Preprint. Paper to be presented at EEDAL'03

Energy efficiency of computer power supplies

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1. Introduction and problem setting

This paper is based on a research project (Aebischer and Huser, 2002) financed by the Swiss Federal Office of Energy and supported by the Canton of Geneva and CEPE.

1.1 Starting point

The importance of energy losses and power distortion by power supplies in ICT-equipment were recognised in two studies carried out in the early 1990s:

- "The Hidden Juice Guzzlers" (SFOE 1993) drew attention to the benefit of switched network components versus standard components with large, heavy 50-Hz transformers and high stand-by losses. Using switched power supplies increases the degree of efficiency from 30-50% to 60-90%.
- Roturier's "OT3-Report" (Roturier et al., 1994) showed that a few years ago, power transformation in ICT equipment meant heavy power distortion. The typical power factor of a personal computer in 1993 was found to be of the order of 0.6.

The efficiency and the power factor of power supply units are strongly dependent on the workload at which the unit is used. Attention to the low workload at which ICT-equipment are usually used came first from the side of HVAC-dimensioning. Not so long ago, the dimensioning of the electrical infrastructure and of the cooling capacity was based on the nameplate-wattage (i.e. full capacity, workload at 100%) of the equipment. Measurements of many equipment showed that the actual power was at about 1/3 to 1/2 (at the best) of the nameplate-wattage. Today, the partial load of the equipment is often considered in the dimensioning process of the infrastructure, but the inefficiency in power conversion due to the oversize of the power supply was not tackled.

A number of studies have been carried out on energy losses resulting from recharging devices, particularly in view of the extremely rapid development in the area of mobile phones and the growing awareness of high stand-by losses associated with battery chargers, and these studies have led to a variety of political measures (e.g. voluntary agreement of the industry with the European Commission[1]).

Recently, Calwell and Reeder (2002) investigated in detail energy saving potentials in power supplies. The work was focused on external power supplies ("wall packs" or "bricks") and on internal power sullies for entertainment electronics (TV, stereo and monitor). They found that most external power supplies were of the linear power supply type with efficiencies varying between 20 and 75%, whereas most of the internal power supplies are of the switch-mode type with efficiencies between 50 and 90%. The authors claim that the typical efficiency in linear power supplies of 50 to 60% could be improved to 80% or more and in switching power supplies from typically 70 to 80% to 90%. The incremental cost for the improved power supplies is said to be less than one USD. The sections on power supplies (pp. 177, 189 and 207) in the IEA-publication "Cool Appliances" (IEA, 2003) are widely based on these findings.

Little is known about larger power supplies for PC, servers and other IT-equipment and about the quantitative relation between the workload at which these devices are operated and the efficiency of the power supplies.

1.2 Objective

The objective of the study by Aebischer and Huser (2002) was threefold:

- determine for ICT-equipment - primarily PC - the efficiency of power supply units in function of their workload and the typical workload at which they are used;
- estimate the technical electricity saving potentials;
- propose strategies and measures in order to realise these potentials.

2. Approach/Method

In order to get an insight into the relation between efficiency and workload we did under laboratory conditions (power supply unit disconnected from the ICT-equipment) detailed measurements of six power supply units for PCs and servers/routers. The nominal output power of these units range between 160 and 660 W. They were manufactured between 1990 and 2000. These units were not selected, but we took what we got and therefore the results may not be representative for all units on the market and the observed variations between older and newer units are not necessarily a general trend. The main characteristics we measured are:

[1] Code of conduct concerning efficiency of external power supplies, dated 15 June 2000 (limited to external power supplies drawing 75 watts or less)

- efficiency (defined as the ratio of power out to power in) in function of the overall workload (defined as the ratio of power out to nominal or maximal power out) and of the relative split of the load between the different DC-levels,
- power losses (defined by the difference between power in and power out) in function of the overall workload and of the relative split of the load between the different DC-levels,
- power factor in function of the overall workload and of the relative split of the load between the different DC-levels.

To learn more about the workload of power supplies in modern PCs and the related efficiencies we did additional measurements on power supplies, which were actually delivering power to the PC. Measurements of workloads, of the relative split of the load between the different DC-levels and of the efficiencies of power supplies were done for five modern PCs in four different operating modes:

- off mode,
- standby mode,
- on mode with processor working at low capacity,
- on mode with processor working at full capacity.

