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A REVIEW OF LARGE-SCALE SOLAR HEATING SYSTEMS IN EUROPE

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Abstract—Large-scale solar applications benefit from the effect of scale. Compared to small solar domestic hot water (DHW) systems for single-family houses, the solar heat cost can be cut at least in third. The most interesting projects for replacing fossil fuels and the reduction of CO_2-emissions are solar systems with seasonal storage in combination with gas or biomass boilers. In the framework of the EU–APAS project ‘‘Large-scale Solar Heating Systems’’, thirteen existing plants in six European countries have been evaluated. The yearly solar gains of the systems are between 300 and 550 kWh per m^2 collector area. The investment cost of solar plants with short-term storage varies from 300 up to 600 ECU per m^2. Systems with seasonal storage show investment costs twice as high. Results of studies concerning the market potential for solar heating plants, taking new collector concepts and industrial production into account, are presented. Site specific studies and predesign of large-scale solar heating plants in six European countries for housing developments show a 50% cost reduction compared to existing projects. The cost–benefit-ratio for the planned systems with long-term storage is between 0.7 and 1.5 ECU per kWh per year. © 1998 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

Large-scale solar heating plants have been under development in Europe for more than ten years. In the eighties in Sweden and Denmark and since 1992 in Germany several pilot plants were built. Three large-scale plants with seasonal storage are currently put into operation in Germany. Large-scale solar applications benefit from the effect of scale. The investment cost referred to the collector area is only 20–30% compared to small solar systems for single-family houses. Furthermore, large systems make it possible to use seasonal storages to store the solar heat collected in summer for space heating in winter, which is the most interesting application from the viewpoint of replacing fossil fuels and reduction of CO_2.

There are two major large-scale solar heating applications: systems with short-term (diurnal) storage (CSHPDS = Central Solar Heating Plants with Diurnal Storage), see Fig. 1, designed to supply 10–20% of the total annual load by solar energy or approximately 50% of the domestic hot water (DHW) heating requirements, and systems with long-term storage (CSHPSS = Central Solar Heating Plants with Seasonal Storage), see Fig. 2, capable of supplying 50–70% of the overall heating demand for space heating and DHW in residential buildings.

2. NEW APPROACH—COMPREHENSIVE ENERGY CONCEPT FOR BUILDINGS OR HOUSING DEVELOPMENTS

The rational use of energy (RUE) and the utilization of solar energy are required to achieve a remarkable reduction of fossil fuel consumption and CO_2-emission for the energy supply of buildings. The new approach is not asking: Is the energy saving measure cost-competitive with the conventional energy cost based on the actual gas or oil price? Instead of an aimed reduction of the fuel consumption and CO_2-emission, the cost-optimal combination of measures, e.g. improved insulation of buildings and implementation of solar heating plants and rational heating technologies, is determined in the ‘‘Comprehensive Energy Approach’’ (Hahne *et al*., 1993).

Fig. 3 shows the range of the ‘‘equivalent’’ heat costs of different measures to reduce the heating demand of new building developments in Germany (reference: actual thermal insulation standard - Wärmeschutz-Verordnung 1995, WSchVO 95).

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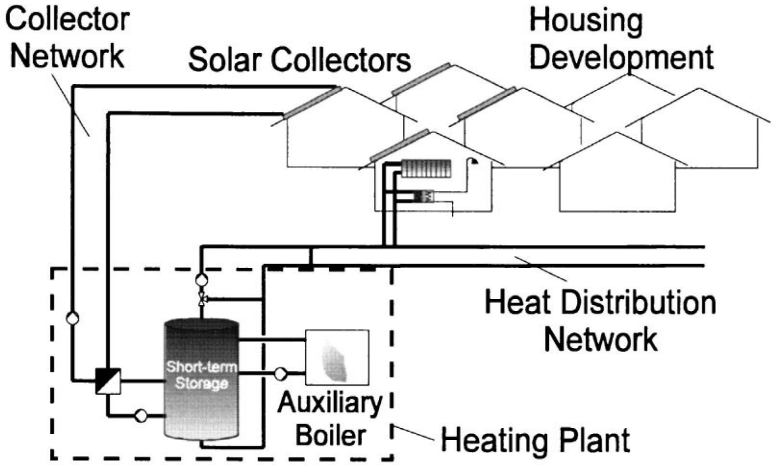

Fig. 1. Central solar heating plant with diurnal storage-CSHPDS.

The use of a gas condensation boiler instead of a conventional gas boiler is the most cost effective measure and the equivalent heat cost is less than 0.05 ECU kWh^{-1}. Additional thermal insulation measures of the building envelope (referred to the WSchVO 95) up to a heat demand index of approximately 50 kWh per living area per year results in a heat cost between 0.05 and 0.17 ECU kWh^{-1}. The use of solar energy in large-scale systems (>100 m^2 collector area) can be cost-competitive with insulation measures, especially if the requirements are more than 25% below the present German standard (Fisch *et al.*, 1996a,b).

