Material and Energy Demand for selected renewable energy technologies

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Table of symbols

$Symbol_{english}$	$Symbol_{german}$	Dimension	Meaning
ced	kea	MJ/Kg	Specific Cumulative Energy Demand
CED_T	KEA_T	MJ	Cumulative Energy Demand of Transport
d	d	km	Distance of Transport
CED_P	KEA_H	MJ	Cumulative Energy Demand of Production
CED_U	KEA_N	MJ	Cumulative Energy Demand of Utilisation
CED_D	KEA_E	MJ	Cumulative Energy Demand of Disposal
$EYR_{primary, net}$	$EF_{prim,net}$	-	Energy Yield Ratio for Primary Energy
$EYR_{physical, net}$	$EF_{physikal., net}$	-	Energy Yield Ratio for Electrical Energy
$F_{supply, electricity}$	$F_{Be, el}$	-	Factor of Supply for Electricity
$F_{supply, fuel}$	$F_{Be, Br}$	-	Factor of Supply for Fuel
$F_{supply,powerplant}$	$F_{Be, KW}$	-	Factor of Supply for Power Plant
G.I.	-	-	Galvanised Iron
LDPE	LDPE	-	Low Density Poly Ethylene
m	m	kg	Transported Weight
$m_{material}$	$m_{material}$	kg	Weight of Component
PE	NG	-	Potential Efficiency
PV	PV	-	Photovoltaic
PVC	PVC	-	Poly Vinyl Chloride
SWG	-	-	Standard Wire Gauge
$W_{el, net}$	$P_{el, netto}$	W	Net Electrical Power Output
$W_{prim, net}$	$W_{prim,netto}$	GJ	Net Equivalent Primary Energy Harvest
WEC	WEK	-	Wind Energy Converter

1 Aims and objectives

Renewable energy technologies are becoming popular mainly because of the reason that for obtaining useful power output there is very little or no requirement of energy input. The conventional technologies on the other hand have limitations like second law of thermodynamics. However, both the technologies have their own material and energy demands for construction and operation of plants. Regenerative technologies are source based, while conventional technologies are resource based. A share of the known resources is being consumed in meeting the energy demand for the production of different materials hence, the regenerative technologies indirectly consume some of the resources in the form of material and process energy. Estimation of cumulated energy demand gives an idea of increased load on the resources due to any technology. This project aims to find the material and energy demand of selected renewable energy technologies, so that choice between regenerative and conventional technologies can be made with an ultimate aim of reduction of load on energy resources.

Due to the differences in climatic conditions and resources, suitability of these technologies is different for India and Germany. This project also provides a comparison of both the countries for renewable energy technologies.

Following energy systems have been taken into account:

- Hard coal power plant
- Wind energy converter
- Photovoltaic system
- Solar hot water heater
- Electrical hot water heater
- Oil + Natural gas hot water heater

2 Methodology

The whole study has been divided into two main sections namely India and Germany that make chapters 3 and 4 of this report respectively. Being the three most popular types of regenerative energy systems wind energy converters, photovoltaic systems and solar water heating systems have been selected from amongst the regenerative technologies. Since the renewable energy has to compete with the already existing conventional options, the study has been sub-divided into competitive scenarios. Scenarios also help to understand the possibility and scope of use of regenerative technologies in the two countries. Such competitive scenarios are largely governed by the climatic conditions and resources available in a country and are therefore quite different for India and Germany. The scenarios are :

For India:
- Wind energy converters v/s Coal power plants for electricity generation
- Photovoltaic system v/s Electric charging of household accumulator
- Solar hot water system v/s Electric hot water system

For Germany:
- Photovoltaic v/s Coal power plants to provide electricity to the grid
- Photovoltaic v/s Wind energy converters with grid connection
- Solar Water Heating System v/s Oil + Natural Gas Water Heating System and Electric Water Heating System

To obtain the energy demand for the production of a power plant, the whole facility has to be split up into components, sub-component and their respective materials. Using this material balance with specific data for material and energy resources (which are found by process chain analysis and can be found in various literature) it is possible to calculate the cumulated energy demand of production (CED_P).