Again, the PCs were taken next door and may not be fully representative of the market. But they may be considered as typical for a modern office/consulting environment in Switzerland and possibly elsewhere.

The evaluation of saving potentials and of appropriate policy measures is based mainly on the experience of the authors acquired in their long-term involvement in the field of energy efficiency in ICT on the national and international level (Bertoldi et al., 2002; Aebischer/Huser, 2002/2; Varone/Aebischer, 2000; Aebischer 1996; Bachmann/Aebischer, 1995; Bachmann/Aebischer/Brüniger, 1993). But very valuable inputs came from discussions with various experts (see section 5) and from the literature – particularly from the study by Calwell and Reader (2002).

3. Outcomes/Results

3.1 Power supply units for PCs and servers/routers in laboratory conditions

The results of the measurement of power supplies in laboratory condition are summarised in Table 1. Detailed measurement protocols are published as appendices of the main report
http://www.cepe.ethz.ch/download/projects/Bernard/sb_power_supply_full.pdf .

Table 1: Technical characteristics of power supply units for PCs and servers/routers

	Servers/routers				Personal computers			
	Artesyn		Cisco		Minebea		Compaq	
Pmax (W)	660		400		200		160	
U2 (V)	5.2		12		3.4		3.6	
P2max (W)	470		400		66		32	
U3 (V)	12				5		5.2	
P3max (W)	178				80		78	
U4 (V)					11.8		12.5	
P4max (W)					93		50	
etamax (%)	78.3		84.8		76.16		79	
Pges/Pmax (%)	58		50.2		84.4		70.43	
P2 (W)	315	67%	200.9	50%	15.23	23%	5.3	17%
P3 (W)	60	34%			59.68	75%	57.7	74%
P4 (W)					93.94	101%	49.8	100%
eta100 (%)	77.6		83.1		72			
eta50 (%)	77.5, 76.7		84.8		72, 65		78, 73.5	
eta30 (%)	74.9, 71		83		68, 64		74.5, 68.5	
eta20 (%)	68		82		60, 55		69, 64	
eta10 (%)	58		73					
eta2 (%)	30		48					
Pv0 (W), Pv0/Pmax (%)	27.2	4%	6.7	2%	22.6	11%	7.6	5%
slope	0.23	1.51	0.17	0.69	0.23	0.46	0.25	0.40
Pvmax (W), Pvmax/Pmax (%)	179	27%	74.7	19%	68.6	34%	47.6	30%
lambdamax	98.24		98.7		62.7		76	
lambda50	93.6		96.4		61.5		73	
lambda30	86.7		94		60		71	
lambda20	84		86		58.7		70	
lambda10	72		71					
lambda2	40		35					
lambda0	31		13					

Legend:	
Pmax	Maximal power output, nominal power
U2, U3, U4	Voltage level of 1st, 2nd, 3rd DC output level
P2max, P3max, P4max	Maximal power of 1st, 2nd, 3rd DC output level
etamax	Maximal efficiency
Pges/Pmax	Workload at which maximal efficiency is reached
P2, P3, P4	Power of 1st, 2nd, 3rd DC output level at which maximal efficiency is reached,
	in absolute value and relative to maximal power of that DC level
eta100, eta50, ..., eta2	Efficiency at 100%, 50%, ...,2% of maximal workload
	(several values for different relative splits of the load between the different DC-levels
Pv0	Power loss at 0 workload, no load loss
Pv0/Pmax	No load loss relative to nominal power
slope	growth of losses with increasing power output (in absolute values of Watt)
	and growth of losses with increasing power output (measured in % of maximul power output)
Pvmax	Power losses at nominal power output
Pvmax/Pmax	Power losses at nominal power output relative to nomiunal power
lambdamax	Maximal value of power factor
lambda50, lambda30, ...,lambda0	Power factor at 50%, 30%, ..., 0% workload

The main observations can best be summarised in comparing the two power supplies for servers and the two power supplies for PCs:

1. Major variations from Artesyn, an older, to Cisco, a newer power supply unit for servers:
   - From several DC-output levels to single DC-output level

- Higher maximal efficiency (etamax)
- Maximal efficiency at lower workload (50% instead of 58%)
- Steep decrease of efficiency starts at lower workloads
- Decrease in "no load" loss
- Slower increase of no load losses with growing workload

2. Major variations from Minebea to Compaq, two older power supply units for PCs:
   - Slightly higher maximal efficiency (etamax)
   - Maximal efficiency at lower workload (70% instead of 84%)
   - Decrease in "no load" loss

Due to a different measuring set-up the characteristics of two other power supplies for personal computers are not included in Table 1, but are worthwhile a discussion.