3. EXISTING LARGE-SCALE SOLAR HEATING SYSTEMS

In the framework of the EU–APAS project ''Large-scale Solar Heating Systems'', thirteen existing plants in six European countries have been evaluated. This projects and some recently built large-scale solar plants (see Table 1) in six European countries represent the development during the last twelve years in Europe. A detailed description of all systems and a summary of the results are presented in (Dalenbäck, 1997). Table 1 shows the major project data of these large-scale systems.

The main results of the evaluation of the existing projects are:

- The investment costs are about one third of the costs of small systems (see Fig. 4).
- The system output is about 400 kWh per m^2 collector area per year.
- Systems with short-term storage are working efficiently and reliably.

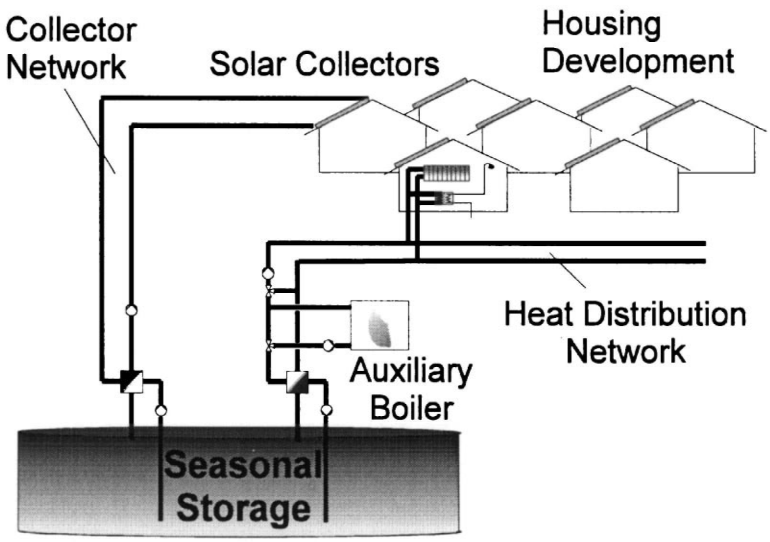

Fig. 2. Central solar heating plant with seasonal storage-CSHPSS.

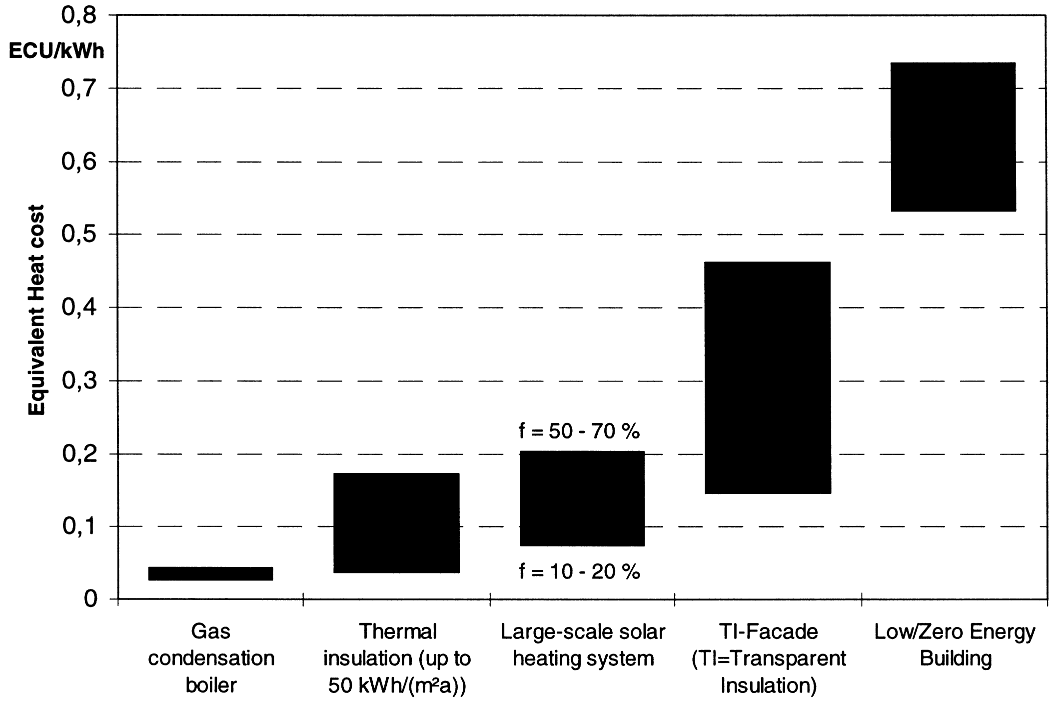

Fig. 3. Equivalent heat cost for various measures to reduce the heating demand of new building development in Germany.