The total CED_P of a plant can be found through:

$$CED_{P,total} = \sum_{Components} CED_{P,Components}$$

with

$$CED_{P,Component} = \sum_{Material} \left[ced_{material} \cdot m_{material} \right] \cdot F_P$$

The energy demand of production processes (e.g. assembly of parts) is taken into account by multiplication of the material-based energy demand with the production-factor F_P [Wag97].
Manufacturing factors have been assigned to the materials depending upon their form of usage in the plant. It is quite possible to find two different factors for the same material in different components. This is due to the reason that the amount and nature of processing differs from case to case.
Where available data of energy consumption for transportation has also been included. In these cases the most common mode of transportation for a certain type of component in the respective country is considered. However, because of the large distances in India a sensitivity analysis has been carried out to find the possible

variation in CED due to transportation. The following formula using the distance (d) and weight (m) has been used for finding the energy demand for transportation:

$$CED_{Transport} = ced_{Transport} \cdot d \cdot m$$

Data for the transport-processes are taken from various sources [GEMIS95, Lufth96, Frisch94] and own calculations.

The energy demand for the disposal and recycling of the material used in the plant after the end of plant life has also been included where available. The following formula has been used for finding the total energy demand:

$$CED_{Total} = CED_{\Pr oduction} + CED_{Utilisation} + CED_{Disposal} + CED_{Others}$$

The detailed material and energy balances have been given towards the end of this report in separate appendices. Coal power plants data used in this study have directly been taken from [Heit98]. Similarly the energy content of silicon wafers has also been directly taken from suitable literature [Kato97, Koha97]. The specific energy contents of materials have been considered to be same for both countries.

The average climatic data of several years have been used for the calculations in India to avoid the possibility of misleading results due to favourable or unfavourable climate in one particular year. Unlike Germany, in India there is a wide range of climatic conditions, therefore the climatic classification of India in six climatic zones done by [Ban95] have been taken as reference and one representative city of each climatic zone has been analysed assuming no variation of climatic conditions within one zone. Appendix-A1 shows general climatic conditions of these climatic zones and the representative cities considered in this study.

The method of finding the annual energy output of the systems is not the same for all the technologies. For wind energy the wind energy power curve provided by the manufacturer has been used. For the solar hot water system in India hourly data for radiation and temperature have been used with a transient simulation software (TRNSYS13) to find the annual output. For photovoltaic systems a lifetime efficiency of conversion has been considered with the minimum value of average daily radiation as it has to satisfactorily serve its purpose even during the low radiation days. For such systems a minimum output is taken as basis for calculation of module area. The annual plant load factors of the coal power plants have been taken from relevant sources [Power98] and are used to find the annual output.

In some scenarios the energy payback period of the competing technologies has not been compared due to the reason that conventional technologies (specially fossil fuel based technologies) have a payback that is higher than the expected lifetime. In these cases the cumulative energy demand over lifetime has been found and the Energy Yield Ratio (EYR) has been used for comparison. EYR is given by the following formula:

