2
The Salient Facts

2.1
Solar Tower Power Plants as the Basis for Cost Estimates: Cost Analyses

Although in this book all variants of solar thermal energy production are considered, we wish to emphasize the solar tower plant concept, since it has the best chance – according to most studies – of being implemented. To be sure, it is still much too early to make this prediction with certainty. We therefore point out that based on current knowledge, all the solar thermal and in particular all the light-concentrating technologies must be treated as being nearly equivalent, and thus they should all be developed with the same priority. Various studies in the past 30 years, such as for example that of Sargent and Lundy (2003), carried out for the US Department of Energy on the medium- and long-term costs of solar thermal power plants, arrived at the result that for electrical power generation on a large scale, tower plants have the greatest economic potential. This is related, among other things, to the high temperatures obtainable with this technology and thus their high efficiencies, and to the cost-effectiveness of heat storage in this case. In addition, they have relatively less stringent requirements in terms of the maximum slope of their location, which in particular could be important for sites in Spain.

In the USA, in 1996 a pilot solar tower plant of a type which can be used for base-load power generation was put into operation and tested through 1999: the "Solar TWO" power plant (Figure 2.1). This type of power plant uses molten salts as heat-transfer medium (molten-salt technology). The solar radiation that is reflected from a large number of movable mirror units (heliostats) is concentrated onto a so-called receiver, which is located at the top of a tower, and in which the molten salt is heated (solar tower plant). A portion of the hot salt is used immediately for steam generation for the turbine, while the larger portion is stored in a tank for nighttime operation. Thanks to this generously dimensioned heat storage system, the power plant can generate electrical energy around the clock, as long as the sun shines during the daylight hours. Figure 2.2 shows a schematic drawing of the molten-salt circuit.

Since during the day, solar energy must be stored for nighttime use, the mirror field and the receiver are correspondingly larger than for a power plant of similar

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Figure 2.1 The solar tower power plant Solar TWO (Barstow, California) (SANDIA).

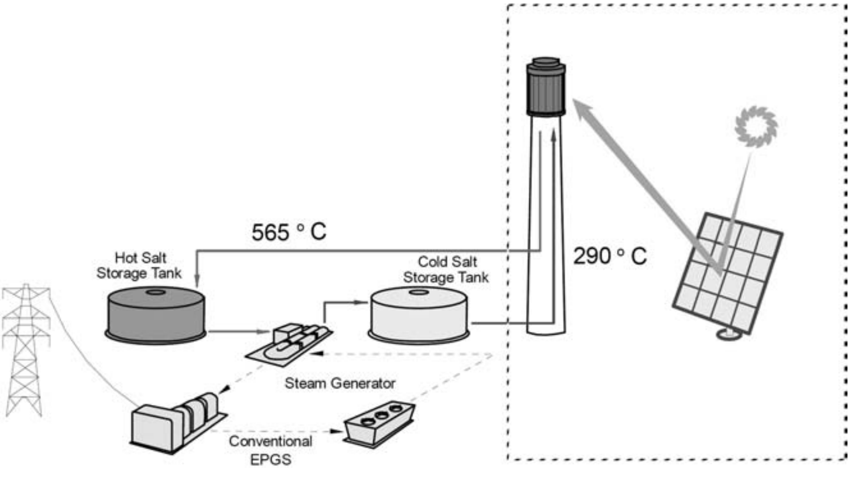

Figure 2.2 Schematic drawing of a solar tower plant with molten-salt technology (SANDIA).

output power without a heat storage system. The enlargement factor is called the “solar multiple” (SM).

The US national research institute Sandia National Laboratories in Albuquerque, New Mexico, carried out *cost estimates* in connection with the Solar TWO project, giving an indication of the costs of later, larger power plant units (Kolb, 1996a).

In these estimates, however, they considered only production series which were small in terms of the overall energy-economical scale. The results, however, already permit the clear-cut conclusion that for large-scale production, for example, the construction of 1000 MW of installed capacity each year, after intensive development work it would be possible to attain power costs of the same order as those from fossil-fuel power plants. (These results confirm, incidentally, several comprehensive studies dating from the 1970s and 1980s.[1]) The Sandia data form the *basis for the cost analyses* in this book. The expectations for large-scale production derived from them are compared here in detail with several newer studies based on higher production rates, which lead to practically the same conclusions (cf. Chapters 4 and 6).

2.2
The Combined System of Solar and Backup Power Plants (“Solar Power System”)

One disadvantage of the concentrating solar power plant is its requirement of direct solar radiation, which in Central Europe and in most other centers of power consumption, such as the American East Coast, is available to only a limited extent.[2] The solution of this problem lies in shifting the site locations of the power plants to regions with a generous supply of solar radiation. (In the cloud- and haze-free desert regions, one not only has considerably more solar irradiation on the whole, but at the same time, only a small proportion of diffuse radiation.) The electrical energy must then be transported via transmission lines to the region where it is to be consumed. For the power supply to Europe, possible sites are located especially on the semiarid plains of southern Spain and in the desert regions of North Africa (Sahara). There are a certain number of possible sites in southern Italy and in Greece, but the available areas are not ample, so that the potential of these countries would be sufficient at most to supply their own energy demands. Furthermore, the annual number of hours of insolation is not as great as in southern Spain or especially in the Sahara.

A similar situation to that of Europe is also found in the USA. There lies a very large solar potential of the sunny Southwest within the country itself. The southwestern states of the USA have among the best sites worldwide. From here, the eastern part of the country could be supplied with solar electric power. The distances would be roughly the same as those between North Africa and Central Europe (of the order of 3000 km). The *cost data*, which are given below for locations

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[1] The most important previous study was the so-called Utility Study of 1988, whose import can also be seen from the fact that – as its name implies – it was carried out with the significant participation of American power-generating operators (Hillesland, 1988).

[2] In contrast to the concentrating systems, a solar chimney power plant can make use of the diffuse irradiation, in addition to the direct insolation.

in *Morocco*, are therefore very similar to those for the *USA* (power supplies for the Eastern Seaboard).

The transmission losses and the required investments for transmission lines naturally enter into the economic considerations, but they are, at the current state of transmission technology, not a serious problem. With today's high-voltage direct-current (HVDC) transmission at a voltage of ±800 kV, the losses over the distance from southern Spain–Central Europe (2000 km) are ca. 8%. At a distance of 3000 km, they lie around 11.5%. The latter corresponds to the case of North Africa–Central Europe or the US-Southwest–East Coast. For example, the distance from the favorable sites in the south of the state of New Mexico to Washington, DC, is 3000 km, while the distance to Chicago is about 2300 km. High capacity utilization contributes to the low transport costs. Thus only base-load power, and not peak-load power, can be economically transported over these distances (at least not with comparable cost effectiveness). Since the large-scale power supplies we are considering here are mainly relevant to the base load, these desirable uniform energy transport rates can be taken for granted.

2.2.1
Solar Base-Load Plants

The day-night problem (base load) can be solved by using heat storage for solar thermal power plants. The problems of cloudy weather and the seasonal changes in the angle of the sun cannot, however, be efficiently solved by energy storage, since storage of heat over many days or even weeks is too expensive.[3] For this reason, in the present investigation, we compare nuclear and fossil-fuel base-load power plants with the model of a *combined system* (for solar base-load): it consists of solar thermal power plants (including energy transmission) and of fossil-fuel backup power plants, and will be referred to in the following for brevity as a "solar power system."

As reserve power plants (also called the *backup system*), one could envisage for example natural-gas fired gas- and steam-turbine power plants (combined-cycle gas-turbine (CCGT) plants, often briefly referred to simply as CC plants), or also coal-fired power plants. If these are located in the region of high power consumption, for example, in Germany, they guarantee power supplies in the event of an interruption of the transmission lines or even in the case of a hypothetical very long shutdown of the solar power plants (e.g., due to natural catastrophes). CC power plants can be operated both with natural gas as well as with domestic fuel oil. Even in the hypothetical case of a simultaneous failure of the solar plants and the gas supply, the continued provision of electric power could be guaranteed. Furthermore, gas turbines have a very short startup time and would be available

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3) There are plans, for example in connection with the Italian solar thermal development program, to bridge over cloudy periods of several days by using very large thermal storage systems (ENEA, 2001). The heat losses of the storage reservoir are not a problem here; instead, investment costs are the limiting factor. In the end, the question of economic optimization must be dealt with.

within minutes in the event of a sudden failure of the long-distance electrical transmission.[4)]

If today's coal-fired plants were all replaced by solar power plants (to release the coal supplies for other uses), the coal plants would remain available as backup systems at practically no cost.[5)] This is also true for the current base-load gas-fired plants, if they were to be replaced by solar power plants.

2.3
How Much Does Solar Power Cost?

In the following section, we present an overview of the cost estimates for solar tower plants with molten-salt cycles. In the later sections, we then give more details for solar tower plants and also for the other types of solar thermal power plants.

2.3.1
Introductory Remarks

Predictions of the production costs of various components of solar thermal power plants in mass production are necessarily limited in their accuracy. From the present viewpoint, we can thus not be certain that the costs estimated by Sandia in connection with the Solar TWO project, and the resulting derived costs for mass-produced plants, will apply in practice. The same holds for the prognoses related to the other solar thermal variants. Further research and development will, however, clarify this point. The general perspective that solar thermal power plants have the potential of low, economically feasible costs, is however already plausible today: there are, as we have pointed out, other solar thermal technologies in addition to solar tower plants, which offer in principle a similar economic perspective, although their chances of success may not be quite as favorable. Each of them has, considered from today's level of development, the potential of acceptable costs for mass-produced series. Since these systems are basically different, the R&D tasks

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[4)] A CC power plant consists of a gas turbine and a steam turbine, which follows it in the power train. About two-thirds of the output power of the plant is produced by the gas turbine and one-third by the steam turbine. Gas turbines can be started up on a routine basis in 15 min, and even more quickly in an emergency. The steam turbine part of the plant previously required ca. 1 h for a normal startup (not an emergency start). In newer plants, it can be started up in 30 min (cf. Chapter 10). In order to ensure the rapid switch-on time of the gas turbines (only a few minutes in an emergency) for the whole backup power plant, the present cost estimates for the solar power system include *additional* gas turbines in the CCGT backup plants, corresponding to the power output of the steam-turbine part, that is, one-third of the overall power output. Thus the power plant can provide its total rated output power within a few minutes after start-up.

[5)] Coal-fired power plants must be supplied with supplemental facilities in order to be able to start up rapidly; using either gas turbines or diesel engines (with the full output power of the coal-fired plant). If superseded coal-fired plants are to be maintained at low cost as backup plants, these additional facilities lead to tolerable supplemental costs for the overall backup plant system.

with the goal of reduced costs for mass-produced series are also different. The inability to meet these goals for one or another of these technological paths would not be a decisive failure. Owing to the great degree of independence of these paths from one to other, the probability that at least one of the technologies would attain the predicted cost for power produced is relatively high. We can illustrate this point with a numerical example: if we assume for four equivalent individual technologies that the probability of success for each one is 33%, then the probability that at least one of them will succeed is 80%. If the individual success probability is 50%, then the overall probability of success with at least one is 94%. (To be sure, such "probability considerations" must generally be taken with caution due to the difficulty in defining the input values precisely.)

2.3.2
Investments and Power Costs

In Tables 2.1–2.3, the costs which are to be expected based on current information for a large-scale solar energy-supply system, including transmission and the backup systems, are summarized in compact form. A more detailed treatment is given in Chapter 4. Tables 2.1 and 2.2 give an overview of the investment costs, while Table 2.3 shows the resulting power costs (the latter in comparison to gas-fired, coal-fired, and nuclear power plants). As mentioned, for the solar plant, the cost estimates are based upon those found in connection with the project *Solar TWO*; there, however, for relatively small production series (Kolb (Sandia) 1996a). They were adapted to mass-production series under assumptions which will be discussed later. The basis of these cost estimates will be explained in detail in later chapters, see especially Section 4.2.