- There is a need for R and D of cheap concepts for seasonal storage.

In Fig. 4 the investment cost referred to the delivered heat, the so-called cost–benefit-ratio, in ECU per kWh per year is presented. The graph shows the range for the different types of systems and in comparison to small SDHW-systems. The investment cost and thermal performance of custom made small solar domestic DHW-systems are valid for the German market (Fisch *et al.*, 1995). Between single small SDHW-systems and CSHPDS, which have a comparable solar fraction, there is a cost factor of about 3 to 4. However in a recently built housing development in the Netherlands (Apeldoorn) with 1000 individual small solar DHW- systems (2.75 m^2 collector area per flat) a cost–benefit-ratio of approximately 1.7 ECU $(kWh \cdot a)^{-1}$ was achieved.

Seasonal storage leads to a ratio for the CSHPSS twice as high as for CSHPDS (see Fig. 4). Figs. 5–7 show the collector-fields of existing large-scale solar heating plants.

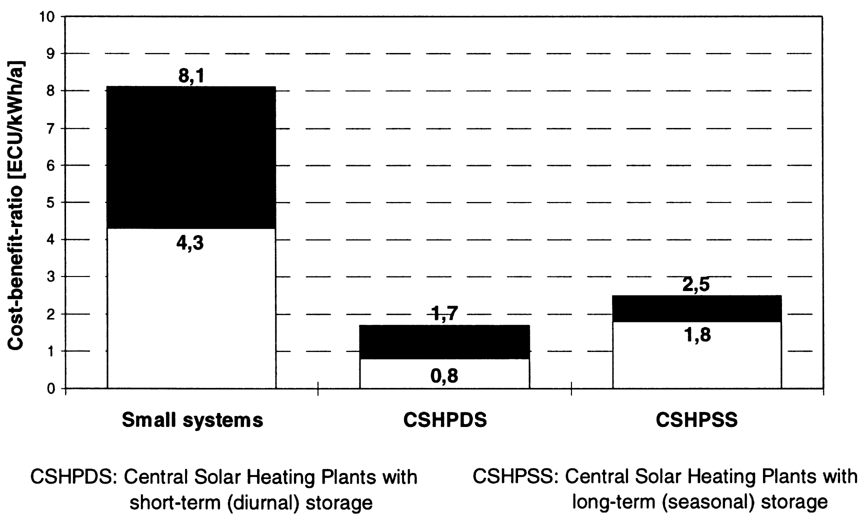

Fig. 4. Cost–benefit-ratios of the different solar systems.

Table 1. Large scale solar heating plants - major project data

Plant	Collector	Storage	Application
Block heating			
Groningen	2400 m^2	23 000 m^3	New residential area;
1984, NL	RM ET	ground storage	~65% solar coverage
Treviglio	2727 m^2	43 000 m^3	Existing residential area;
1985, IT	RM FP	ground storage	~70% solar coverage (HP)
Hammarkullen	1760 m^2	4 × 20 m^3 welded	Existing residential area;
1986, SE	RI FP	steel tanks	~35% solar coverage (DHW)
Särö	740 m^2	640 m^3 folded	New residential area;
1989, SE	RI FP	steel tank	~35% solar coverage
Bornholm	412.5 m^2	9 m^3 buffer	Existing block heating plant;
1989, DK	GM HT FP	(+ network)	~23% solar coverage
Lykovrissi	162 m^2	500 m^3 welded	New residential area;
1989, GR	RM ET	steel tank	~70% solar coverage
Andersvænge	224 m^2	10 m^3 buffer	Existing block heating plant;
1990, DK	RI FP	storage (steel)	~13% solar coverage (DHW)
Ravensburg I	115 m^2	5 + 1 m^3 buffer	New residential area;
1993, DE	RI HT FP	storage (steel)	~45% solar coverage (DHW)
Ravensburg II	137.5 m^2	5 + 1 m^3 buffer	New residential area;
1993, DE	RM HT FP	storage (steel)	~35% solar coverage (DHW)
District heating			
Saltum	1000 m^2	(district heating	Existing district heating plant;
1988, DK	GM HT FP	network)	~4% solar coverage
Ry	3000 m^2	(district heating	Existing district heating plant;
1989, DK	GM HT FP	network)	~4% solar coverage
Falkenberg	5500 m^2	1100 m^3 welded	Existing district heating plant;
1989, SE	GM HT FP	steel tank	~6% solar coverage
Nykvarn	**7.500 m^2**	**1.500 m^3**	**Existing district heating plant;**
1984, SE	**GM HT FP**	**steel tank**	**~12% solar coverage**
Otrupgaard	**560 m^2**	**1.500 m^3**	**Block heating plant;**
1995, DK	**GM HT FP**	**pit**	**~50% solar coverage**
Marstal	**8.040 m^2**	**2.000 m^3**	**Existing district heating plant;**
1996, DK	**GM HT FP**	**steel tank**	**~10% solar coverage**
Lisse	**1.200 m^2**	**1.000 m^3**	**Process heat;**
1995, NL	**FP**	**buried tank**	**~65% solar coverage**
Eibiswald	**1.250 m^2**	**105 m^3**	**District heating - residential area**
1997, AT	**RI FP**	**tank**	**~12% solar coverage**

