0	[11]
Silicone for lens array	1680	2·1	[11]
High-voltage interconnection board	2000	2·5	[16]
Further module materials	20	0·03	[17]
Energy for module fabrication	260	0·3	Estimated
Zinced steel	29 000	36·1	[16]
Concrete foundation	3600	4·5	[15]
Energy for system installation	270	0·3	Estimated
Inverter	3000	3·7	[20]
Tracking sensor and electronics	220	0·3	Estimated from[21]
AC and DC wiring	1400	1·7	[16]
Transport of the system (Germany to Spain)	8000	10·0	[13]
Total	80 266	100	

An important aspect calculating the CED is the uncertainty in the parameters. The largest contributions to the CED will also have the strongest effect on the uncertainty of the calculated EPBT. Therefore, the uncertainty of the CED for zinced steel elements is essential. The mass of the overall tracking system is crucial and may differ by 100–200 kg depending on the installation. On the other hand the CED/mass value of 29 MJ/kg is rather high as parts of the tracker may be built of conventional steel elements with a much smaller CED/kg. Hence the uncertainty of the CED is estimated to be of the order of $\pm 15\%$. The uncertainty of the electric energy generation is not considered, the uncertainty concerning the conversion factor R_{prim} is assumed to be negligible. From the above the EPBT for a FLATCON® system which is produced in Germany and installed in south Spain is found to be between 8 and 10 months.

If the system is assumed to be manufactured and operated in Germany, the transport effort for the total system is not considered. Also another conversion factor for the generated electric energy[13] is used in this case (2·9 instead of 2·5). It is assumed that the system is operating in Freiburg im Breisgau, where the annual direct insolation has been measured at the Fraunhofer ISE over 5 yr and it is on average about 1000 kWh/(m^2 yr). Under these conditions the EPBT of the FLATCON® system is between 12 and 16 months.

CONCLUSION

Every human product has an ecological impact and this is specifically true for today's electricity production. Conventional energy technologies, burning fossil fuels, are by no means sustainable, as natural resources are limited and CO_2 emissions lead to global warming. For renewable energy technologies, the environmental impact depends on the amount of energy and the kind of materials used for the fabrication and operation of the technology versus the generated electricity. The energy payback time is a good measure for the sustainability of a renewable energy technology. It is also a measure for the ability of the technology to reduce CO_2 emissions. It is important to mention that the energy payback time is infinite for conventional electricity plants using fossil fuels, as the primary energy of the fuel also contributes to the cumulated energy demand of the technology. For renewable energy systems the fuel is wind or sunlight with unlimited availability. Therefore, the fuel for renewable energy technologies does not contribute to the energy payback time calculation. On the other hand, large amounts of energy are sometimes used during production, transport and operation of a renewable energy system. For most of today's flat-plate PV modules the energy payback time is about 3 yr. This is mainly due to the large amount of energy associated with the high-purity semiconductor crystals. For a PV system working at high concentration levels, such as the FLATCON® concentrator, the cell area is reduced by a factor of 500. Therefore, less semiconductor material is needed. The energy payback time of this system is dominated by elements such as steel and glass. Furthermore, the FLATCON® system has a much higher efficiency than conventional PV, increasing the power output per area and year and consequently reducing the energy payback time. The energy payback time of this unique concentrator system has been carefully evaluated in this paper, resulting in values between 8 and 16 months, depending on the operating site. This number is close to values published for wind energy turbines. With the ongoing development of this new technology, resulting in increasing system efficiencies as well as the development of recycling concepts for the steel and glass elements, the energy payback time can be further reduced in the future. Hence the energy payback time can be similar to values of wind energy turbines.

All major primary materials and energy demands during production as well as transportation, system losses and operation of the system have been included in this study. The low energy payback time value shows the high potential of the FLATCON® technology to contribute to a sustainable electricity production in the future.