$$EYR_{net,primary} = \frac{W_{net,primary}}{CED_{total}}$$

where

$$W_{net,primary} = \frac{W_{net,physical}}{PE}$$

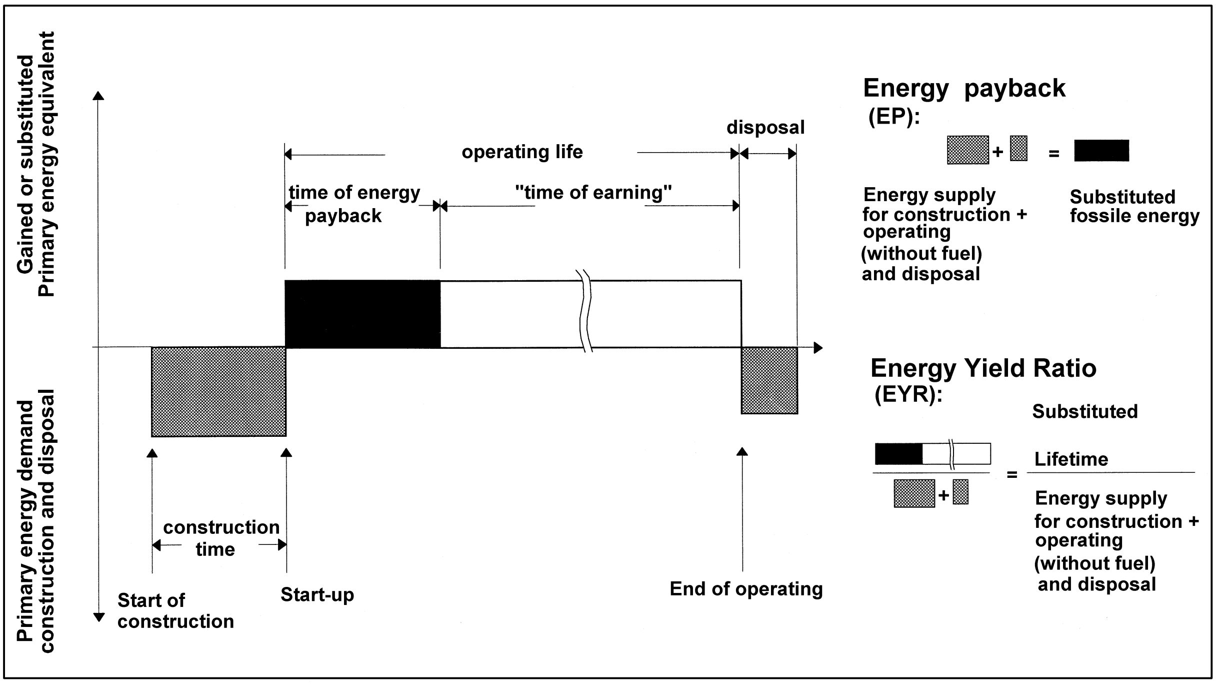


Figure 2.1: Energy Payback and Energy Yield Ratio

Figure 2.1 shows the relationship between lifetime, Energy Payback and Energy Yield Ratio.
One possibility to calculate the equivalent primary energy harvest is by dividing the net energy output of for example a coal power plant by the average potential efficiency of coal steam-electric stations. The average potential efficiency for India and Germany is found to be 0.35 using the following formula:

$$F_{\sup ply,electricity} = \frac{\sum_{fuel} input_{fuel} \cdot F_{\sup ply,fuel} \cdot F_{\sup ply,powerplant}}{output_{electricity}}$$

In some cases like water heating systems, primary energy required for using the regenerative technology has been compared with the primary energy requirement in absence of regenerative system for equivalent output. This has been done because the solar water heating system replaces only some part of electricity or natural gas requirement, not the whole system. Rather the system for renewable energy technology consists of both the parts: renewable energy system and the conventional system for the make-up energy. Therefore, the energy demand for the former in terms of material only reduces the electricity or gas requirement and hence has been compared in terms of primary energy.

The system boundary considered for this report primarily encompasses the direct energy demands through materials, manufacturing and assembly processes, operational energy demand, transportation, disposal. However, the process chain data in itself may include the energy demands for the previous stages like the *specific ced* of aluminium including the production, operation and disposal of aluminium manufacturing plant.

3 India

In spite of having low conversion efficiency for the process chain of primary to end energy, 74.89% of the electricity produced in India comes from coal based power plants [Power98]; hence a wind energy system option needs to be compared with the coal power plant for generation of electricity. Due to frequent power failures and load-shedding, the small inverter-accumulator systems are very common in medium class Indian houses as stand-bye power supply option. These systems consume a lot of electricity for the charging of accumulator. Consequently, photovoltaic charging systems are considered as a replacement of the charging from the grid. In addition, a solar hot water system has been compared with an electric hot water system as such systems are very commonly used in India.

General figures and assumptions considered for India in this report are:

- The electricity mix is 74.89% thermal, 23.5% hydro, remaining nuclear & others [Power98].
- Conversion efficiency of primary energy to end energy (electricity mix) is 35% as calculated by process chain analysis.
- Power plants are run throughout the year as the base load plants.

3.1 Wind Energy Converter v/s Hard Coal Power with power line connection

3.1.1 Wind Energy Converter

Wind energy converters (WEC) are being considered as a promising clean alternative to the conventional coal power plants that enjoy a share of about 75% [Power98] in the electricity mix of India. Out of about 50 sites identified as having potential for generation of electricity from wind energy three sites located in different climatic and different surrounding conditions have been chosen. Out of the six climatic zones of India [Bansal95] only three climatic zones have the considerable potential of wind energy. Sites have been selected carefully to ensure that there is one site of each of the three types of locations namely coastal, near coastal and inland site. These are Rameswaram, Bamanbore and Sultanpet respectively. Details of these sites and wind data are given in appendix-A2.