Projects in bold letters are not evaluated in the EU project APAS.
Legend: R = Roof, G = Ground, I = Integrated, M = Mounted, HT = High Temperature, HP = Heat Pump, FP = Flat Plate, ET = Evacuated Tube Collector, DHW = Domestic Hot Water NL = The Netherlands, IT = Italy, SE = Sweden, DK = Denmark, GR = Greece, DE = Germany, AT = Austria.

Fig. 5. Installation of ground mounted collectors-Project Falkenberg, Sweden (1989).

Fig. 6. Project Bornholm, Denmark (1989).

4. POTENTIAL AND COST REDUCTIONS

The evaluation of the data about the energy situation and building structure in the EU–APAS participating countries led to a technical and economical potential of about 14 TWh a^{-1} for large-scale applications and about 20 TWh a^{-1} for small systems in the year 2015 (Zinko *et al*., 1997). With a heat generation of about 370 kWh for large and 320 kWh for small systems per m^2 collector area per year, the corresponding collector areas are 38 million m^2 (2 million m^2/year) and 63 million m^2 (3 million m^2/year). The values are valid for the six participating countries; for all member states of the European Community it is about twice as much.

To investigate the possible cost reductions for solar collectors, most of the manufacturers of solar collectors in Europe were interviewed. With increased sales, cost savings can be achieved by a reduction of material input and by industrial mass production. This leads to a reduction of **the prime cost for flat plate collectors of about 50%** based on today's design principles. A design for a new

Fig. 7. Installation of roof integrated collectors (site built)-Project Ravensburg, Germany (1992).

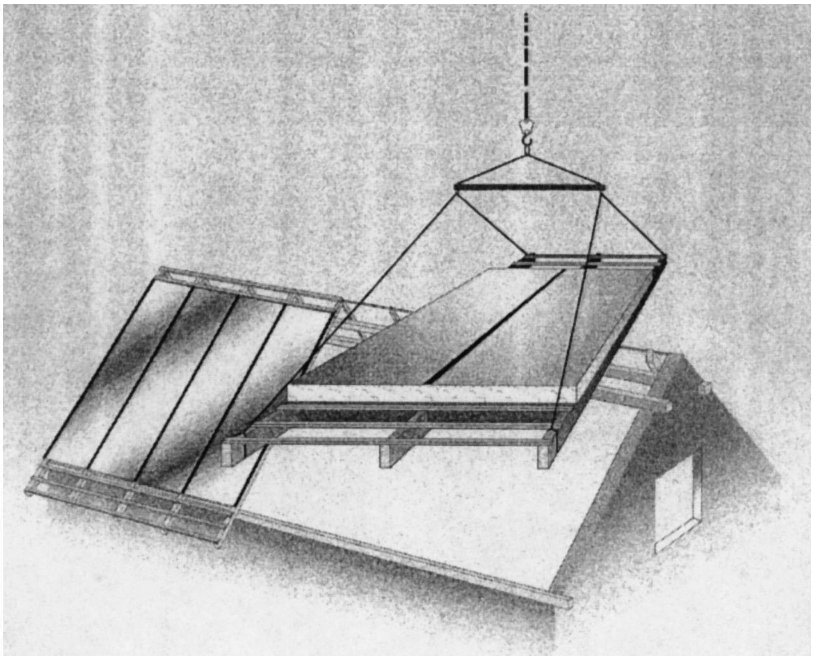

Fig. 8. Design of the ‘‘Solar roof module’’.

improved roof module collector is being developed and tested in Sweden and Germany. With this concept of prefabricated roof/collector module an improved integration in the construction process and further cost reductions have been achieved. Fig. 8 shows the design and Fig. 9 the installation of a roof module collector.