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REFERENCES

1. Green MA, Emery K, King DL, Igari S, Warta W. Solar cell efficiency tables (version 23). *Progress in Photovoltaics: Research and Applications* 2004; **12**(1): 55–62.
2. Yamaguchi M, Takamoto T, Agui T, Kaneiwa M, Araki K, Kondo M, Uozumi H, Hiramatsu M. Japanese activities of R&D on III–V concentrator solar cells and modules. *Proceedings of the 19th European Photovoltaic Solar Energy Conference and Exhibition*, Paris, 2004, vol. II; 1017–2014.
3. Bett AW, Dimroth F, Hein M, Lange G, Meusel M, Schubert U, Siefer G. Development of III–V-based concentrator solar cells and their application in PV-modules. *Proceedings of the 29th IEEE Photovoltaic Specialists Conference*, New Orleans, 2002; 844–847.
4. Bett AW, Baur C, Dimroth F, Lange G, Meusel M, v Riesen S, Siefer G, Andreev VM, Rumyantsev VD, Sadchikov NA. FLATCON(TM)-modules: technology and characterisation. *Proceedings of WCPEC-3*, Osaka, 2003; 634–637.
5. Rumyantsev VD, Hein M, Andreev VM, Bett AW, Dimroth F, Lange G, Letay G, Shvarts MZ, Sulima OV. Concentrator array based on GaAs cells and Fresnel lens concentrators. *Proceedings of the 16th European Phtovoltaic Solar Energy Conference*, Glasgow, 2000; 2312–2315.
6. Swanson MR. The promise of concentrators. *Progress in Photovoltaics: Research and Applications* 2000; **8**(4): 93–111.
7. Nieuwlaar E, Alsema E. PV power systems and the environment: results of an expert workshop. *Progress in Photovoltaics: Research and Applications* 1998; **6**(2): 87–90.
8. Alsema EA. Energy pay-back time and CO_2 emisions of PV systems. *Progress in Photovoltaics: Research and Applications* 2000; **8**(1): 17–25.

9. Krohn S. The energy balance of modern wind turbines. *Wind Power Note* 1997; **16** (http://www.windpower.org/en/publ/enbal.pdf, July 2004).
10. Meijer A, Huijbregts MAJ, Schermer JJ, Reijnders L. Life-cycle assesment of photovoltaic modules: comparison of mc-Si, InGaP and InGaP/mc-Si solar modules. *Progress in Photovoltaics: Research and Applications* 2003; **11**(4): 275–287.
11. Streicher E, Heidmann W, Müller H. Methodik zur Ermittlung der energetischen Amortisationszeit von thermischen Solaranlagen. *OTTI—12. Symposium Thermische Solarenergie* 2002; 123–128.
12. Wagner HJ. Energieketten von A bis Z—Erntefaktor und energetische Amortisationszeit. *Elektrizitätswirtschaft* 1996; **8**: 448–456.
13. German Federal Environmental Agency. *Prozessorientierte Basisdaten (ProBas) für Umweltmanagement-Instrumente*, (http://www.probas.umweltbundesamt.de/php/, May 2004).
14. Verein Deutscher Ingenieure. *Cumulative Energy Demand Terms, Definitions, Methods of Calculation*, VDI 4600 (Beuth Verlag GmbH, Düsseldorf, 1997).
15. Hutter C, Köhler D, Lilleike J, Schwärzer M. *Ganzheitliche Bilanzierung von Grundstoffen und Halbzeugen (GABIE), Teil II Baustoffe*, 065.1/KEA (Research Institute for Energetic Economy, Munich, 1999); 49–61, 127–134.
16. Corradini R, Köhler D. *Ganzheitliche Bilanzierung von Grundstoffen und Halbzeugen (GABIE), Teil III Metalle*, 065.1/KEA (Research Institute for Energetic Economy, Munich, 1999); 30–32, 102–105.
17. Tzschleutschler P. *Ganzheitliche Bilanzierung von Grundstoffen und Halbzeugen (GABIE), Teil IV Kunststoffe*, Vol. 065.1/KEA (Research Institute for Energetic Economy, Munich, 1999); 5–11, 49–51.
18. Plaza DM. Annual report 2002. *Plattaforma Solar de Almeria*: 7–13.
19. Pietruszko SM, Gradzki M. 1 kW grid-connected PV system after two years of monitoring. *Opto-Electronics Review* 2004; **12**(1): 91–93.
20. Fischer P, Sauter M. Entwicklung eines recyclingfähigen Solarwechselrichters. *13. Syposium für Solarenergie*, Köln, 1998; 987–993.
21. Dreier T, Fischer F, Wagner U. Ganzheitliche Bilanzierung eines Personal Computers. *Energiewirtschaftliche Tagesfragen* 2000; **50**: 232–236.