System Details
Out of the wide range of wind energy converters, the largest WEC of 1.5 MW capacity produced by a German manufacturing company has been considered in this report. However the using the results of [Pick98] it has been found that the variation in energy yield ratio for different types of WEC is within 10% only. Salient features of 1.5 MW WEC are as follows:

- Peak Output: 1.5 MW
- Hub height: 67 meter
- Rotorblade diameter: 66 meter
- Cut-in speed: 2.5 m/s
- Cut-out speed: 25 m/s

General assumptions used in this analysis are [Bunk98]:
- The selected sites represent the average wind condition of their respective climatic zones with no or little variation within permissible limits.
- Wind velocity distribution within a year and within a month follows Weibul´s distribution.
- The velocity profile of wind velocity with altitude is exponential in shape.
- All the components except the foundation is made at the plant situated in northern Germany and transported to India.
- The machinery is transported by ship to the nearest port in India and by railway thereafter to the site.
- Lifetime of plant is 20 years.
- Coating on rotorblades is required again after 10 years.

Material and Energy Balance
For finding the material and energy balances the WEC has been considered to be divided in six parts which are as follows:
- rotor blades
- generator
- rest of machinery
- tower
- grid connections
- foundation

Separate material and energy balances for each of the above six parts have been prepared and given in appendix-A3. To take into account the energy consumption for the manufacturing processes, manufacturing factors have been assigned to individual materials using the factors of [Wag97] with suitable modifications for Indian conditions, wherever found necessary. Energy consumption for transportation has also been taken into account as the wind energy converters are manufactured at the plant located in the northern part of Germany and from there transported to India for erection on site. Table 3.1.1 gives the break-up of CED of WEC including transportation and maintenance. Major share of maintenance goes in replacement of blades after every seven years (as recommended by manufacturers). While calculating the energy for transportation, two additional sets of blades for replacement in the 20 year plant lifetime have also been considered.

Table 4.1.2: Break-up of CED (incl. manufacturing-processes) of 1.5 MW wind energy converter

	coastal		near coast		inland	
component group	energy content (GJ)	%	energy content (GJ)	%	energy content (GJ)	%
rotor blades	1147	8,2	1147	8,3	1147	8,3
generator	2877	20,6	2877	20,9	2877	20,8
rest of machinery	1814	13,0	1814	13,2	1814	13,1
tower	3774	27,0	3774	27,5	3774	27,2
grid connection	1512	10,8	1512	11,0	1512	10,9
foundation	1493	10,7	1350	9,8	1350	9,7
assembly	402	2,9	402	2,9	402	2,9
transportation	743	5,3	657	4,8	746	5,4
maintenance incl. transportation	23	0,2	33	0,2	55	0,4
CED	13960	100,00	13742	100,00	13852	100,00

The CED for the three selected sites is different for the following reasons:

- Distance for transportation of equipment is different. Appendix-A4 shows the calculation of energy demand for transportation for each site. The figures for specific energy requirement for transportation have been taken from [GEMIS95].
- The type of foundation depends upon the nature of soil at the site. Normally, at coastal sites a deep foundation is required that has a higher CED. Appendix-A3 shows calculation of CED for both types of foundations.

Energy Harvest

For calculating the energy output or energy harvest the wind energy data for the three sites of India have been taken from [Mani93] (appendix-A2). For Rameswaram and Bamanbore three year average and for Sultanpet five year average data have been considered as per their availability. Hellmann´s exponent that governs the relationship between wind velocity and altitude, has been found by using wind velocity at 10 and 20m heights. Power curve that is a plot of output in kW v/s wind velocity the energy harvest. The power curve is a characteristic of each type of system and is provided by the manufacturer. Typical power curve for the 1.5 MW system has been given in appendix-A5.

The Weibul´s size and shape parameters take into account the probability distribution of velocity, these parameters are found from the wind velocity data. The yearly average wind velocity and Weibul parameters for the whole year have been used in conjunction with the power curve to calculate the power output . However, harvest calculations have also been done using the monthly figures for average velocity and Weibul parameters but the difference in the results is less than 1%.

About 0.35% of the energy harvest is used by the system itself for different devices and controls. Therefore the net harvest is 99.65% of the total harvest. Harvest for Rameswaram is highest, 6033.25 MWh per year while the lower figure is for Sultanpet, 1846.31 MWh per year.