5. FUTURE OF LARGE-SCALE SOLAR HEATING SYSTEMS

Within the APAS project mentioned above, site-specific feasibility studies of planned large-scale solar heating systems in six European-countries were carried out (Fisch *et al.*, 1997). Six of

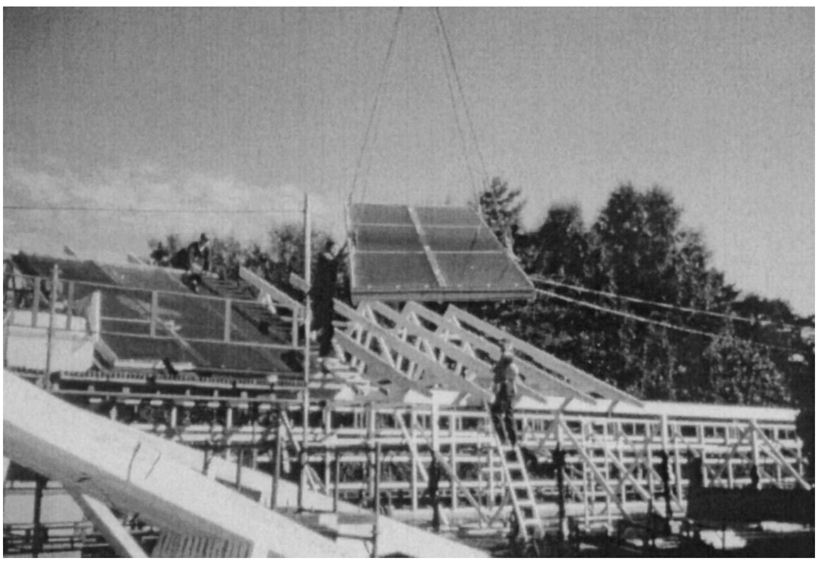

Fig. 9. Installation of roof module collectors-Project Onsala, Sweden (1995).

the fourteen projects are CSHPDS (see Fig. 1) without a seasonal storage and the others are CSHPSS (see Fig. 2).

Major project cost and performance data for these projects are presented in Table 2 and Table 3. In total, the projects comprise a collector area of about 110 000 m^2. All projects are planned with flat plate collectors. Two of the projects, Kungälv and Ekerö (SE), are planned with ground mounted collectors with reflectors between the collector rows, which improve the efficiency of the collectors and lead to a reduction of the necessary collector area. In the project in Lidköping (SE), a newly developed roof module collector, which has already been tested in a small project (Onsala, SE, see Fig. 9), will be used to build up the collector fields on the roofs of the houses. This type of collector shows a very low investment cost compared to the other projects, see Table 3.

Several projects with seasonal storage (CSHPSS) involve the development of new concepts or an improvement of existing concepts for seasonal storage. In Zwammerdam and in Rastatt, a natural aquifer will be used for seasonal storage. The aquifer store in Rastatt is planned with a man-made sealing wall around the storage region, because of ground water flow. Marstal and Skørping are planned with a new concept of a pit store with a clay liner based on a pilot storage in

Table 2. Feasibility and predesign studies - major project data

Plant	Collector	Storage	Application
Individual			
Sapes, GR	1350 m^2 RM FP	1 m^3 per system (tank)	New residential area, 150 res. units in individual houses, ~29% solar fraction
Block heating			
Ekerö, SE	8040 m^2 GM HT FP with reflector	25 000 m^3 earth pit (stainless steel liner)	New residential area, ~100 res. units, 4 840 MWh/a, ~75% solar fraction
Rastatt I, DE	1670 m^2 RI HT FP	50 m^3 buffer storage (steel tank)	New residential and commercial area, 770 units in multifamily buildings and terraced houses, 5.096 MWh/a, ~12% solar fraction
Rastatt II, DE	6780 m^2 RI HT FP	23 000 m^3 natural aquifer storage with sealing walls	New residential and commercial area, 770 units in multifamily buildings and terraced houses, 5 096 MWh/a, ~41% solar fraction
Lidköping, SE	2500 m^2 RMC	15 000 m^3 duct storage in clay	New residential area, 40 two family houses, 980 MWh/a, ~70% solar fraction
Zwammerdam, NL	6600 m^2 RI HT FP	120 000 m^3 natural aquifer storage	Existing residential area, 7 182 MWh/a ~35% solar fraction
Nieuwegen, NL	120 m^2 RI HT FP	6 m^3 buffer storage (steel tank)	Existing residential area, 144 res. units in multifamily buildings, 231 MWh/a (DHW), ~23% solar fraction (DHW)
Gallaratese, IT	1440 m^2 RM HT FP	78 m^3 buffer storage (steel tank)	Existing residential area, 1 956 app. in 35 multifamily buildings, 1 440 MWh/a (DHW), ~52% solar fraction (DHW)
District heating			
Marstal I, DK	8000 m^2 GM HT FP	2 000 m^3 buffer storage (steel tank)	Existing residential area, 1300 houses, 26 GWh/a ~13% solar fraction
Marstal II, DK	26 000 m^2 GM HT FP	70 000 m^3 pit storage (clay liner)	Existing residential area, 1.300 houses, 26 GWh/a ~29% solar fraction
Skørping, DK	26.250 m^2 GM HT FP	78.000 m^3 pit storage (clay liner)	Existing district heating network, 17,5 GWh/a, ~55% solar fraction
Hørby, DK	1.700 m^2 GM HT FP	500 m^3 pit storage (plastic liner)	Existing district heating network, 6,6 GWh/a, ~10% solar fraction
Ry, DK	8.000 m^2 GM HT FP	1.500 m^3 welded steel tank	Existing district heating network, 33,0 GWh/a. ~10% solar fraction
Kungälv, SE	10.000 m^2 GM HT FP with reflector	no storage	Existing district heating network, 84,9 GWh/a, ~5% solar fraction