The "capital costs" per kWh associated with the investments are calculated using the *real interest rate* throughout this book. This is the nominal interest rate reduced by the inflation rate. These costs are thus given in "inflation corrected" form (for details see Section 4.4). The amortization time is assumed throughout to be 45 years, for gas-fired, coal-fired, and nuclear power plants as well. This time period corresponds to the technical life expectancy of the power plants, in contrast to financial or tax amortization times which are in general taken to be considerably shorter. The costs are – with a few exceptions – quoted in *US dollars as valued in the year 2002*. Sources which give costs in Euros (€) are usually recalculated and quoted directly in 2002-US$ without mentioning this specifically in each case.

The conversion of EUR into dollars was not carried out using the exchange rate (from the year in question), but instead using *purchasing-power parity*. The exchange rate is subject to wide fluctuations, which have nothing (or very little) to do with the manufacturing costs of a product within a country. It, therefore, reflects the factual production costs in another country only in a very limited fashion. Purchasing-power parity is the preferred quantity for this purpose. Using the figures of the OECD (see Appendix B), it was in the range of 1–1.1 in the past 15 years; that is, 1 EUR (or the equivalent in the German predecessor currency DM) corresponded over this period of time with respect to its factual buying (purchasing)

Table 2.1 Investment costs for solar tower plants with a molten-salt circuit (2002-$).

Investment costs	Solar TWO advanced technology	Spain	Morocco/USA
Solar multiple	2.7	4.4	3.7
Heliostat costs	138 \$/m^2	83 \$/m^2	83 \$/m^2
	Million dollars (2002) per 1000 MW installed		
Heliostat field	1710	1670	1400
Receiver + tower	295	480	405
Horizontal salt circuit	–	180	150
Heat storage reservoir	355 (13 h)	435 (16 h)	435 (16 h)
Conventional components	590	590	590
Land preparation costs	60	95	80
Land purchase costs		140	
Sum (“direct costs”)	3010	3590	3060
Indirect costs[a]			
Interest during construction	240	145	125
Owner’s cost	180	105	90
Planning and project management	270	145	125
Miscellaneous/unexpected costs	210	–	–
Overall investment costs (wet cooling)	3910	3985	3400
Dry cooling (+8.7%)			295
Total investments	3910	3985	3695

The cost data from Sandia (Kolb, 1996a), based on the Solar TWO project (but assuming a receiver with “advanced technology”) were adapted with certain assumptions to a future large-scale, mass production scenario with mature technology; this concerns especially the heliostat costs and the indirect costs.

a) The indirect costs according to Kolb are given in Section 4.3.1.

Table 2.2 Investments for the overall power plant system (solar power system).

Investment costs	Spain	Morocco/USA
	Millions of dollars (2002) per 1000 MW	
(Solar power plants per 1000 MW at the plant site)	(3985)	(3695)
Solar power plants per 1000 MW after power transmission[a]	4335	4175
Transmission lines	500	665
Backup power plants (natural gas CC power plants)	715	715
Total investment costs	5550	5555

a) 1000 MW at the end of the transmission line requires 1090 MW at the plant location for Spain (2000 km, 8.1% losses), and for Morocco or USA (3000 km, 11.5% losses), 1130 MW would be required.

Table 2.3 Power costs of the solar power system based on solar tower power plants, compared to gas-fired, coal-fired, and nuclear plants.

Power costs		**Solar power system**		**Gas-fired**[a]	**Coal-fired**[a]		**Nuclear power**[b]
		Spain	**Morocco/USA**				
		US-cents per kWh (2002)					
Capital costs[c]		3.1	3.1	0.3	0.7		0.7
Operation and maintenance	Solar	0.7	0.7	0.3	0.7		1.0
	Backup	0.1	0.1				
Gas[d]		1.3	0.8	4.1	–	–	–
					EU	USA	
Coal[e]		–	–		2.5	1.3	–
Uranium	Fuel cycle[f]						0.5
	Natural uranium[g]						0.2
Power cost		5.2	4.7	4.8	3.9	2.7	2.4

a) Gas-fired power plants: 615 M$/GW, 8000 operational hours/a, efficiency 60%. Coal-fired power plants (without CO_2 sequestration): 1200 M$/GW, 8000 operational hours/a, efficiency 45%.

b) Nuclear power plants in mass production (new American type): 1100 M$/GW, 8000 operational hours/a.

c) Real cost estimate: 4% real interest, 45 years operating life.

d) Gas price (2002-$): 2.5 US-¢/$kWh_{gas}$ = 40 $/barrel oil = 6.6 $/MMBTU (HHV) = 0.68 ¢/$ft^3$ = 22 US-¢/Nm^3 (8.8 kWh LHV) = (assumed: €1 = $1.25) EUR 2 ¢/kWh.

In the case of price increases for natural gas, the backup power plants of the solar power system could be supplied with gas from coal gasification, which is available at roughly the same cost (for large-scale users with a separate gas line) (see Section 11.2). The proportion of backup power from gas-fired plants would be 30% for solar plants in Spain, and 20% for solar plants in Morocco or the USA.

e) Coal price (2002-$): Europe (imported coal) 90 $/tce (= 1.1 ¢/$kWh_{coal}$); US 45 $/tce (= 0.55 ¢/$kWh_{coal}$).

f) Fuel cycle not including the cost of natural uranium (but including waste-disposal costs according to WNA (2005) for the USA).

g) Natural uranium costs:

- Uranium price assumed: 130 $/kg U (= 50 $/pound U_3O_8). This is in the upper cost range for disposal of the uranium reserves. (For comparison, the maximum uranium price up to now (in mid-2007) was 350 $/kg U; in mid-2008, the price was 115 $/kg U, in August 2008 it was 135 $/kg U.)
- Assuming a *reduced future natural uranium consumption* of 14.5 kg U/GWh_{el}. With today's reactors, the world average consumption is 25.5 kg U/GWh_{el}. (At this consumption rate, the cost factor due to natural uranium in the power price range would be 0.33 ¢/kWh.)

power to $1–1.1. In the year 2002, the year on which the costs estimates in this book are based, it was given by $1 = €0.96.

In the first column of Table 2.1, those costs are set out which Sandia (Kolb, 1996a) estimated for a 200-MW solar tower plant (converted to 2002-$ instead of the original 1995-$, inflation factor 1.18). For clarity, the costs were extrapolated to an output power of 1000 MW.[6] The 200 MW plant corresponds in principle to the Solar TWO technology (10 MW), but with a receiver of the design denoted by Kolb as "advanced technology."

In the two right-hand columns, the costs are set out for a power plant optimized for base load (with a high annual total operating time, i.e., a large solar multiple (SM)). Which annual total operating time a solar power plant (with a thermal storage system) can attain at a particular site depends significantly on the size of its mirror field. If the mirror field is made only large enough to allow the power plant to just attain 24 hours of full-output power on a cloudless winter day, then even a small decrease in solar radiation would permit operation at only less than nominal output power. With a larger field, the power plant would operate at full capacity even with a minor decrease in solar radiation, as often occurs. The size of the mirror field is thus an important aspect of the economic optimization. (We have already mentioned that the relative size in relation to a power plant of the same electrical output power without a heat-storage reservoir is termed SM.) If the conditions of solar radiation are similar to those in southern Spain, and an annual capacity factor of 70–75% is to be achieved, one requires an SM of 4.4. In Morocco or in the USA, where the solar radiation is more even and stronger, an SM of 3.7 suffices in order to achieve ca. 80% annual capacity factor. The mirror field in the two right-hand columns was, therefore, increased relative to the initial data from Sandia (SM = 2.7) for locations in Spain by 63% (SM = 4.4) and for locations in Morocco by 37% (SM = 3.7) (and at the same time the capacity of the heat-storage reservoir was increased from 13 to 16 hours). The proportion of the power required from the backup power plants for uninterrupted service from the solar power system (at 100% of nominal output power) is then for Spain only ca. 25–30%, and for Morocco or the USA only 20%.

Extrapolating to a *mass-production scenario* was carried out as follows (cf. also Chapter 6 and Section 4.3.1):

- Regarding the costs of the heliostat field (conventional glass-mirror heliostats), estimated by Kolb for a production rate of only 2500 heliostats per year (each

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[6] A 200 MW_{el} plant at a solar multiple of 2.7 (receiver: 1400 $MW_{thermal}$) as described by Kolb corresponds for a solar multiple of 4.4 (in Spain) – that is, with a larger mirror field relative to the output power of the plant – to only 125 MW_{el}. A solar plant with a nominal output power of 1000 MW_{el} (and an SM of 4.4) would thus consist of eight such solar tower installations. The tower and mirror field of a solar tower plant cannot be enlarged arbitrarily; the optimum size for an individual tower installation lies roughly in the range of 1400 $MW_{thermal}$ (at the receiver), as described above. Making use of thermally insulated molten-salt piping (i.e., a *horizontal salt circuit*), however, allows several individual tower installations to be connected to a single central steam power plant (power block); that is, they can be "interconnected" to form a larger solar power plant. Ideally, this interconnection would comprise five to six tower installations of the size mentioned (in the case of smaller installations, correspondingly more of them must be interconnected). This yields a base-load solar power plant (at an SM of 4.4) of ca. 700 MW_{el} output power, with the advantage that efficient, reasonably priced, and reliable steam turbines in the widely used 700 MW class, as in current coal-fired power plants, could be employed.

with 150 m^2) to be 138 \$/m^2, we assume that with a mature technology and a production rate on the order of 100 000 heliostats per year, a reduction to 83 \$/m^2 could be realized. This corresponds to a construction rate for power plants of roughly 1 GW/a installed output power.[7]

- An additional assumption refers to the so-called indirect costs. These include for example, the interest which accrues during the period of construction and the costs for the infrastructure. These costs are also strongly subject to economies of scale, the construction time for a power plant decreases for higher production rates, since the fabrication of the parts, for example, the heliostats, is the limiting factor for construction time. Therefore, assumptions are made that generally correspond to mass-production series as required in the case of a large-scale system. This point will be discussed in more detail later.
- In the two columns for Spain and Morocco in Table 2.1, the costs for a "horizontal" molten-salt circuit are shown. They include the coupling of several tower installations to a larger overall power plant by means of connecting pipes for the molten-salt heat-transport medium (horizontal molten-salt piping – in contrast to the vertical pipes which connect to the receiver at the top of the tower).
- Since at desert locations such as in Morocco, wet cooling does not usually appear to be practicable, the investments for a solar power plant in this case were increased by 8.7% to take into account the additional expense of dry cooling.[8] This also holds for solar power plants in the USA.

In Table 2.2, the investments for the overall "solar power system" are set out. They refer to a capacity of 1000 MW at the end of the transmission line (thus e.g., in Germany). The required power plant capacity at the location of the solar plants is larger, owing to the transmission losses.

Table 2.3 shows the estimated costs for electric power generated by the solar-fossil combined system (the *solar power system*), compared with the costs of power from gas-fired, coal-fired, and nuclear power plants (in 2002 US \$). In the case of "Spain," solar power would cost 5.2 ¢/kWh; in the case of "Morocco/USA," 4.7 ¢/kWh. This corresponds roughly to the cost of power from natural-gas-fired power plants at the current price for gas.

With the assumptions mentioned above (including 4% real interest and 45 years operating lifetime for all the power plants compared), nuclear power from light-water reactors (future reactor types constructed on a *very large scale*) would cost 2.4 ¢/kWh, and power from coal-fired plants (without CO_2 sequestration) in Europe using imported coal at current prices would cost 3.9 ¢/kWh, while in the USA at current coal prices, it would cost 2.7 ¢/kWh.