Energy Payback and EYR:
For calculation of the energy payback the net harvest has been converted to equivalent primary energy. Instead of dividing it by the primary energy conversion factor of average electricity mix, a factor of 0.41 has been used as we are comparing generation of electricity from WEC with coal power only not with the grid average. Table 3.1.2 shows total and net harvest as well as the energy payback for the selected sites.

Table 3.1.2: Yearly Energy Harvest, Payback and EYR of WEC in India

	coastal (Rameshwaram)	near coast (Bamanbore)	inland (Sultanpet)
Energy harvest (kWh/a)	6054447	2128941	1852798
Energy harvest (net)	6033256	2121490	1846313
$W_{prim, net}$ (GJ)	52974.93	18627.72	16211.53
CED (GJ)	13960	13742	13852
Payback (yr.)	0.26	0.74	0.85
$EYR_{net, primary}$	75.89	27.11	23.41

3.1.2 Hard Coal Power Plant

System Details
Hard coal power plants are the state of the art systems in the field of thermal power generation. Capacity of a typical plant is 509MW net output with a net efficiency of 43%. The study conducted by [Heit98] has been taken as reference for this section, assuming the plant to be located in India. Operating conditions for the plants have been considered as per Indian conditions.

Following parameters have been considered while finding the CED:

- Plant efficiency (net): 43% at 509 MW net electrical output
- Yearly plant load factor: 0.64 (average figure for India in 1996-97)
- Operating life of plant: 40 years

Material and Energy Balance
Cumulated energy demand for the plant has been calculated with a break-up for production, utilisation and disposal of the plant. The tables for CED_P , CED_U and CED_D have been given in appendix-A10. Table 3.1.3 shows overall energy balance for the plant.

Table 3.1.3: Energy balance of hard coal power plant in India

Component	Sub component	CED (TJ)	Percentage of plant
Plant	Production Utilisation Disposal	2635 5909 -339	32% 72% -4%
	Total	8205	100%
Fuel	Hard coal	1014758	
Grand total		1022963	

Energy demand without considering hard coal results in a CED_U of 5.9 PJ, whereas the energy demand with hard coal taken into consideration increases to 1014.8 PJ, increasing the grand total from 8.2 PJ to 1023 PJ.

For disposal of the hard coal power plant the energy demand is negative as the energy content of recyclable materials is to be subtracted from the cumulated energy demand. Since, only a few materials have to be deposited the total amount comes to a credit of 339 TJ.

Energy Output

With an annual plant load factor of 0.64 and a net power generation capacity of 509 MW the annual output is 2853 GWh_{el}. With an estimated operating life of 40 years a total net energy of 114.14 TWh_{el} will be generated. This amount is equivalent to 278.39 TWh of primary energy.

Energy Payback and EYR

Using the potential efficiency of 0.41 (a resultant of 43% plant efficiency and 95.5% efficiency for obtaining coal) the energy yield ratios obtained are as follows:

$EYR_{net,physical}$ = 0.40

$EYR_{net,primary}$ = 0.98

These figures show, that the influence of energy demand for production and disposal can be neglected and that the “physical“ energy yield ratio for a conventional power generating plant is oriented towards the net efficiency of the plant. The “primary“ energy yield ratio is approaching unity due to the same reason.

3.1.3 Comparison

A comparison of WEC and hard coal power plants show that the $EYR_{net, primary}$ of the former is about 23.41 to 75.89 times higher than that of the later. A value of EYR less than one shows that the fossil fuel based power plant consumes more energy than it delivers over its lifetime. The payback of both the plants cannot be compared as this term looses it’s importance for the fossil fuel based power plants.

3.2 Photovoltaic System v/s Grid Electricity for Stand-By Accumulator

3.2.1 Photovoltaic System

System Details

Single-crystalline photovoltaic modules are manufactured in India by private and semi-government producers. The Central Electronics Limited (CEL), Sahibabad is a semi-government organisation where silicon wafers are processed to make solar cells and photovoltaic modules subsequently. The wafers are indigenously manufactured and are also imported from foreign countries to meet the manufacturing demand. Following are the specifications of a module produced by CEL:

- Type: Single crystalline
- Output: $35W_{peak}$
- Cell efficiency: 13% at standard test conditions (1000W radiation, 25°C temperature and air density 1.51 kg/m^3)
- Module dimensions: 1006 X 398 mm.

A 2 kWh capacity accumulator has been considered to meet the electricity requirement during grid supply failure. This requirement has been estimated to be 1 kWh per day. Other specifications of inverter and accumulator have been given in appendix-A8.