Legend: R = Roof, I = Integrated, FP = Flatplate, M = Mounted, G = Ground, HT = High Temperature, RMC = Roof-Module Collector NL = The Netherlands, IT = Italy, SE = Sweden, DK = Denmark, GR = Greece, DE = Germany, AT = Austria

Table 3. Feasibility and predesign studies-major cost (per m^2 coll. area) and performance data (based on simulations)

Plant	Collectors [ECU m^{-2}]	Storage [ECU m^{-2}]	Total [ECU m^{-2}]	Net gain [kWh m^{-2}]	Total [ECU/kWh/a]	Type
Individual						
Sapes, GR	–	–	470 [1)]	~318	~1.48	SDHW + SH
Block heating						
Ekerö, SE	227	165	392	~396	~0.99	CSHPSS
Rastatt I, DE	341	–	375	~375	~1.13	CSHPDS
Rastatt II, DE	316	107	448	~310	~1.45	CSHPSS
Lidköping, SE	190	53	264	~274	~0.96	CSHPSS
Zwammerdam, NL	225	65	326	~380	~0.92	CSHPSS
Nieuwegen, NL	430	–	872	~434	~2.01	CSHPDS
Gallaratese, IT	265	–	424	~558	~0.76	CSHPDS
District heating						
Marstal I, DK	191	–	243	~406	~0.6	CSHPDS
Marstal II, DK	213	108	321	~309	~1.04	CSHPSS
Skørping, DK	157	109	315	~366	~0.86	CSHPSS
Hørby, DK	235	–	235	~400	~0.59	CSHPDS
Ry, DK	250	–	250	~400	~0.63	CSHPDS
Kungälv, SE	235	–	235	~450	~0.52	CSHP S

Legend: [1)] 150 SDHW + SH systems, SDHW = Solar Domesic Hot Water, SH = Space Heating NL = The Netherlands, IT = Italy, SE = Sweden, DK = Denmark, GR = Greece, DE = Germany, AT = Austria.

Otterupgård, DK (Dalenbäck, 1997). In Ekerö an improved concept of existing pit stores in Sweden with stainless steel liners is used. Compared to former pilot plants, all concepts are promising a reduction of the investment cost for the stores.

One project with small individual systems for domestic hot water and space heating (DHW + SH) is planned for an existing housing development in Sapes (GR). The feasibility study shows rather low investment cost compared to small SDHW-systems in other European countries. The investment costs referred to the yearly solar gain have been estimated to 1.48 ECU $(kWh \cdot a)^{-1}$ and are even lower than in the existing project at Apeldoorn (NL), where 1000 small SDHW- systems have been evaluated, see Dalenbäck (1997).

Fig. 10 compares the cost–benefit-ratio for the existing and planned projects. For the next generation of CSHP, a remarkable improvement of the cost-effectiveness is expected.