For solar power plants, the *capital costs* are the most important determining factor. They are computed from the investment costs and the operating lifetime by

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[7] A base-load power plant of 1000 MW with a solar multiple of 4.4 consists of 135 000 heliostats of 150 m^2 each. A construction rate of 1 GW/a then corresponds to the production of 135 000 heliostats each year.

[8] It is assumed here that the power output of a solar plant would be 8% lower in the case of dry cooling, which corresponds to an increase in the specific investment cost of 8.7%; cf. Section 4.3.7.

multiplying the investment costs (per GW) by the so-called annuity factor of 0.0483 or 4.83% (corresponding to 4% real interest and 45 years operating life). This yields the annual costs resulting from *interest and repayment of the principal* of the invested capital. (The annuity factor quoted above assumes the debt to be completely repaid in 45 years.) These annual capital costs are then divided by the amount of energy generated per year at an overall power capacity of 1 GW so that the *capital costs per kWh* are obtained. The amount of energy produced annually is found from the capacity factor of the power plant and its power output capacity.

For the solar power system – a double system consisting of solar and backup power plants – the capacity factor is 100%. This yields an annual energy production of 8760 GWh (1 GW × 365 d × 24 h/d = 8760 GWh). In the case of gas-fired, coal-fired, and nuclear power plants, we assume 8000 hours of full-capacity production per year (corresponding to a capacity factor of 91%), that is, 8000 GWh of electrical energy per year.

The operation and maintenance costs in Table 2.3 are shown separately for the solar and the backup power plants. An additional point in the cost estimate is the fuel cost. In the solar power system, this refers to the natural-gas consumption of the backup power plants. Given the poorer insolation conditions in Spain, the expected proportion of backup power is 30% of the overall power production; in the more favorable desert sites in Morocco and in the USA, a proportion of ca. 20% is reasonable. This is reflected in the difference in natural gas costs shown in Table 2.3.

The costs for power from coal-fired plants shown in Table 2.3 refer to today's coal plants *without* separation and storage of CO_2 (so-called sequestration). It is, however, clear that the use of coal for energy production in the mid- to long term must be accompanied for the most part by sequestration, which will make the electrical energy more expensive. In these costs, one must distinguish on the one hand the cost of separating the CO_2 at the power plant, and on the other, that of transporting the CO_2 to the storage point and of storing it in a depot (former gas-field or a so-called aquifer, or even passing it into the ocean). Employing the data from (EIA AEO, 2007) for computing the costs of power plants, the cost of power would increase due to separation of the CO_2 alone (without transport and storage), for power plants with integrated coal gasification (IGCC) and assuming the cheaper American coal costs (45 $/tce), from 2.7 ¢/kWh (conventional power plants) to 3.4 ¢/kWh; for the case of the more expensive imported coal in Europe (90 $/tce), it would increase from 3.9 ¢/kWh (conventional) to 4.7 ¢/kWh (see Tables 4.3 and 10.2).

Regarding the costs of transport and disposal of the separated CO_2, there are widely divergent estimates. The literature available to the present authors quotes costs ranging from ca. 5 $/t coal (tce) up to 70 $/t coal (tce) (recalculated as an equivalent increase in the coal price).[9] The former would increase the price of

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[9] In the literature, the costs are quoted in $/t CO_2; they vary between 2.7 and $25 /t CO_2. Here, we have recalculated these costs as $/t coal (tce), which has the advantage that then, in the cost table in Chapter 10 "Fossil-fuel power plants", the influence of these costs on the price of electric power can be seen directly. (1 t coal (tce) = 0.75 t C (carbon); 1 t C = 3.66 t CO_2; 1 tce = 2.75 t CO_2.)

Table 2.4 Comparison of the electric energy costs from solar and nuclear power plants.

	Solar plants	Nuclear plants 1100 \$/kW at the plant	Nuclear-plant pools 1100\$/kW power transmission over 1000 km	Difference solar–nuclear
Operating life	45 a	45 a	45 a	
Power transmission	±800 kV		±800 kV	
	US-¢/kWh (2002)			
Morocco/USA	Solar power system			
4% Real interest	4.7	2.4	2.9	2.3/1.8
2% Real interest	3.8	2.2	2.6	1.6/1.2
	At the solar plant			
4% Real interest	3.3	2.4		0.9
2% Real interest	2.5	2.2		0.3
Spain	Solar power system			
4% Real interest	5.2	2.4	2.9	2.8/2.3
2% Real interest	4.3	2.2	2.6	2.1/1.7
	At the solar plant			
4% Real interest	4.1	2.4		1.7
2% Real interest	3.1	2.2		0.9

power from coal-fired plants by an additional 0.14 ¢/kWh, the latter by an additional 2.0 ¢/kWh[10] (for more details of the cost estimates, see Section 10.3). The overall costs of power from coal-fired plants would thus lie within the range of 3.6 to possibly 5.4 ¢/kWh in the USA; in Europe from ca. 5.0 up to possibly 6.7 ¢/kWh. If, for example, one assumes disposal costs of 10 US \$ /t CO_2 (27 \$/tce), the resulting energy cost would be 4.2 ¢/kWh in the USA or 5.5 ¢/kWh in the EU (cf. Table 4.3). In comparison with these coal-fired power plants, solar power would then not be much more expensive in the USA (4.7 ¢/kWh) or (depending on the development of sequestration costs) possibly even cheaper; in Europe (at 5.2 ¢/kWh) it would at least cost the same, but in fact would probably be even cheaper.

2.3.3
Are the Additional Costs Compared to Nuclear Plants Affordable?

In Table 2.4, the cost difference between solar and nuclear electric power is displayed. For locations in Morocco and the USA, this difference is 2.3 ¢/kWh; for sites in Spain, it is 2.8 ¢/kWh. In Table 2.4, in addition to the power costs as shown in Table 2.3

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10) Passing the CO_2 into the oceans would lead to additional costs; for the case of a transport distance of 1000 km on land (pipeline) plus a distance over the ocean of 2000 km, they would correspond to additional effective coal costs of \$30 to \$130 per tce (i.e., an increase in electric power cost of 0.7 to 3.6 ¢/kWh).

(i.e., the capital costs assuming 4% real interest), also the expected power cost at 2% real interest and furthermore the power costs at the solar power plant and – for nuclear power plants – the costs for the case of nuclear power-plant pools located far from the large consumer centers are given. These three points are discussed only briefly here. (For more details concerning lower interest rates, see Tables 4.2 and 4.3 and Section 4.4; regarding nuclear power-plant pools, cf. Table 4.3).

2.3.3.1 Burden on the Economy Due to Higher Power Costs (The Cost Difference Solar Energy – Nuclear Energy)

The burden on the economy due to possibly higher costs of solar power will be summarized in the following with a list in outline form, using as examples the USA and Europe. In spite of the assumed massive substitution of fossil energy sources, the economic burdens would in both cases be tolerable (USA 1.8%, EU 1.9% of the annual gross domestic product (GDP)).

Example: USA

- Assumption: *Difference in power cost = 2.3 ¢/kWh*
- Assumption: *1000 GWa$_{el}$* solar or nuclear power generation per year*

* This is 11 times today's annual power production from nuclear power plants. (For this production, with a capacity factor of 91% (2004), a nuclear power plant capacity of *1100 GW$_{el}$* would be required in the USA; currently, it is 105 GW$_{el}$)

Compare USA (2004):

Electric power generation: in total *450 GWa$_{el}$*, of this 90 GWa$_{el}$ from nuclear energy; coal-fired plants 230 GWa$_{el}$, gas-fired plants 80 GWa$_{el}$.

Primary energy consumption: in total 3100 GWa (coal 750 GWa); without primary energy sources for electric power generation (coal 670, gas 190, oil 35, nuclear 250, hydro 80 (cf. Appendix C) = 1225 GWa), this amounts to ca. *1900 GWa.*

The assumed 1000 GWa$_{el}$ corresponds, for example, to 350 GWa for the electric power supply (this should correspond roughly to the *total base-load* portion of the electric power generated in the USA) and 650 GWa for the substitution of primary energy sources in other areas (assumption: substitution by electric power) corresponding to *33%* of the *primary energy* consumption (1900 GWa). In evaluating the scope of this substitution scenario, the production of gas from the coal which would be substituted in the power plants (280 GWa of gas from coal gasification) must be considered, as well as ca. 80 GWa of natural gas which would be conserved in the gas-fired plants; cf. Section 11.2.9. All together, around 1000 GWa, out of 1900 GWa primary energy (mainly oil and natural gas), could thus be replaced outside the power plants, i.e., 53%.

With the assumptions given above, the additional costs to the economy amount to *$200 billion annually.*

(2.3 ¢/kWh × 0.0876 billion $/GWa* × 1000 GWa/a = 202 billion $/a).

*1 ¢/kWh = 0.01 million $/GWh = 87.6 million $/GWa = 0.0876 billion $/GWa

Comparison: *Gross Domestic Product* (GDP) USA 2003: 11 000 billion $.
The additional costs (200 bill. $/a) thus correspond to *1.8%* of the GDP

Comparison: *Defense spending* (USA)

2000 (before 11th Sept. 2001):	in total 390 billion $*
2006:	in total 590 billion $* (Defense Department budget: 410 billion $**)

* Source: World Military Spending 2007 ** Amadeo 2007

The additional costs estimated above (200 billion $/a) thus correspond to:

- *50%* of the total defense spending in the year 2000 (before 11th Sept. 01)
- *33%* ″ ″ ″ in the year 2006
- *100% of the increase* in defense spending from 2000 to 2006

Example: Europe (EU-25) – plant sites in Spain

- Assumption: *Difference in power cost = 2.8¢*/kWh
- Assumption: *800 GWa_{el}* solar or nuclear power generated per year*

* This is seven times today's annual power production from nuclear power plants. (For this production, with a capacity factor of 91% (2004), a nuclear power plant capacity of *880 GW_{el}* would be required in Europe; currently, it is 113 GW_{el}.)
Compare EU-25 (2004):
Electric power generation: in total *360 GWa_{el}*, of this 113 GWa_{el} from nuclear energy; coal-fired plants 110 GWa_{el}, gas-fired plants 70 GWa_{el}.
Primary energy consumption: in total 2280 GWa (coal 410 GWa). The primary energy sources for electric power generation are not listed in the EU statistics. Making use of assumed average efficiencies for electric power generation (efficiency: coal 38%, natural gas 50%, oil 50%), a rough estimate yields the following amounts: coal 280, gas 140, oil 30, nuclear 290, hydro 100 = 840 GWa. The primary energy consumption without energy sources for electric power generation thus amounts to roughly *1440 GWa*.

The assumed 800 GWa_{el} corresponds, for example, to 280 GWa for the electric power supply (this should correspond roughly to the *total base-load* electric power production in Europe) and 520 GWa for the substitution of primary energy sources in other areas (assumption: substitution by electric power); this is *35%* of the *primary energy* consumption in Europe (1440 GWa). In debating this substitution scenario, the possible gas production from the substituted power-plant coal (110 GWa gas from coal gasification) should be considered, as well as ca. 50 GWa of natural gas which would be conserved in the gas-fired plants; cf. Section 11.2.9). All together, around 680 GWa, out of 1440 GWa of primary energy (mainly oil and natural gas), could thus be replaced outside the power plants, i.e., 47%.

With the assumptions listed above, the additional burden on the economy amounts to *\$200 billion annually* (the same total as found for the USA)

(2.8 ¢/kWh × 0.0876 billion \$/GWa* × 800 GWa/a = 196 billion \$/a).
*1 ¢/kWh = 0.01 million \$/GWh = 87.6 million \$/GWa = 0.0876 billion \$/GWa

Comparison: *Gross Domestic Product* (GDP) EU-25 2002: 9900 billion €. Converted to US \$ at purchase power parity according to the OECD (2002 1 \$ = 0.96 €), this amounts to 10300 billion \$. The additional costs estimated above (200 billion \$/a) then correspond to *1.9*% of the European GDP.