- Lead Year, again an older power supply, shows efficiency figures similar to Compaq.
- The modern power supply HP does not show substantial improvements in efficiency at high and medium workloads – possibly due to the correction of the power factor (not measured for the HP unit) - but due to an additional 5 V DC-output for very low workloads (standby and other low-power modes of equipment) the efficiency is still as high as 60% and 40% at 2% and 0.4% of nominal output power (Figure 1) – to be compared with the efficiencies of 25% and 10% at 2% and 0.4% of nominal output power of the older power supplies for PCs.

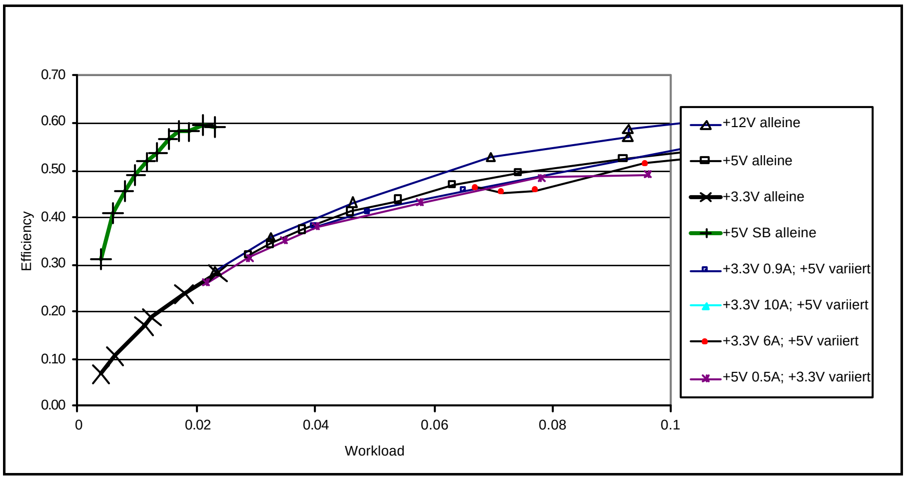


Figure 1: Efficiency of the modern HP power supply unit for personal computers at very low workload

In two recent issues of the c't-journal Steffens/Ahlers (2003) and Ahlers/ Steffens (2003) compare efficiency, power factor, noise and retail price of PC power supplies with a nominal power around 300-350 Watt. The measurements were done at 80% workload. The efficiency varies between 64 and 77% and the power factor between 55 and almost 99% showing three clusters characteristic for the technology chosen: no power factor correction (pfc), passive pfc and active pfc (Figure 2). Power units with a higher power factor tend to have also a higher efficiency, indicating clearly that a substantial effort is undertaken to compensate the decline of the efficiency (usually estimated to some 10%) due to power factor correction. Power supplies with higher power factor tend to have a higher retail price (Figure 3), but the unit with the highest power factor is not more expensive than the ones with a poor power factor and the retail price varies even more with the reduction of the noise level (sample 1 = normal noise level; sample 2 = reduced noise level). The power supply with the highest efficiency costs more than twice as much as the cheapest one with the lowest efficiency (Figure 4), but it is hardly more expensive than the units with an efficiency around 70%.

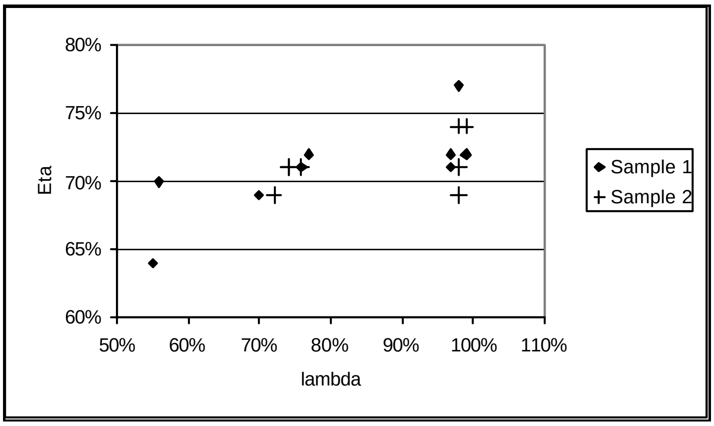


Figure 2: Efficiency (eta) and power factor (lambda) of PC 350-Watt power supply units. Sample 1 with normal, sample 2 with reduced noise level. (Source: Steffens/Ahlers (2003) and Ahlers/ Steffens (2003))