Within the eight year (1994–2002) development program "SOLARTHERMIE 2000" in

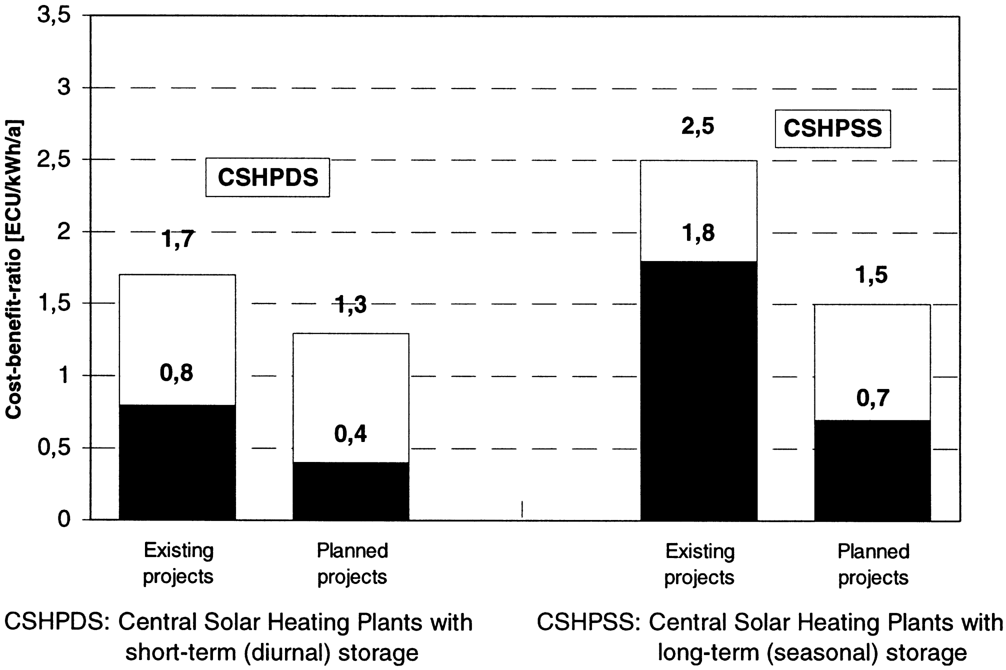

Fig. 10. Cost–benefit-ratios of the different solar systems.

Fig. 11. Collector fields on the roofs of the terraced houses in Hamburg.

Fig. 12. Collector fields on the roofs of multi-family buildings in Friedrichshafen.

Table 4. Data of the housing development and the solar plants in Hamburg and Friedrichshafen (Germany)

		Hamburg	Friedrichshafen
Houses			
House type	–	terraced houses	multi family
No. of houses/dwellings	–	124/124	8/586*⁾
Living area	m^2	14 800	39 500
Heat demand Space heating	MWh/a	1045	2736
ref. to living area	kWh/(m^2a)	71	69
Total gas demand	MWh/a	1686	4106
per m^2 living area	kWh/(m^2a)	114	104
Climate			
No. of degree days	K · d	3837	3717
Solar radiation (horiz.)	kWh/m^2a	978	1177
Solar plant			
Collector area	m^2	3000	5600
Storage volume	m^3	4500	12 000
Solar contribution	MWh/a	800	1915
ref. to collector area	kWH/(m^2a)	268	342
Gas demand per m^2 living area	kWh/(m^2a)	58	55
Solar fraction	%	50	47

*⁾to date 4 house-blocks with 270 dwellings have been built.

Germany, numerous large-scale solar heating plants without and with seasonal store have been built and will be completed in the near future.

The first three CSHPSS (see Fig. 2) in Germany were recently completed in Hamburg-Bramfeld (see Fig. 11), Friedrichshafen-Wiggenhausen (see Fig. 12) and Neckarsulm-Amorbach and were put into operation in 1996 and 1997 (Schulz, et al., 1996). The housing development in Hamburg consists of 124 terraced houses and in Friedrichshafen of 586 dwellings in eight multi-family buildings (only about 270 dwellings in eight buildings were established in the first phase). The characteristic data of the projects and the climatic conditions are summarised in Table 4.

In both pilot projects, a hot water pit is used as long-term storage. The concrete container is almost buried in the ground; water tightness is achieved by a stainless steel liner and mineral wool is used as thermal insulation. In Friedrichshafen a store without pillars but with a conically shaped self-supported concrete ceiling has been constructed (see Fig. 13 and Fig. 14). The overall construction cost of the store come up to approximately 220 DM (ca. 110 ECU) per m^3 volume (without planning cost).

Based on the experiences gained in these two projects, several ‘‘second generation’’ plants are presently in preparation in Hannover, Rostock, Chemnitz and Berlin (Germany). New heat storage concepts will be applied, such as duct storage (Neckarsulm), natural aquifer, man-made aquifer