Comparison: *Defense spending* (European NATO countries 2002) 161 billion US \$ (IMI 2002). (This is only 27% of the defense budget of the USA in the year 2006). The additional costs estimated above (200 billion \$/a) then correspond roughly to the current defense spending in Western Europe (only 25% more).

2.3.4
Possibly Lower Cost Differences, Potential for Further Development

Regarding the comparison of power-generating costs in Table 2.4 and the resulting burden on the national economy, several aspects should still be considered that might change the estimated costs noticeably:

- The cost difference of 2.3 ¢/kWh (USA) or 2.8 ¢/kWh (Europe) (Table 2.4) is based on the cost of nuclear power from plants in urban areas. If the plants were to be constructed far away from populated zones (nuclear-plant pools), which is reasonable in view of the large number of nuclear power plants needed, and if the electric power must, therefore, be transported over a distance of, for example,1000 km via transmission lines, then the resulting power costs are greater. The cost difference would then be reduced in both cases (EU/US) by about 20% and the additional burden on the economy with solar power would then be correspondingly lower.
- A noticeable decrease in the cost difference would also result in the case of lower interest rates, for example, for 2% instead of 4% real interest.[11] This, of

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[11] Many economists now believe that in future, when economic growth in the industrialized countries has stagnated, it will be possible to avoid a high proportion of unemployment only by maintaining a relatively low real interest rate. Considering the long amortization times for power plants (operating lifetime 45 a), it is thus quite plausible that this changeover to an employment-oriented finance policy might occur relatively soon, for example, within 10 or 20 years. The greatest part of the investment financing for future power plants would then take place at low interest rates. Under these economic boundary conditions, solar power, which is capital intensive, becomes more economically favorable than with today's comparatively high real interest rates.

course, reduces the costs of power both from solar plants and from nuclear plants, but not to the same extent. At a real interest rate of 2%, and in comparison to nuclear power-plant pools (with power transmission to consumer centers), the cost of nuclear energy in the USA would be 2.6 ¢/kWh, and the cost from the solar power system only 3.8 ¢/kWh. The difference in costs of 1.2 ¢/kWh is then only half as great as assumed in the previous considerations (2.3 ¢/kWh). In Europe (solar sites in Spain), the difference would be only 1.7 ¢/kWh as compared to the value of 2.8 ¢/kWh assumed above.

- In this calculation, the construction of *new* gas-fired backup power plants is assumed. In the case of a strategy involving the rapid replacement of the present, mostly relatively new coal- and gas-fired base-load plants, the plants replaced would be available at quasi "zero cost" as backup plants for the solar power system. (If the fossil-fuel power plants were to be replaced by nuclear plants, on the other hand, they would be shut down.) The power cost from the solar power system would be reduced effectively by ca. 0.5 ¢/kWh in comparison to nuclear power plants (cf. Section 4.1).
- The expected improvements in power-transmission technology, especially with superconducting transmission lines, would also shift the cost balance in favor of solar power plants. A decrease in transmission costs by more than half is not unthinkable.
- The true costs of solar power plants, by the way, could be considerably lower than assumed above, considering the *very large* production scenarios (and the accompanying intensive development of the power plants), which would be required. The numbers quoted above for solar power plants are based on a construction rate corresponding to less than 1 GW of new generating capacity per year (at an SM of 3.7), while the construction rate assumed for the nuclear power plants is a factor of 3 to 12 higher (see Chapter 12). Under the assumption of such a very large production scenario, it can be expected that simply the optimization of the power plants (making use of the overall *innovation potential*[12]) would give rise to a cost reduction compared to the costs assumed

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[12] Making use of the innovation potential is, however, in part already included in the above cost estimates, namely in the heliostat costs. A new large-scale heliostat cost study by Sandia (see the chapter on heliostats) yielded nearly the same heliostat costs for large production series (i.e., 80 $/m^2 in 2002-$) as assumed by the present authors in 1998 (70 $/m^2 in 1995-$, corresponding to 83 $/m^2 in 2002-$). These costs (Kalb/Vogel 1998) were, therefore, adopted in this book without change (and simply recalculated to 2002-$). The value of 80 $/m^2 quoted in the Sandia study, however, already includes a cost reduction through further technical development; it amounts to ca. 15% cost reduction. Fulfilling the innovation potential for the heliostats is thus, at least partially, already taken into account in the cost estimates for solar power given above. For all the remaining components of the solar power plant, this is, however, not the case. Furthermore, the cost-reducing effect of improvements in fabrication processes for the various power plant components (the so-called "learning curve") is also not included in the cost estimates. Here, and to a limited extent even for the heliostats, the large-scale application of solar energy should lead to further cost reductions.

above. The precondition for this is that the previously assumed costs, based on relatively low construction rates, are correct. This could be determined after only a short time in the course of the required intensive development phase (within ca. 2 to 3 years).

- Concerning the innovation potential, we should mention a particular point: simply the introduction of supercritical steam circuits might well yield a considerable cost reduction. This is shown in Table 4.6 and in Appendix A for the "SunLab 220 MW" power plant. These advanced steam circuits for coal-fired power plants are just coming on the market. (However, for "SunLab 220," along with these steam circuits, lower heliostat costs were also assumed, namely \$76 instead of 96 \$/m^2). In the USA or in Morocco, the advanced steam circuits would lead to energy costs "at the solar plant" of only 2.5 ¢/kWh (in spite of the lack of wet cooling), compared to 3.3 ¢/kWh (Table 2.4) and 2.4 ¢/kWh for nuclear power plants. (The energy costs "at the power plant" are relevant both in view of the provision of electrical energy for regions in the immediate neighborhood of the solar power plants, and for hydrogen production.) Supercritical steam circuits are, however, a special topic in connection with the development of solar power plants. Since there are no concrete statements on this point in the literature (and thus also not in S&L 2002!), we shall not consider them in more detail in this book. In order to achieve the higher steam temperatures required, the temperature of the molten-salt circuit (receiver, heat-storage reservoir) would have to be accordingly increased by ca. 100 °C. This, however, approaches the temperature range in which the currently used salts become unstable. What advantages such high-temperature steam circuits might in fact hold for solar power plants can thus not be readily judged. It is, however, clear that this possibly important opportunity has to be intensively investigated in a research program dedicated to the improvement of solar power plants.

If the present cost basis is thus confirmed, the costs in the later development stages of solar power plants will be lowered. Taking the considerably higher production rates into account in addition, we can expect correspondingly lower power costs.

- In contrast, for nuclear power plants it is to be feared that with strongly increased construction rates and accompanying limited construction capacity, a wide margin in the price calculation of the producers would be present; this could lead to prices that might be *substantially higher* than those quoted above, which follow closely the projected production costs based on current conditions and represent the lower limit of the cost range considered possible. Nuclear power plants, *in contrast* to solar power plants, are manufactured by only a few system suppliers owing to their complexity so that here a supplier cartel would be possible. This will be discussed in more detail in Chapter 12. A similar cost-increase effect is possible for the price of natural uranium.

"At the power plant," the cost difference between solar energy and nuclear energy is relatively minor (see Table 2.4). Thus for *site-proximate power-consuming centers,* the cost balance looks somewhat different from the above example (where the distance from the power-plant site was assumed to be 3000 km). Power transmission is unnecessary, or at most it is required over short distances. This holds, for example, for the West Coast of the USA, but also for Spain or the North African countries. With a view to the provision of base-load power, a backup system is indispensable. Insofar as the solar plants replace operating fossil-fueled power plants (which then, as mentioned, would be available "at zero cost" as backup plants), the energy costs would be roughly those given in Table 2.4 "at the power plant."

Energy costs "at the plant" are also relevant to solar H_2 production (electrolysis). Compared to nuclear H_2 production, however, somewhat higher costs for the transport and storage of the hydrogen gas must be assumed. In the USA, a difference of 1.5 ¢/kWh_{H_2} would then result (see Section 4.1). In the case of truly large-scale production series, and with full realization of the development potential, the difference would probably be negligible.

Regarding the cost problem, we must remember that it is much more important to avoid high oil and gas import prices than to prevent such (tolerable) cost increases as described above. No one can predict the developments in the Near East with certainty. A scenario involving a sudden increase in the oil price to 200 $/barrel sometime within the next 10 years is not unthinkable. (100 $/barrel (in 2008-$) corresponds to 6.3 ¢/kWh (2008-$) or to 5.3 ¢/kWh (in 2002-$).) If this should indeed happen (accompanied by the inevitable economic disturbances), it would not be important whether the replacement energy were especially cheap, but rather that it be available as quickly as possible. The question of whether, for example, solar hydrogen would cost 4.7 ¢/kWh (in 2002-$) (= 90 $/barrel of oil in 2008-$), or 3.2 ¢/kWh (= 60 $/barrel of oil), as for nuclear power (compare Tables 4.2 and 4.3), would then be irrelevant.

By the way, we should mention that the costs given here for nuclear power are based on future advanced reactors (generation III and III+) and adopted from a study carried out at the University of Chicago for the US Department of Energy (Chicago Study, 2004). The nuclear-power experts expect that these new reactor series will yield clear-cut cost reductions compared to the current reactors of generation II, in addition to improved security. Also, the costs assumed in the above estimates are based on very large production series for the nuclear reactors. The current reactors were considerably more expensive. These higher costs were accepted without complaint, and this would have been the case even if the reactors had been used on a much larger scale than was in fact the case.

2.3.5
"Hidden" Costs of Conventional Power Plants

In the cost comparisons given above, only the microeconomic costs of power generation were taken into account. This holds both for nuclear power plants and for coal-fired plants. However, power generation also gives rise to economic burdens for the general public, which are not contained in the construction and operating costs of the plants ("external" or "social" costs).

2.3.5.1 **Nuclear Power Plants**

In the case of nuclear power plants, these social costs refer especially to the risk of a major nuclear accident to the environment of the power plant. (Only the loss of the power plant itself as a result of the accident is insured, not damage to its environment.) This nuclear risk is naturally not easy to evaluate, and the various studies which have been carried out in the past years have arrived at quite different conclusions. The order of magnitude of the costs which can be expected becomes clear when one considers, for example, the study carried out by the noted Swiss Prognos Institute in 1994. It was prepared for a committee of the German parliament with the goal of estimating the costs associated with the risk of major nuclear catastrophes (Enquete Commission, 1994). The result was a price increase amounting to 3¢/kWh (2002)[13] for nuclear-generated electric power. Other studies have arrived at results lying notably lower, but some also higher. If we use the Prognos result as a working value, the costs of nuclear power would thus increase by 3¢/kWh (corresponding to the risk represented by currently operating reactors, on which the study was based); this means an increase in the value from 2.4¢/kWh[14] given in Table 2.3 to 5.4¢/kWh. This can be compared to the energy cost of power from the solar power system of 5.2¢/kWh (Spain) or 4.7¢/kWh (Morocco/USA).

For future reactor series with improved security – in particular for inherently completely safe reactors (the so-called generation IV) – this risk supplement would be negligible (however, these reactors are more expensive, and furthermore one expects for them a development time of the order of 30 years). The Prognos value is, as mentioned, not to be taken as a “scientifically verified” number, and there are estimates that lead to much higher and much lower costs. Nevertheless, we can use it to give a rough orientation. A decisive aspect for the comparison with solar energy is in any case that those who make policy decisions must completely accept these external costs, which has thus far been the case; supplementary costs of this order (or the associated economic burden) were thus in their opinion economically tolerable. Therefore, similar costs for solar energy should also be tolerable. Furthermore, the prognoses estimates include only those supplemental costs resulting directly from a possible nuclear catastrophe, but not the associated human and social tragedies. Another aspect that cannot be quantified is the long-term problem of nuclear wastes, which is being passed on to future generations, while the possible consequences associated with the proliferation of nuclear weapons-grade fissionable material cannot even be assessed.