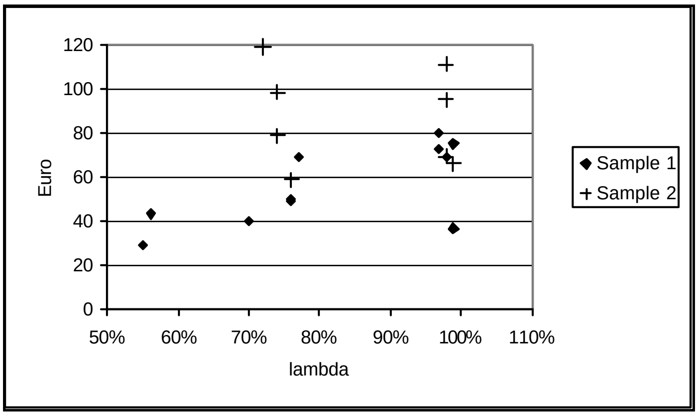


Figure 3: Retail price (Euro) and power factor (lambda) of PC 350-Watt power supply units. Sample 1 with normal, sample 2 with reduced noise level. (Source: Steffens/Ahlers (2003) and Ahlers/ Steffens (2003))

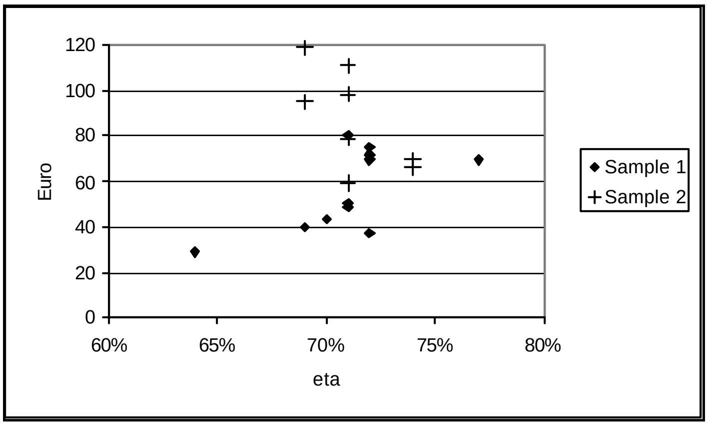


Figure4: Retail price (Euro) and efficiency (eta) of PC 350-Watt power supply units. Sample 1 with normal, sample 2 with reduced noise level. (Source: Steffens/Ahlers (2003) and Ahlers/ Steffens (2003))

3.2 Power supply units in PCs in different operating modes

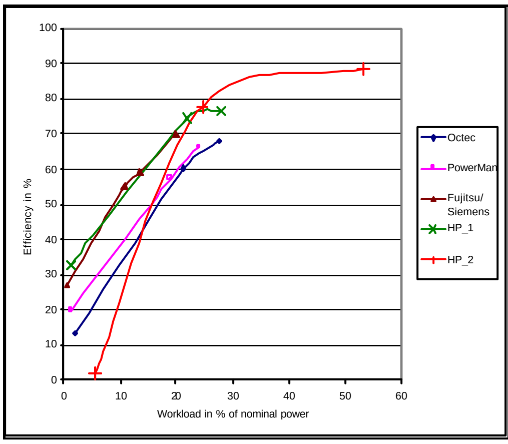
For five PCs described in Table 2 the efficiencies of the power supply units were measured for four operating modes of the PCs:

- off mode,
- standby mode,
- on mode with processor working at low capacity,
- on mode with processor working at full capacity.