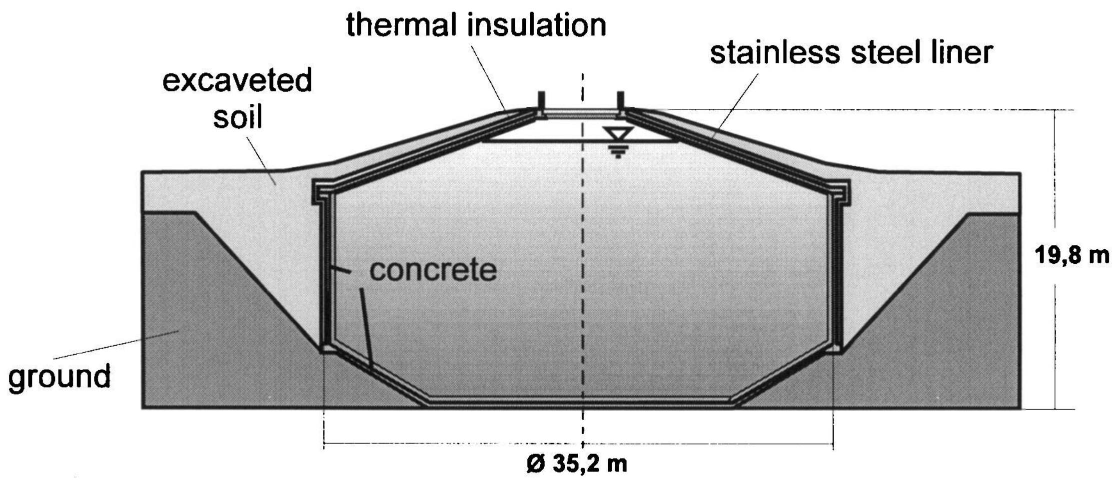

Fig. 13. Cross-section of the Hot Water Storage Pit in Friedrichshafen-Wiggenhausen, Germany.

Fig. 14. Construction of the store ($V = 12\ 000\ m^3$) in Friedrichshafen-Wiggenhausen, Germany.

(Chemnitz), as well as advanced pit storage (Hannover) concepts using high performance concrete and new construction technologies.

In Marstal and Skørping (Denmark), a new concept of a pit store with a clay liner based on a pilot store in Ottrupgaard is planned. All new storage concepts are expected to reduce the investment cost by 20–25%.

Also a new generation of roof integrated collectors, which combine roofing structure and solar collector (''solar roof''), has been applied (eg. Project in Neckarsulm, DE and Onsla, SE see Figs. 9 and 15).

6. CONCLUSIONS

The evaluation of existing large-scale solar

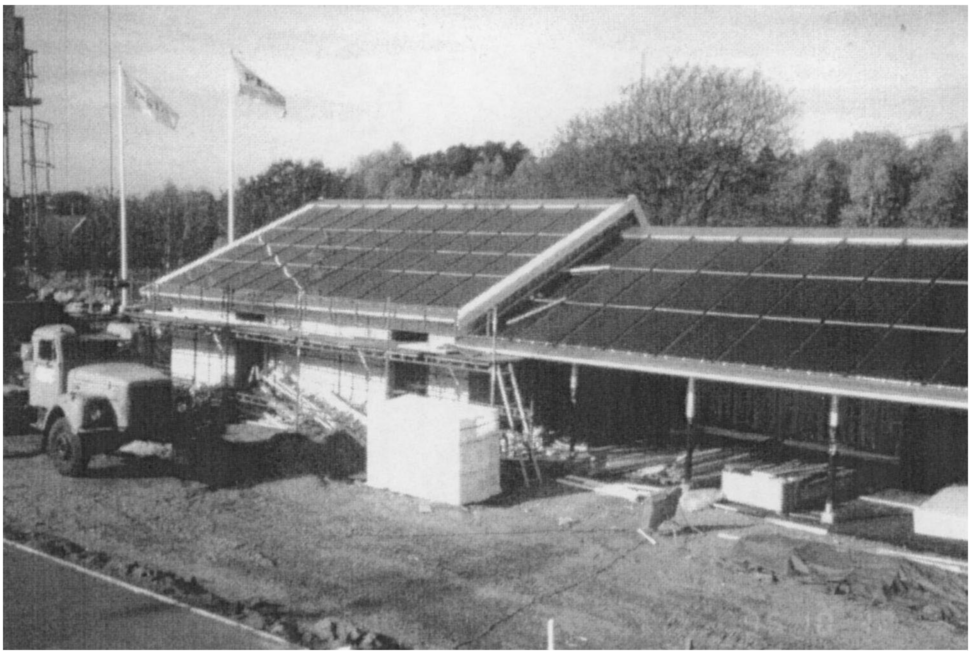

Fig. 15. ''Solar-roof''-Project in Onsala, Sweden.

heating plants has shown considerable development as well as cost reductions in the last ten years in Europe. One important result is, that there exist a number of potential manufacturers who are able to deliver collectors for large-scale applications. Although not fully cost-competitive, systems with short-term storage (CSHPDS) have become a more or less established technology in several countries. The ratio between the investment cost and the delivered heat for these plants is around 1 ECU per kWh per year. Further cost reductions can be achieved by industrial mass production of solar collectors.

For systems with seasonal storage (CSHPSS), which are the most interesting applications concerning the replacement of fossil fuels and CO_2-reduction, this ratio is still twice as high. The construction of more experimental plants with new seasonal storage concepts is a prerequisite on the way to cost-competitive plants. The need to build full-scale experimental stores puts restrictions on the number of projects which can be financed by national funds. This makes international cooperation and R and D funding necessary.

Integrated energy concepts, polarisation of planned housing developments, advanced heat storage concepts and further improved technology will guarantee further development and wider application of large scale solar heating. Well designed and functioning solar heating projects will continue to promote market growth for solar thermal energy applications.

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