One more general remark on such risk-assessment studies is as follows: they are in principle always based upon the calculation of “damage from a major catastrophe multiplied by the probability that such a catastrophe will occur.” In a lecture (“On the responsibility of scientists to the public”) at the Spring Meeting

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13) Prognos: 1992, 0.046 DM/kWh (= 2.3 Eurocent/kWh 1992) = 3.0 US-¢/kWh (2002) (inflation in Germany: × 1.20; €1 = 1.96 DM; purchasing power parity (OECD) 2002: €1 = US $1.043).

14) It should in fact be taken into account that the value of 2.4¢/kWh is already based on a new generation of cheaper reactors. All in all, this simplified consideration should still be valid.

of the German Physical Society in 1994, Werner Buckel[15] (the former president of the European Physical Society) made the following statement about such calculations:

> "... However, I hold it to be unscientific to try to quantify the risk of a serious accident in a nuclear power plant in terms of probabilities. For the computation of a probability in the scientific sense, one needs a large number of events; or, if one wishes only to extrapolate, a complete set of parameters and their mutual interdependencies. We have neither for the nuclear power plants." (Buckel, 1994) Considering the above-mentioned possible level of damage resulting from a single nuclear accident, he spoke on another occasion of the "lack of sense made by risk calculations of the type 'multiplication of zero by infinity'." (Buckel, 1996)

If in fact it is possible to develop inherently safe nuclear power plants with a catastrophe probability of zero, this argument would become irrelevant as applied to reactor safety. Considering the no less relevant problem areas of permanent waste storage and proliferation, as well as environmental damage in the uranium mining regions, it however maintains its validity. For high-temperature reactors (inherent design), however, the reprocessing of fuel elements has yet to be perfected (and it is evidently more difficult than for current reactor types). Therefore, in terms of the supply situation for uranium alone, using high-temperature reactors as sole energy supply is not feasible (as is also true of the currently used light water reactors), so long as uranium cannot be extracted from seawater. Instead, fast breeder reactors would have to be employed. These sodium-cooled reactors are, however, generally considered to be anything but "inherently safe."

2.3.5.2 **Coal-Fired Power Plants**

For coal-fired power plants, in terms of the external costs we must distinguish between power plants with or without CO_2 sequestration. In the case of sequestration, that is, separation and absolutely secure storage of the CO_2 for very long times, the external costs are reduced (i.e., those related to the effects of the CO_2 emissions on the climate), but power generation is more costly. We have already discussed these supplemental costs in Section 2.3.2. With typical disposal costs of 10 \$/t CO_2, power from coal-fired plants in the USA would cost 4.2 ¢/kWh, and in Europe 5.5 ¢/kWh.

In the long term – according to the most recent climate studies even in the medium term – generation of base-load power with coal (and also gasification of coal) on a large scale will be permissible only with accompanying CO_2 sequestration. For large amounts of CO_2 on a worldwide scale, the terrestrial depots are

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[15] Professor Werner Buckel (1920–2003), previously director of the Physics Institute at the University of Karlsruhe, was president of the German Physical Society from 1971 to 1973 and president of the European Physical Society from 1986 to 1988.

probably too small (although in some countries they might be sufficient). Then, only disposal in deep ocean regions would be adequate. Whether this can be carried out in practice, whether it would guarantee secure and permanent entrapment, and what it would cost, are all questions which remain to be addressed. Investigations into CO_2 disposal in the oceans are still at the stage of "basic research."

The costs of terrestrial disposal are also still highly uncertain, since no one as yet knows the sites of the depots which would be suitable for this purpose (in the future, they would require a very large total volume). Whether or not CO_2 storage in geological formations can in fact be carried out with absolute reliability will have to be demonstrated by further research. The potential storage capacity appears to be sufficiently great in some countries (e.g., in the USA, with its large land area). In many countries, this is however uncertain (for more details see Section 11.3.3).

Concerning storage in the oceans, Jochem (2004) – quoting Tzima and Peteves (2003) and Mazzotti *et al.* (2004) – states that "The possibility of discharging CO_2 into deep ocean regions is dismissed by the majority of experts owing to its considerable risks (authors' note: the risk that the stored CO_2 would again escape into the sea and rise to the surface) and the associated ecological damage." Three German ministries in a joint report to the German Federal government likewise rejected ocean storage (BMWi, 2007).

If CO_2 is not sequestered, as is the case for current coal-fired power plants, the external costs due to the effects of CO_2 on climate change must be taken into account. There have been many scientific investigations into this extremely complex subject in the past 20 years. The general tendency of the results is that the significance of fossil-fuel power plants on *public health* is not as serious as considered in the mid-1990s, at least not in terms of its monetary effects[16]. Krewitt (2002a) quotes a value in 2002 for bituminous-coal power plants of 0.7 ¢/kWh, likewise (apparently using the same database) the European Commission (2003). In a new expertise for the German government in the year 2006, as a mean value for Europe (EU-25) in the case of bituminous-coal power plants, a value of *0.3 ¢/kWh* is given (Krewitt and Schlomann, 2006). In the same expertise, in contrast, referring to the *greenhouse effect* of the CO_2 emissions (likewise from bituminous-coal-burning power plants), external costs of *70 \$/t* CO_2 are quoted; recalculated in terms of the amount of carbon in the coal, this corresponds to an increase in the coal price by 190 \$/tce[17]; that is, a cost rise for power from coal-fired plants by over *5 ¢/kWh*$_{el}$. The costs of power from modern coal-fired plants (without CO_2 sequestration) in Europe (using imported coal at 90 \$/tce) of nearly 4 ¢/kWh would thus increase by more than 100% when these external costs are

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[16] These changes relate not only to potential technical improvements in the power plants (SO_2, NO_x), but also to new scientific findings (e.g., the effects of particulate emissions) and simply to a changeover in methods, in particular for the monetary evaluation. We refer the reader to the excellent analysis by Krewitt (2002b).

[17] 1 t coal (tce) = 0.75 t C (carbon); 1 t C = 3.66 t CO_2; assumed efficiency of the coal-fired plants: 45% for the computation of ¢/kWh$_{el}$.

taken into account. A remarkable fact in this connection is that in spite of intensive research, the bandwidth of the cost estimates ranges from \$15 up to around 300 \$/t CO_2.

In the German expertise mentioned above, the following statement on this topic is made: "The effects of a global climate change are various and possibly very great. The interactions between the global climate system, the ecosystem, and the socio-economic system are extremely complex. A study by the English Environmental Ministry (UK Department for Environment, Food and Rural Affairs – Defra) comes to the conclusion that the costs for damage resulting from climate change are with a high probability greater than a lower limit of 15 €/t CO_2. Model calculations using the integrated assessment model FUND in this study show that with plausible assumptions, damage costs of up to 300 €/t CO_2 result. After evaluation of the relevant literature and taking special account of the results of the Defra study, we recommend that as "best estimate" for computing the external costs due to CO_2 emissions, a value of *70€/t* CO_2 should be used (lower limit:15 €/t; estimated upper limit: 280 €/t)."

2.3.5.3 **Fossil-Fuel Backup Power Plants for the Solar Power System**

The problem mentioned above basically affects a solar power system as well, if the backup power were to be generated by coal-fired plants. In that case, however, the CO_2 emissions would be comparatively small owing to the small percentage of backup power within the overall power generated. For solar power plants in Morocco or in the USA, only ca. 20% of the power would need to be generated by the backup plants. This should be compared with the remaining ca. 10% CO_2 emissions from IGCC gas turbine plants with sequestration (CO_2 separation efficiency 90%). For the case "USA/Morocco," the reduction of the CO_2 emissions would thus not be much less than for an IGCC base-load power plant (80% instead of 90%), but for the case "Spain" (with a backup power fraction of 30%), the CO_2 emission would be reduced to a lesser extent.

As mentioned above, gas-fired CCGT backup plants could be fueled with gas from coal gasification instead of natural gas; either with syngas (without CO_2 separation) or with hydrogen (with CO_2 separation, insofar as in the future, CO_2 disposal could in fact be carried out at the costs given). Hydrogen should be available through "advanced technology" both in USA as well as in Germany (there using cheap lignite coal) at a cost which *roughly* corresponds to the current price of natural gas (2.5 ¢/kWh_{gas}) (see Section 11.2). For hydrogen production, CO_2 is separated at the end of the gasification process and then disposed of. With this type of backup power generation, there would thus be no more CO_2 emissions from the solar power system (except for the remainder of ca. 10% which results from coal gasification).

We can summarize as follows: (1) for backup power generation using gas from coal gasification in CCGT power plants, CO_2 emissions from the solar power system can in principle be avoided. (2) Even in the case of backup power generation using conventional coal-fired plants, the emissions would be limited and future carbon penalties would play only a minor role in the final power cost.

2.4
Possible Time Scales for the Operational Readiness of Solar Thermal Power Plants and the Comprehensive Replacement of Current Power Plants

Some *fundamental* remarks on the question of time scales for development, which is discussed in detail below, and on the necessary research program were already made in the "Preliminary Remarks and Summary" and are presupposed here.

2.4.1
Special Aspects of Solar Power-Plant Development

For the substitution of oil and natural gas, the major options of nuclear energy, coal, and solar thermal power plants can be considered. The characteristics and problems of nuclear and coal-fired power plants are generally well known as a result of lengthy public debates on their relative merits. In contrast, those aspects typical of solar power plants have hardly been present in the public consciousness or that of decision makers. This applies especially to the question of how quickly and comprehensively this alternative energy source can be mobilized.

For solar power plants, several aspects are important which distinguish them *fundamentally* from conventional power plants. These will be discussed here using the example of solar tower power plants:

1) **The simplest technology (the solar field)**
   This applies in particular to the mirror systems, the main cost item of solar power plants. For solar tower plants, these are the *heliostats* which can be rotated about two axes. The consequence of their technical simplicity is that their development can be carried out very rapidly. It is indeed true that the heliostat field of a solar tower plant is exceedingly large. However, since this field is completely modular – consisting of many simple, identical structural elements – we can see that "large size and high cost" are by no means synonymous with "great development effort."

2) **Construction from mass-produced components**
   This has the consequence that the development tasks (regarding the solar field) can be concentrated more strongly on production aspects than on the technology of the heliostats themselves. The reliable predictability of mass-production costs is here an important – and for power-plant construction unique – element of the required research and development.

3) **Mainly conventional technology for the remaining power-plant components**
   A solar power plant has a completely conventional *electric power generating system* (power block), as in a coal-fired power plant.

   The *heat-storage system* also consists simply of insulated containers filled with molten salt. This salt is a mixture of sodium and potassium nitrates, two materials which have been produced by the fertilizer industry in large quantities for many years. Molten nitrate salts have been in use for some time also in the chemical industry as a heat transfer medium, although not at the composition required for solar plants. Therefore, the *heat-transfer circuit (molten-salt circuit)* of a tower power plant is in fact nothing new. The salt piping, the pumps, the associated control facilities, the construction materials, etc. need only to be optimized for the application at hand. The main difficulty will be overcoming the initial "teething problems"; this holds also for the steam generator, which is heated using the molten salts.

Only the *receiver* can be regarded as an essentially new component. There, the concentrated solar radiation is employed to heat the molten salt flowing through its tubing. The goal is to use tubes with walls as thin as possible, and solidification of the molten salts within the receiver tubing must be avoided at all cost. Along with a suitable choice of materials, careful dimensioning and a precise control of the salt flow are of great importance. However, even in the case of the receivers, one is in principle still in the realm of conventional technology (heat exchangers).