Table 2: Characteristics of measured personal computers

Brand of PC	Brand of power supply unit	Nominal power of power supply unit [W]	Microprocessor, frequency, RAM	Peripheral components
Indiv. configured 1	Octek	250	Pentium 3, 866 MHz, 256 MB	2 x CD-ROM, ZIP drive, floppy drive, 2 x hard disk
Indiv. Configured 2	PowerMan	300	Pentium 3, 866 MHz, 256 MB	2 x CD-ROM, ZIP drive, floppy drive, 2 x hard disk
Fujitsu/Siemens Cordant	Fortron	250	Intel Pentium 3, 700 MHz, 128 MB	1 x CD-ROM, floppy drive, 1 x hard disk
HP Vectra VL 420 MT	Lite_ON (HP_1)	250	Intel Pentium 4, 2.2 GHz, 256 MB	1 x CD-ROM, floppy drive, 1 x hard disk
HP e-pc 42	Delta Electronics (external) (HP_2)	150	Intel Pentium 4, 1.8 GHz, 256 MB	1 x CD-ROM, 1 x hard disk

In standby and off modes the efficiency of the power supplies of the five PCs varies from 2% to almost 35% (Figure 5). These large variations are reflected by the large distribution of the standby power (real input power) of the five PCs ranging from 1 to 8 Watt.



Brand of power supply unit	Workload [%]	Efficiency [%]
Octec		
off	2	13
on low processor activity	21	60
on high processor activity	28	68
PowerMan		
off	1	20
on low processor activity	19	57
on high processor activity	24	66
Fujitsu/Siemens		
off	1	27
Standby	11	55
on low processor activity	14	59
on high processor activity	20	70
HP_1		
off	1	33
Standby	1	33
on low processor activity	22	74
on high processor activity	28	77
HP_2		
off	6	2
Standby	6	2
on low processor activity	25	78
on high processor activity	53	89

Figure 5: Efficiency of power supply units for three or four operating modes characterised by the workload of the power supply (measured in percent of its nominal power).

In on mode with the processors working at low capacity we measured workloads of the power supplies between 14% and 25% (mean = 20.2%) of nominal power and efficiencies of the power supply units between 57% and 78% (mean = 65.6%) (Figure 5).

With the processor working at full capacity, the workload of the power supply unit of the HP e-pc model increases from 36 W to 63 W (+ 75%!), the workload reaches over 50% and the efficiency almost 90%. This high efficiency is possibly needed because of the special configuration of the power supply unit: it's an external power supply, is hermetically sealed and the heat load can therefore not be evacuated by air flowing through the power supply unit.

The dramatic variation of power consumption with the activity level of the processor raises the question of the mean activity level of the processor over a typical working day. We determined the mean processor load of the HP e-pc computer used by a secretary doing mainly word processing tasks using the MS Office application “Word”. The mean processor load over a workday was 7% and the mean power consumption was 40 W. When a software developer used the machine, the mean processor load increased to 16.3% and the mean power consumption was 44 W.

In three of the tested PCs, most of the power load is carried by the +5V level (Table 3). In the HP computers, the +5V output is hardly used. The HP Vectra relies mainly on the +3.3V and the +12V level, whereas the HP e-pc model with it's external power supply uses the +12V and an uncommon +19V DC-level.

Table 3: Split (in percent) of output power by DC output level in the 5 PCs for two operating modes

PC brand and operating mode	DC output +19V	DC output +12V	DC output +5V	DC output +3.3V
Indiv. configured 1				
Standby mode	-	14%	86%	0%
On mode, processor under load	-	7%	93%	0%
Indiv. configured 2				
Standby mode	-	18%	82%	0%
On mode, processor under load	-	10%	90%	0%
Fujitsu/Siemens Cordant				
Standby mode	-	15%	85%	0%
On mode, processor under load	-	7%	93%	0%
HP Vectra VL 420 MT				
Standby mode	-	20%	1%	79%
On mode, processor under load	-	32%	1%	67%
HP e-pc 42				
Standby mode	42%	58%	-	-
On mode, processor under load	19%	81%	-	-

Windeck (2002) reports measurements, which are similar to our HP-measurements. He finds that in modern PC main boards, the 5V DC level is only of secondary importance (2-3% of total power supplied). Approximately 2/3 of the power is drawn from the 12V level, and the remaining 1/3 from the 3.3V level.

3.3 Power supply system and measures to improve energy efficiency

The voltage level of modern processors is as low as 1.5 V and will even decrease in the near future. The DC-output levels of a power supply unit lie usually between 12 V and 3.3 V and a secondary (or even third) power transformation is needed at the main board and the electronic components itself. For the DC-DC converter required for this purpose it may be assumed that with the use of switching regulators (down or buck converters) the mean efficiency is around 85%, or 50-65% if linear voltage regulators are used (details provided by manufacturer). This means that, in the complete chain of conversion from 230V AC down to 1.5V DC, the overall efficiency is approximately 50%.

The most important technical measures to increase the energy efficiency of the power supply system for ICT equipment are:

- using power supply units with an adequate nominal power in order to reach operating points of 50% or more;
- setting-up a separate power supply system from 230 V AC to 1.5 V DC for low power modes of the ICT equipments.

The technical saving potential of these two measures is for PCs of the order of 30% of today's electricity consumption. The annually saved electricity cost (without savings in the investment for infrastructure and energy savings on the infrastructure side) is therefore of the order of 10 EU/year for heavy users (office and computer freaks) (own estimates) and 2 EU/year for a typical private user (Cremer et al., 2003).

We did not investigate possible additional costs associated with improving the efficiency of power supply systems. Choosing a smaller power supply should reduce costs. But a separate DC-output for low power modes and an increase of the maximal efficiency of a power supply unit may cost a few Euro – an important amount compared to the price of a power supply, but almost negligible with respect to the investment for a personal computer and even more for a server/router[2]. More information on the cost effectiveness of more efficient power supplies will be published shortly in (RMI, 2003).

[2] The typical cost of a 200-watt power supply unit is around 16 US dollars. It is used for operating IT and communications equipment that typically costs around 1,000 US dollars (Calwell and Reeder, 2002)

4. Conclusions

The main insights can be summarised in five points:

1. It is difficult and for an ordinary end-user almost impossible to get technical information of power supplies.
2. The scope of the ordinary end-user is very limited. But, a large variety of power supplies are available on the market and larger buyers should be able to specify technical characteristics - like efficiency and power factor - of the power supplies used in their equipment.
3. The isolated investigation of power supply units does not cover the full problem of power losses and power distortion. A system-view of the power supply, including DC/DC conversion on the main board and the processor is needed.
4. Requirements regarding the power load of PCs in the standby/sleep mode – e.g. EnergyStar – had clearly some repercussion on the efficiency of power supplies (at very low workloads).
5. Requirements regarding the power loads of the entire PC (or ICT-equipment in general) have an important advantage compared to requirements for power-supply-units only, because they affect the total power transformation (including DC/DC on main board and processor).

Our recommendations are grouped in five points:

1. More research is needed
   - on the macro-level (power supply systems of (groups) of ICT-equipment) with the paper of Margaritis, B. und P. Ide (2001) as possible starting point and
   - on the micro level where two questions are in the foreground: trends and alternatives regarding the DC-level at the chips and how to bring the needed power to the chip (DC-DC conversion).
2. An information/formation/education campaign addressing primarily large buyers and data centre operators may result in some market-pull for a more efficient power supply layout.
3. An Energy Declaration of power supply units should be worked out on an international/global level. The structure of table 1 could be used as a starting point.
4. Strengthen the use of Energy Labels in two directions:
   - reinforce of the requirements regarding power loads in the standby/sleep mode and
   - initiate requirements regarding power loads in the on mode.
5. Energy Labels (addressing power loads of the entire equipment) have clear advantages over requirements regarding individual components (e.g. power supplies). But from the policy point of view it makes probably sense to proceed both ways. It leaves - in the case of negative negotiations regarding improvement/reinforcement of the energy labels - the way open to proceed via requirements regarding components.

Abstract

The efficiency of computer power supplies operated at least at 20% of their nominal power lies between 60% and 80%. At lower operating points the efficiency is decreasing rapidly. For PCs in actual use ("On-mode – but low processor activity") we measured operating points of the power supplies between 14% and 25% and a mean efficiency of the power supply units of 66%.

The voltage level of modern processors is as low as 1.5 V and will even decrease in the near future. The DC-output levels of a power supply unit lie usually between 12 V and 3.3 V and a secondary (or even third) power-transformation is needed at the electronic component itself in order to reach the 1.5 V level. The resulting overall efficiency of the power supply systems is therefore of the order of 50%.

The most important technical measures to increase the energy efficiency of the power supply system for ICT equipment are:

- using power supply units with an adequate nominal power in order to reach operating points of 50% or more;
- setting-up a separate power supply system from 230 V AC to 1.5 V DC for low power modes of the ICT equipments.

The technical energy saving potential of these two measures is for PCs of the order of 30% of today's electricity consumption.

At the policy level we recommend to pursue two strategies:

- introduction of an energy declaration for power supplies;
- reinforcement of the requirements of maximal power loads for ICT-equipments in low-power modes and elaboration of similar requirements for the power loads in the on-mode.