4) **A limited complexity of the overall power plant – the separate development of the components is possible**

In contrast to nuclear power plants or modern coal-fired plants (e.g., with integrated coal gasification), solar power plants involve a relatively simple technology even for the parts outside the mirror field. A similar conclusion holds for the interactions of these plant components with each other and with the mirror field. There is no complex overall process (such as in particular in a nuclear power plant with its many safety systems, redundancy of components, and the associated intricate control facilities), but rather the individual subsystems (mirror field, tower circuits, heat-storage systems, molten-salt piping, steam circuit with its cooling system) are essentially simply connected in series, without complex feedback effects. The result is that the individual components of the plant can be operated during the developmental phase essentially independently, that is, they can be developed and tested individually. For this purpose, only certain ancillary facilities are required, which replace the remaining power-plant components for the purposes of operational testing.

For example, the development of the heliostats does not require a molten-salt circuit (receiver) and can thus be carried out completely independently of the receiver development. For testing the optical quality of the heliostats, one merely requires a beam characterization system including a target area.

A similar conclusion holds for the remaining components of the power plant (and thus with reservations also for the receiver), that is, for the *thermal systems* of the solar power plant. These include all those components involved in heat transport or the conversion of heat energy into electrical energy, that is, heat storage media, steam generators, turbines, etc. One requires no solar field and no receiver to perfect all these components; instead, the molten salt can be heated using a *gas-fired* test facility. In this manner, the same temperatures, temperature variations, and salt flows can be obtained as in operation with solar heat. We are thus dealing with a complete *fossil-fuel power plant* with *liquid-salt technology*, consisting of a gas-fired heater (instead of the receiver), molten-salt piping, heat-storage system, and steam power block. With the gas-fired heater, temperature variations such as those that occur when clouds pass over the solar plant or during start-up and shut-down can be simulated precisely. All these tests and the complete development of the molten-salt components can thus be carried out with such a facility. The planning and construction of such a fossil-fuel test facility could be begun immediately, without the need to wait for the completion of a solar field and a tower installation.

For the receiver development, the situation is basically similar. Here, too – very probably – test installations will be possible in which the concentrated solar radiation can be simulated: namely by using the thermal radiation from a combustion chamber (natural-gas-fired radiation chamber). In such a chamber, similar radiation densities should be attainable as from a real solar field. (Such a relatively simple gas-fired installation could be planned and constructed within a short time.) If the required radiation values cannot quite be achieved, the receiver components would have to be tested additionally in the established test centers at Almeria or in Albuquerque (Sandia), or possibly in the available (relatively small) solar tower power plants (Solar TWO in the USA (if it can be reactivated) or PS 10 in Spain). If the existing tower power plants are – contrary to expectations – not sufficiently large for this purpose, one of them could be expanded relatively quickly into a complete large receiver test installation[18]. The optimization of the technology for the receiver could thus be begun comparatively quickly. The receiver will, however, most likely be the component which requires the longest development time (but also not an extremely long time).

In summary, for the development of the individual components, a large solar test power plant is *not* required; on the contrary, this would even be disadvantageous.[19] After the individual parts have been tested in the manner suggested above and optimized for mass production, one can begin with their fabrication on a large scale.

5) The interdisciplinary character of the development program

Development of solar energy cannot be limited – in contrast to the development of nuclear or coal-fired plants – to a particular special subject area. Nearly

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[18] Since currently available heliostat designs could be utilized for this expansion (even though they are not optimized in terms of cost), an enlargement of the mirror fields could be begun immediately and the expansion program could be completed very rapidly, if needed (at an increased cost and under time pressure).

[19] In the case of nuclear or coal-fired (IGCC) power plants, such large research and development facilities were and are indispensable. There, several stages of improved and increasingly larger test plants were constructed in order to profit from the experience gained with the previous stage (scaling-up procedure).

In the area of renewable energy sources, within the research support and planning in the past one could discern a tendency toward the construction of large, expensive, but not very innovative test facilities (public "justification" of the R&D activities). A new, larger solar power plant (using a single technology, e.g., for the heliostats) would yield only minor advances in the technological development, but would cause an immense loss of time.

all the topics for research require a broad-based, interdisciplinary approach. By this, we mean that only a very small portion of the tasks lies within the field of development of solar technology in the narrow sense. Most of the tasks are situated in other areas; an example is the determination of the costs for mass production of the heliostats.

6) **Special requirements for the organization of the research and development program**
   The characteristics mentioned above have serious consequences for the organization of the required research program. Given their special nature, an orientation toward a research organization such as is applied, for example, to the development of nuclear power plants (in particular the establishment of new, large central research institutions) would not be expedient.

In the following sections, some of these special characteristics will be discussed in more detail.

2.4.2
The Simplest Technology – Consequences for Development and Construction on a Large Scale

The decisive factor, namely the *simplicity* of solar thermal power plants, will be demonstrated in more detail in this section using the example of the heliostats. The reader is expressly challenged to form his or her *own* opinion in this connection. This is readily possible even for nonprofessionals, given the clarity of the situation. Only then will he or she be sufficiently prepared to judge the numerous inaccurate predictions regarding the necessary development time which are currently circulating, that is, regarding the time when solar thermal power plants could be operational on a scale relevant to the energy economy. At present, the date when a substantial contribution from solar thermal technology to the overall energy supply can be expected is frequently estimated to be in the years 2040–2050. Such estimates are due solely to unthinkingly equating solar energy to the classical energy technologies in terms of the aspects discussed here. With nuclear or coal-fired plants, the technological complexity indeed determines the speed of development, and it sets a limit to an increased annual rate of deployment (in particular in the case of nuclear power plants). While a nuclear power plant counts among the most complex facilities yet constructed (even in terms of its security systems alone), in the case of solar power plants, we are dealing with – one is tempted to say – a primitive technology. This becomes most obviously clear on considering their major cost item, the heliostats. Their technology is by the way also very much simpler than, for example, that of an automobile, which is a typical mass-produced item.

Figures 2.3–2.14 show various designs for glass-mirror heliostats. Their simplicity can already be seen in the fact that – apart from two movable joints and the associated drive units – they contain only static structures, namely the supporting frame for the mirrors and the pedestal, which is anchored to the base. The sup-

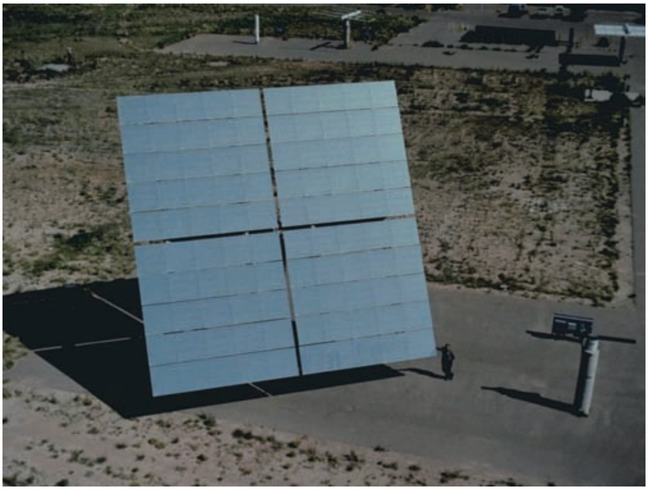

Figure 2.3 ATS heliostat (front side, as in Figure 2.4) (SANDIA).

Figure 2.4 ATS fourth-generation prototype (148 m^2) from the USDOE large-area heliostat development program (1985–1986) (SANDIA).

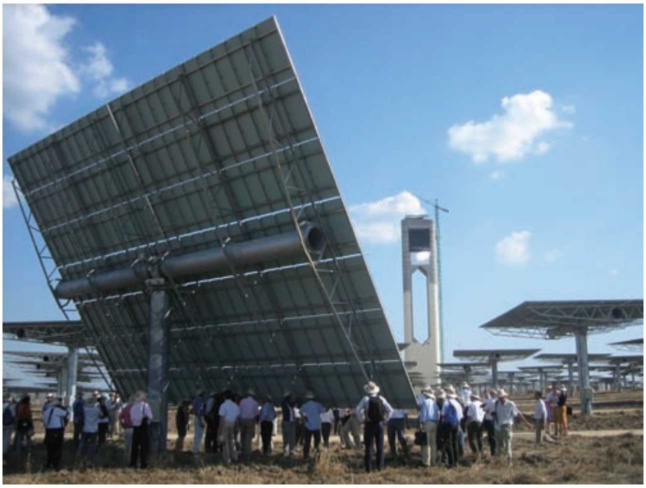

Figure 2.5 The solar tower power plant PS 10 near Seville (Spain): 624 Heliostats (121 m^2) (Photo: DLR).

Figure 2.6 The heliostat field of PS-10 (Spain) (Photo DLR).

Figure 2.7 A heliostat of PS-10 front side (SANDIA).

Figure 2.8 The heliostat field in front of the CESA 1 Tower (Almeria, Spain) (Photo DLR).

porting frame must be able to hold the mirror in the required position even against wind forces, and must not bend too much under load. In spite of the different shapes and sizes which are shown in the figures, all these various frames are constructed merely from elementary components such as sheet metal, angle irons, tubes, or rods. The frame rests with the two rotating joints on the pedestal. The

Figure 2.9 SAIC heliostat design (145 m^2), with 3-m diameter stretched membrane mirror modules (SANDIA). Note the "focal point" of the heliostat (the image of the sun) on the front face of the tower.

Figure 2.10 The back side of the heliostat in Figure 2.9 (NREL).

Figure 2.11 ESCOSolar 20 (Photo DLR).

latter is usually a large steel tube with branches at its lower end to connect it to the base.

For the heliostat designs which have thus far been favored, the drive motors and the gear drives must indeed meet high standards in terms of precision and stiffness under wind load, and at the same time they must be able to withstand strong forces during storms. But they remain entirely within the realm of conventional technology (electric motors, gear drives, linear actuators). The actual (movable) power train of a heliostat thus consists of only two motors and two gear drives.

In contrast, an automobile contains a large number of power trains and components such as motors with gear boxes, heating and air conditioning units, power steering, braking systems, indicators, and numerous electrical drive systems, quite apart from the complex body with its many preformed sheet-metal parts. All together, it contains several thousand different individual parts. The development of an automobile and the associated production system thus involves an immense package of technologies.

A heliostat, however, consists of only a very few *different* individual parts. This becomes especially clear in Figure 2.12 (development of a small-scale heliostat) and Figure 2.14. Large heliostats naturally contain more and larger (but mostly identical) parts; the number of “different” parts increases only slightly (compare Figures 2.4 and 2.5); this becomes still clearer in the case of the collector for a

Figure 2.12 Design of a "small heliostat" ($8\,m^2$) (SHP Australia, now AUSRA) (Photo Solar-Institut Jülich).

parabolic-trough power plant; see Figures 2.15–2.18. The development of a heliostat thus does not correspond to that of a complete automobile, but to only one small portion of one.[20]

This simplicity can already be seen in the relative costs of the technologies. A 150-m^2 heliostat with mass production will cost ca. \$13 000 (83 \$/m^2). The first prototypes are of course more expensive. But even if their *fabrication* costs 10 times as much, this would still be only \$130 000 per heliostat. For the development of nuclear power plants, one is faced with the task of constructing a prototype reactor

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20) Somewhat exaggeratedly, but descriptively, one might say: The development of a heliostat (with only rotational motions, but around two axes) corresponds more nearly to that of an "electrically operated trunk lid" than to a whole automobile.

Figure 2.13 Heliostats similar to those in Figure 2.12, here in the solar test field at Jülich, Germany (Photo Kraftanlagen München).