References

Aebischer, B. and A. Huser (2002): Energy Efficiency of Computer Power Supplies. Swiss Federal Office of Energy, Berne (http://www.cepe.ethz.ch/download/projects/Bernard/sb_power_supply_full.pdf in German; English translation expected in summer 2003)

Aebischer, B. and A. Huser (2002/2). Energiedeklaration von Elektrogeräten, Studie im Auftrag des Bundesamtes für Energie, CEPE Report Nr. 3 , Zurich

Aebischer, B. (1996): Towards greater energy efficiency in the use of computers. UNEP Conference "Implementing Environmental Commitment in the Insurance Industry". London, 20-21 May 1996 http://www.energieanalysen.ethz.ch/literatur/com_lon.pdf

Ahlers, E. and E. Steffens (2003): Ruhig gestellt. Besonders leise ATX-Netzteile zwischen 300 und 350 Watt. c't 2003, Heft 16

Bachmann, C. and B. Aebischer (1995): Market Pull Report. Demand-side measures for the accelerated development of more efficient energy technologies and their market introduction. Swiss examples in an international environment. Swiss Federal Office of Energy. Berne (EDMZ: 805.611 e)

Bachmann, C., B. Aebischer and R. Brüniger (1993): Miniwatt Report. Efficient Use of Energy in Information Technology and in Consumer Electronics. Swiss Federal Office of Energy. Berne http://www.cepe.ethz.ch/download/projects/Bernard/miniwatt_report_e.pdf

Bertoldi, P., B. Aebischer, et al. (2002): Standby Power Use: How Big is the Problem? What Policies and Technical Solutions Can Address It?, Proceedings of the ACEEE 2002 Summer Study on Energy Efficiency in Buildings, 18-23 August 2002, Pacific Grove, Cal. http://www.cepe.ethz.ch/download/staff/bernard/ACEEE02_paper569_official.pdf

Calwell, C. and T. Reeder (2002): Power Supplies: A Hidden Opportunity for Energy Savings. An NRDC Report. San Francisco, CA, 2002

Cremer, C. et al. (2003): Energy Consumption of Information and Communication Technology (ICT) in Germany up to 2010. Summary of the final report to the German Federal Ministry of Economics and Labour. ISI-FhG/CEPE, Karlsruhe, Zürich

IEA (2003): Cool Appliances. Policy Strategies for Energy-Efficient Homes. International Energy Agency, Paris (ISBN 92-64-19661-7)

Kaeslin, H. (2002a): Microelectronics Design Center, Swiss Federal Institute of Technology (ETH), verbal statement, 2002

Kaeslin, H. (2002b): Design of VLSI Circuits – Energy Efficiency and Heat Removal, Microelectronics Design Center, Swiss Federal Institute of Technology (ETH), 2002

Kaeslin, H. (2002c): Fabrication and Verification of VLSI Circuits – Technology Outlook, Microelectronics Design Center, Swiss Federal Institute of Technology (ETH), 2002

Margaritis, B. und P. Ide (2001): Contemporary Architectures for Power Systems Considering Future Trends, Ascom Energy System, in INTELEC 2001, Conference Publication No. 484, 2001

RMI (2003): Design Recommendations for Low-Power Data Centers. Report of the Integrated Design Charrette Conducted 2–5 February 2003 by Rocky Mountain Institute at the Hayes Mansion Conference Center in San Jose, California

Roturier, J. et al. (1994): Energy-efficient office technologies in Europe (OT3E), Commission of the European Communities, Brussels, 1994

SFOE (1993): The Hidden Juice Guzzlers. Standby Losses in Electronic Equipment for Office and Entertainment Use. Nr. 51, series of publication of the Swiss Federal Office of Energy, Berne, 1993

Steffens, E. and E. Ahlers (2003): Kraftstationen. ATX-Netzteile für den erhöhten Strombedarf. c't 2003, Heft 13

Steffens, E. (2001): 14 ATX-Netzteile im Vergleich (*Comparison of 14 ATX power supply units*), in c't magazin für computertechnik, no.10, 2001

Varone, F. and B. Aebischer (2001): Energy Efficiency: the challenges of policy design. Energy Policy 29, pp.615-629, 2001

Windeck, Ch. (2002): Sechs Mainboards für Intels Pentium 4 (*Six mainboards for Intel Pentium 4*), in c't magazin für Computertechnik, no. 21, 2002