Figure 2.14 Solar Energy Development Center of BrightSource Energy, Negev Desert, Israel (BrightSource Energy, Oakland, CA).

with an output power of 1300 MW at a cost of ca. $3 billion, that is, at a production cost and effort roughly 20 000 times greater. Although, of course, such a simple cost comparison cannot be taken too seriously in terms of its information value, and although heliostat development in reality involves much more than just the construction of *one* heliostat prototype – namely the construction of many different

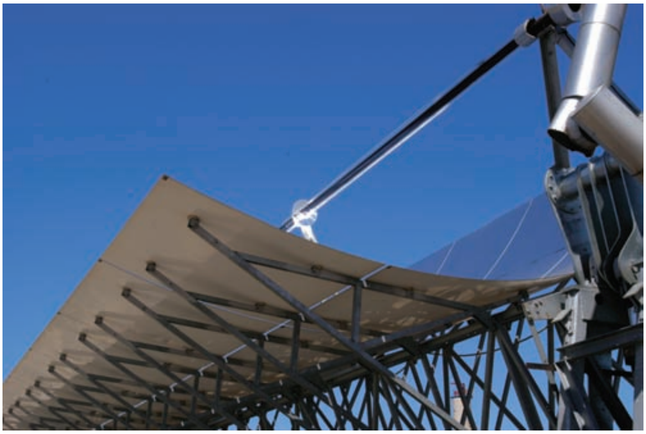

Figure 2.15 A parabolic trough (Photo DLR).

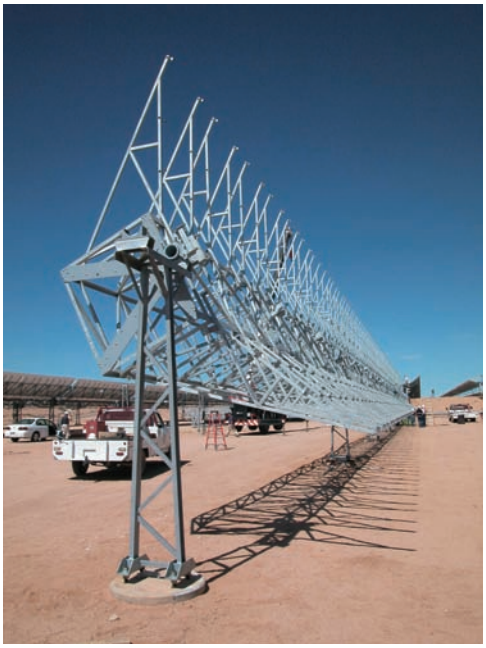

Figure 2.16 The supporting frame for the mirrors of a parabolic trough power plant (SBP).

Figure 2.17 Mounting of a parabolic trough collector in the field (SBP).

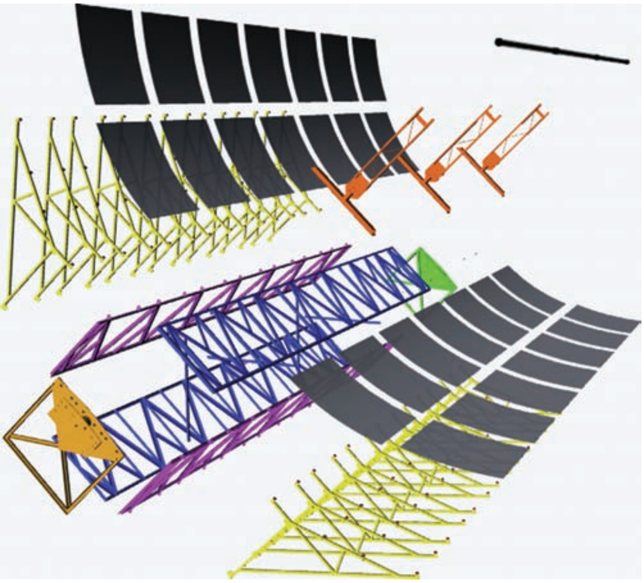

Figure 2.18 Elements of a parabolic trough collector (schematic) (SBP).

types and especially the preparation of cost predictions for each type–this comparison still makes the fundamental situation clear: the *completely* different order of magnitude of the development tasks.

The simplicity of the technology affects not only its development, but also the later stage of *mass production* to a great extent. Let us consider the support frame, which as mentioned consists of elementary steel parts that have to be welded together. These parts could be fabricated in almost any factory in the metalworking industry. They could and will presumably be delivered by a number of different manufacturers. If necessary, the production of even one particular part could be carried out by several different firms. The available production capacity could thus be utilized to its full breadth. In an emergency situation, all the free metalworking resources of a country could be mobilized for this production. This sort of distribution of the fabrication is of course not necessary, but the decisive point is that it would be *possible* if required for a *very rapid* increase in high production rates.

The individual parts, which were fabricated all over the country, would be transported to a central plant for *assembly*, where they would be combined into support frames (or also into a complete pedestal including attachment and mounting parts). In these assembly plants, the relatively large support frames would thus be produced and aligned. Due to the enormous dimensions of large heliostats, the assembly plants will certainly be set up in the neighborhood of the solar power regions.

In view of the very large numbers of such components and the simplicity of their assembly from only a few different parts, practically all the assembly steps could be carried out automatically, including feeding of the parts within the plant. Since a single assembly line would not be sufficient, the production would have to be spread over several parallel lines. As these would be identical (once the production technology had been tested and optimized), they could also be constructed quasi under “mass production” (worldwide, e.g., a total of 10 or 20 assembly lines), which would permit relatively short planning and construction times.

Furthermore, these plants, in contrast to automobile assembly plants, would remain practically unchanged over many years once they were set up. For here, unlike automobile factories, one would not have to contend with ever new models or variations. The small number of different parts (and thus different assembly procedures) simplifies the automation in general insofar as only a few types of assembly robots would be needed.

The complete large support frame, with mirrors and motion drives, will be mounted on the previously delivered and anchored pedestal in the solar field itself. This will also not be done “by hand,” but instead using mobile automatic or semiautomatic machines. The same is true of the attachment and concrete embedding of the pedestal. Here, also, heavy machinery with manipulators will be used, which carry out at least the major portion of the work automatically. The material flow within the solar field will probably be managed by automatic transport systems.

Heliostats thus can be produced and installed rapidly in very large numbers.

This technical simplicity leads by the way to an additional important difference in comparison to conventional power plants: in spite of large-scale mass production, the fabrication of the solar components will not lead to oligopolies or cartels. A development of this type is to be feared in the case of nuclear power plants, in particular if their deployment rate were to be drastically increased. If a manufacturer of individual solar parts (sheet-metal parts, tubing, etc.) were to ask too high a price, one could switch readily to other suppliers without major problems. The setting up of assembly lines is likewise a comparatively clear-cut task (e.g., in comparison to an automobile plant). Here, also, many suppliers could compete for contracts to construct the production robots. The general precondition is of course that the *whole* mass production of the heliostats not be put into the hands of a single private supplier (or only a few); otherwise, one would be subject to their price diktat, in spite of the simple fabrication procedures. Instead, the production should remain under the control of the power-plant operator, possibly with the support of subcontractors (e.g., large planning agencies), who would organize the construction and operation of the assembly plants.

2.4.3
The Basic Development Tasks for Heliostats

As we have seen (regarding the cost of a prototype), the fabrication and construction of a single new heliostat initially represents only a marginal task. With the construction of *one single* variant, however, the task is not completed. Thus, the goal of the development program is to identify those heliostat designs that will be cheaper to deploy in mass production than currently existing types. This requires the development of many different types; and for each of these designs,

a) its stability must be tested, and
b) its costs under mass production must be determined *reliably*.

While the investigations of stability concern purely technical questions (mostly pertaining to the statics of the mounting system and frame) and the performance of tests, the determination of mass-production costs raises a multitude of questions for each of the designs. These encompass the entire production process for each type. A reliable determination of the costs thus includes a number of individual steps and is, therefore (in terms of its scope), one of the major tasks in the development of heliostats. Secure knowledge of the production costs is not only necessary for the identification of the *least expensive* solution among the various heliostat designs, but also it is indispensable for the estimation of the economic potential of the whole solar energy supply system. In the following, we consider both of these developmental tasks more closely.

2.4.3.1 **Stability**

This point will be described in detail in Section 6.4; in anticipation we mention here only the following: an investigation of the stability of heliostats can naturally not be carried out by first constructing the heliostats and then subjecting them to environmental influences and waiting until major stresses occur (storms, hail, sandstorms, earthquakes, and possibly snow and ice), in order to test their serviceability. That would take entirely too much time (and gaps in knowledge of their resistance to certain environmental stresses would still remain).[21] A rapid and reliable investigation presumes the existence of *test installations*, in each of which a particular type of stress can be simulated:

- wind tunnels of a corresponding size (or other wind test installations for the large heliostats; cf. Section 6.4);
- sand blowers in combination with wind machines for testing leakage of the motion drives (and other parts of certain types of heliostats) in sandstorms;
- test beds for earthquake simulation;
- refrigerated chambers and snow machines for testing sensitivity toward snow and ice (for mountainous sites in parts of the USA and Spain), as well as hail machines, which likewise already exist (in the event of snowfall and hail, the mirrors are brought into their vertical positions);
- for plastic-foil mirrors, which are employed in a few heliostat types, aging effects must be investigated to estimate the operating lifetime of the components and how often replacement will be necessary.

We can see that with the exception of the more difficult questions regarding aging of plastics, the problems of stability with respect to environmental influences can be clarified reliably and quickly once the corresponding test installations are available. Thus, as soon as such a "test park" for heliostats has been set up, the actual test experiments are simple and can be carried out speedily, and represent on the whole a purely routine task.[22]

2.4.3.2 **Cost Predictions**

The "actual" task of heliostat development is the preparation of a reliable cost analysis for each design under consideration. This, as mentioned above, is a broad-based and multifaceted task. Not least due to this task, the "interdisciplinary" procedures are necessary. Such tasks are, however, in principle very ordinary in terms of the mass production of other items. Thus for the development of a new automobile model, such a cost analysis of the mass-production costs of new parts or assemblies is indispensable.

The costs need to be calculated for the following areas:

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[21] This "test procedure" was however employed in the past – owing to a lack of alternatives (i.e., lacking a systematic development program) – naturally complemented by calculations and simulations with models. Thus, Kolb *et al.* (2007a, p. 29) write: "The 148-m^2 ATS heliostat has successfully operated for the last 20 years at the NSTTF in Albuquerque. It has survived multiple high-wind events, some in excess of 90 mph ..." Better than such a waiting procedure, however, would be a realistic examination of the stability at high wind velocities in a test facility. Furthermore, the heliostat types being tested could also be set up in locations where the maximum design wind velocity occurs frequently.

[22] Even aging effects in plastics can be at least roughly investigated using time-lapse procedures. This of course also requires the corresponding test facilities.

1) fabrication of the individual parts
2) assembly
3) field installation.

Fabrication of the individual parts. Regarding the costs of individual parts, we look once again at Figures 2.3–2.14. One can readily see how simple the individual components are. Their fabrication costs will thus be easy to determine. This applies in particular to the static components of the heliostats. The gear drives and motors are, however, likewise typical mass-produced assemblies, whose production costs can be estimated precisely and with relative simplicity.

Assembly. The situation regarding assembly is different. In order to determine its cost, the appropriate assembly line for mass production must first be designed. Insofar as the assembly process involves conventional handling steps such as welding, inserting screws etc., the costs can also be determined quickly and precisely (in view of the many comparable procedures in other applications of mass production). For new process steps or unusual dimensions of the parts, however, the corresponding assembly robots must first be designed, built, and tested, since there are no direct comparisons available. Although only a few steps in the overall assembly process would be in this category, this remains the most extensive and difficult task within the entire heliostat development program, in particular since it must be carried out anew and in a different manner for each heliostat design under consideration. This setting-up of assembly lines is thus (together with the construction of a test park as mentioned above) the *essential* development task. Here, incomparably more must be designed and constructed than for the heliostats themselves.

Thus far, there has been only a single investigation of production costs which deserves to be called *detailed* and which also (at least partially) includes the planning of production facilities and assembly lines: The *General Motors* study of 1981 (see Figure 2.19). Whether or not the *whole* production process was planned in this study to the degree of detail required today, and the corresponding investment costs were estimated, cannot be seen from the available reports.

What was said above concerning assembly naturally holds in particular for the "nonclassical" heliostat designs, such as membrane heliostats. There, considerably less experience can be drawn upon from conventional assembly processes. Several new process steps such as, for example, attaching the membrane to its mounting ring are involved. It must thus be assumed that more new assembly robots would have to be designed than for the other heliostat types. But it must still be kept in mind that here, too, only a few different individual parts are involved so that on the whole, the effort required for these developments should remain on a manageable scale.

Field installation. For field installation, the situation is basically similar. Here, too, the costs of the required automatic machines will have to be determined. In contrast to the assembly of the parts, these machines would however be rather similar for the various heliostat types. The installation includes mounting the

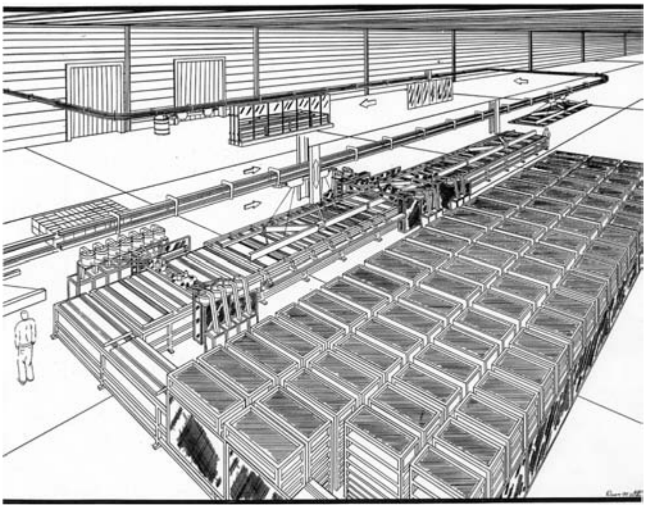

Figure 2.19 A figure from the detailed mass-production analysis performed by General Motors (1981), in which an assembly line was proposed that would be capable of producing 50 000 heliostats (McDonnell Douglas type) per year (SANDIA).

mirror frame onto the pedestal, attachment of the electrical connections, and adjusting the heliostat; furthermore constructing the base including attachment of the pedestal. Likewise, for all the heliostat types, the automatic or semiautomatic systems for material transport within the solar field are all practically the same. Nevertheless, at the beginning a considerable amount of development work will have to be carried out.

Thus, although detailed predictions of production costs lead to a whole series of development tasks and although various types of heliostats must be designed and tested, the costs of heliostat development will in the end be limited to a "modest" level. An estimate of these costs at present, without concrete examples, would be simply speculative. Nevertheless, a range from a few million dollars to some $10 million for the average development costs of each heliostat type would appear to be plausible. If we take $30 million per heliostat type and assume that 10 types would be considered, each differing substantially from the others (i.e., representing more than just minor variations of a particular type), this would yield an overall development cost of $300 million. Amounts of this order are, however, insignificant in comparison to the typical costs of energy research and development.

A certain indication of the price of investigations of production costs – namely the General-Motors study mentioned above – is given by Kolb *et al.* (2007a, p. 28): "The heyday of heliostat development in the United States occurred during the second-generation period ending in 1981. The DOE budget for heliostat development was $7.3 M, equivalent to *$19 M* in today's dollars. This budget level allowed for extensive optimization and cost studies, and more than 100 technical references can be found in Mavis [5]. An example is the detailed mass-manufacturing analysis performed by General Motors [6] in which assembly lines were proposed capable of producing 50,000 McDonnell Douglas heliostats per year. ...” ([5]: Mavis, 1989; [6]: McDonnell Douglas Astronautics Company, 1981.) The cost of the General Motors Study itself was not given. Since the entire development program cost only $19 million (in current monetary value), it can be assumed that this investigation cost at most $10 million. Whether it was sufficiently profound (i.e., sufficiently reliable in terms of current standards) is not clear.

Concerning the time required, as mentioned, one must always keep in mind that there would be no mutual hindrance due to the parallel development of different types of heliostats. With the correct organization of this parallel development program, the time for the overall development corresponds to the development time for a single type of heliostat. Nearly all the tasks of heliostat development (construction of the test park, planning of the assembly lines, design and construction of the plants for individual assembly steps) could be carried out in a short time in the framework of a program designed to be completed rapidly; probably within ca. 4 years. The most important intermediate results could be available even within 2 to 3 years.

In emerging countries without their own nuclear power plant construction industry, another important aspect of the development should be mentioned. Solar technology, owing to its simplicity, could namely be readily applied in these countries using *their own resources*. For nuclear power plant construction, these nations (if they wish to avoid an extremely time-consuming development program of their own) would have to rely on importation of plants, or at least on cooperation with internationally operating nuclear power-plant constructors.

These could, however, dictate their own conditions to a great extent. If either whole power plants or even parts of them must be imported, this would cost hard currency. Solar power plants, in contrast, could not only be manufactured within the country later, but also could be independently developed there. Having their own development program without the constraints of a cooperation would permit later plant construction without the involvement of other countries. In the present book, we in fact compare the economic characteristics of different power-plant technologies in the industrialized nations; there, this aspect plays no role. In the emerging industrial nations, however, a quite different cost relation in terms of different types of power plants might be obtained in the case of completely independent design and construction of the solar plants.

2.4.4
The Most Important Single Point: A Cost Study for the Standard Heliostat

As we have just discussed, an important part of heliostat development programs are cost analyses. Among these, the first would at the same time be the most important: a precise analysis of the mass-production costs of the standard heliostat, that is, complete and detailed comparisons with established processes for mass production, including the design of individual facilities for assembly and field installation. This first major investigation should be carried out with a high priority in order to obtain results as soon as possible. Then, we would finally have secure knowledge about the greatest cost factor – in the case of solar tower power plants – for the overall solar power supply system. Together with the analysis of the costs of molten-salt thermal circuits carried out in parallel, one would then have extensive information on the current developmental state of solar tower power plants. (Thereafter, one is dealing only with further developments and optimization.)

This investigation should, owing to its fundamental importance, even be carried out redundantly and in parallel by completely independent research groups. Differences in the results would then give indications of their reliability (i.e., reproducibility).

2.4.5
The Interdisciplinary Character of Solar-Plant Development

Nearly all the important questions will have to be treated in an "interdisciplinary" fashion. Some examples that we have already mentioned include the following:

- Cost estimates for heliostats by
  - comparison with costs in the automobile industry
  - planning of the production procedures and in the process
  - design of specialized automatic production equipment
- Construction of a test park for heliostats.

This interdisciplinary character, however, holds also for many other development tasks such as:

- development of the components for the molten-salt circuit, including;
- construction of simulation facilities for testing the plant components;
- a series of peripheral questions such as investigations of the insolation, of potential plant sites in Spain and other countries, of dry cooling at the corresponding locations, or of the infrastructure required by the solar-plant regions;
- further development of long-distance power transmission technologies (superconducting transmission lines, undersea cables);
- hydrogen production (among other things the development of high-temperature steam-phase electrolysis) and methanol production.

Nearly all these topics would have to be dealt with by "nonsolar" experts. Solar energy experts could thus carry out only a small portion of the required development program by themselves. Essentially, that portion consists of the technical development of the heliostats, the design of the solar field, and naturally, for example, studies of the overall project.

2.4.6
Consequences for the Organization of Research

The simplicity of the technology on the one hand, and the interdisciplinary character of the research and development required on the other, which goes well beyond solar technology itself, make the following suggestion regarding the organization of the development program attractive.

A large administrative apparatus with its own technical competence should *not* be set up![23] Instead, an *"innovation council"* should be established, which would in the end take all the important substantial decisions,[24] in which it would be supported by a *small* technical and administrative staff. This council should consist for the most part of "external" members, that is, not primarily of solar power-plant experts, but rather of engineers and scientists with proven *experience in innovation*, even though they might come from other (nonsolar) technical areas. Since the most important tasks lie outside the narrow area of solar technology and since many new concrete tasks would arise only in the course of the program, for these council members, a proven competence in innovations and their management would be more important than detailed knowledge in the field of solar technology. The relatively small amount of specifically solar-technical knowledge required could be made available to the council by solar experts. Furthermore, solar technology, owing to its relative simplicity, is readily accessible to anyone with a scientific-technical background.

In the case of the immediate initiation of a massive development program, a correspondingly large council would be required; it would be subdivided into a number of working groups. Such a collection of persons who were involved in the project only as "consultants," that is, with a limited time commitment (alongside their other occupations), could be quickly recruited in spite of its large size. Then the many required tasks could be rapidly carried out. After only a few years, the council could again be reduced considerably in size.

2.4.7
Industrial Initiatives and Start-up Funding

The Desertec initiative of the Club of Rome, which has been launched in Germany (see e.g., Desertec, 2009) and which beginning in the summer of 2009 is also being supported by large industrial companies and is currently entering a concrete planning phase, represents in the main an interesting *complement* to the systematic and in particular more comprehensive development program for an energy system

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23) For nuclear energy, the situation is different: in that case, securing a particular technical competence within the project administration is necessary, that is, setting up a staff of professionals who have expertise on nuclear-technical and also legal questions, and who accompany the further development of a reactor series over decades after their introduction.

24) Above all, the council would have to award contracts for development work to companies working in the corresponding technical areas, and would be responsible for the evaluation of the results.

based on solar power plants, which we suggest here. This initiative can, however, not *replace* such a program. It appears essentially to be aimed at the large-scale realization of a version of the technology which is technically and economically still an intermediate phase. This strategy is expensive and time-consuming, insofar as one considers the (relatively low) power costs discussed in the present book to be a precondition for the large-scale application of solar technology. While the Desertec initiative thus presumes that the current technical state-of-the-art (with moderate further developments) is sufficient for a first major step, and that *governments* should make up the difference to full economic feasibility through corresponding subventions, from a long-term energy-political and national economic point of view, the primary goal must be to elucidate as quickly as possible just what the economic potential of solar energy in a state of advanced development could in fact be (especially considering the likely future increases in oil and gas prices). By initiating a comprehensive and immediate "crash program," cost-favorable technology must be made available as soon as possible, in order to begin in earnest with a true energy turnaround.

The new (industrial) Desertec plan has thus far (July 2009) still not been published in detail. But in any case, it appears – with an overall investment volume of around €400 billion (roughly $550 billion) – to be aimed, at least in its initial phase, toward the deployment of parabolic-trough solar plants in the Sahara, similar to those which have already been constructed in Spain.25)

This initiative – if it indeed goes beyond the stage of "planning" or of a "memorandum of understanding" – could produce an enormous push forward for solar energy within the current political and economic framework. The commitment of very large firms makes it clear to everyone that this technology has great economic potential, and thus lays the political foundations for a large-scale governmental engagement.

Desertec is in particular welcome if the volume of its (subsidized) technical and economic intermediate stage remains relatively modest, and if its conceptual political framework is open to a rapid and broad-scale exploitation of the full economic potential of solar energy. As an "alternative" to the large-scale development program suggested here, however, the disadvantages of the Desertec plan would predominate. Unfortunately, there is reason to fear that just this might happen, since this private-economy initiative has a special "advantage": it takes the pressure off the governmental ministries that would be responsible for the planning and carrying out of a multifaceted R&D program, and frees them from this task and challenge. From the point of view of the responsible agencies, this is the simpler path. It requires only a law permitting subsidies, instead of the manifold measures necessary to carry out a full development program for which there are few role models. The higher overall costs and the time lost may appear to the bureaucracy to be of secondary importance.

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25) Parabolic troughs require sites with flat terrain; these are available to the required extent only in North Africa, not in Spain. This is quite possibly one of the reasons for the fact that the Desertec plan concentrates on sites in North African countries.