Following assumptions are made in calculations for PV systems:

- Lifetime conversion efficiency of PV modules: 5%
- Lifetime of modules: 20 years
- Replacement of glass cover is required after every 7 years

Material and Energy Balance

For finding the CED of photovoltaic system the energy content of silicon wafers has been taken from [Kato 97], the energy consumed for the processing of wafers into modules has been taken from the actual measurements at CEL. Due to propriety reasons more details cannot be given hence, a single final figure has been used. For the maintenance of the system replacement of glass after every seven years has been taken into account, since cleaning of dust and deposits is done manually and specially for small and medium size systems no other energy consumption for maintenance is needed. Appendix -A9 shows the break up of material and energy demand for a 35 W PV module. Table 3.2.1 gives the total energy demand for the photovoltaic charging system for a household accumulator. The value of CED is different for different places as the module area required for the photovoltaic charging depends upon the radiation. One representative city of each climatic zone has been chosen (appendix-A1) and module area has been calculated for the minimum daily radiation condition so that the system works even in the low radiation days. In order to have an idea of the range the maximum and minimum CED cases have been selected from the six cases of different climatic zones. Appendix-A6 shows calculation of module area required for photovoltaic charging system in the six zones.

A sensitivity analysis has been carried out to find the variation in CED due to the difference in the distances for transportation. It shows a possible variation up to 0.08% of the total CED for transportation by railways and 4.3% for the same by truck.

3.2.2 Electric Charging System

System Details

The conventional charging system first converts a.c. of grid electricity to d.c. for storage in accumulator and converts back the d.c. output to a.c. for utilisation at the time of load-shedding. Values considered to find the primary energy demand for this system are:

- Round trip efficiency of inverter-battery system (partial loads included): 60% [Kumar98]
- Load on accumulator: 1 kWh per day

Therefore, the electricity required per day for charging is 1.66 kWh. Having the primary energy conversion factor for electricity mix to be 0.35, the total primary energy demand for 20 years has been found to be 125.14 GJ. The CED of the inverter and accumulator is not considered as it is to be used in both the cases.

Energy Yield Ratio

The energy yield ratio of the photovoltaic charging system with respect to the grid electricity system can be found as the ratio of the primary energy saved to the primary energy input as CED of photovoltaic system. This ratio is considered as $EYR_{primary}$ for the scenario, given in table 3.2.1.

Table 3.2.1: Energy balance for PV charging system in Indian climatic zones

Climatic zone	Hot & dry	Moderate	Composite	Cold & sunny	Warm & humid	Cool & cloudy
Rep. city	Ahmedabad	Bangalore	Delhi	Leh	Madras	Srinagar
No. of modules required	10	9	12	15	9	15
CED (MJ)	51138	46024	61365	76707	46024	76707
$EYR_{primary}$	2.45	2.72	2.04	1.63	2.72	1.63

3.2.3 Comparison

Instead of comparing the energy payback periods, total primary energy demand for both the cases can only be compared. The primary energy demand for the photovoltaic case ranges from 46.02 GJ to 76.70 GJ weather the primary energy demand for the electric charging option is 125.14 GJ for a period of 20 years. The $EYR_{primary}$ has been found as explained above that ranges from 1.63 to 2.72 for different climatic zones. This indicates unit primary energy investment in renewable energy based charging route using photovoltaic modules saves the primary energy consumption by 1.63 to 2.72 units through the grid electricity route.

3.3 Solar Water Heating System v/s Electric Water Heating System

3.3.1 Solar Water Heating System

System Details

Natural circulation single glazed flat plate collectors are the most common type of devices that are used for solar water heating in India. Solar water heating systems face a competition with electric hot water heating systems. It has been found by [Bansal98] that these systems are not sufficient as stand-alone systems for supplying 100 lt. water at 60°C throughout the year. Consequently, solar water heating systems have to be used in hybrid mode with electric heater for the supply of auxiliary energy.

Dimensions and materials for different parts of the solar water heating system are chosen as per the recommendations of the Bureau of Indian Standards, major details are:

- Dimensions of collector: 1000 X 2000 mm
- Hot water tank capacity: 100 l
- Insulation for tank: 100 mm glass wool with 0.5 mm aluminium cover
- Absorber sheet: 30 SWG copper
- Hot water tank: 16 SWG steel
- Glazing thickness: 4 mm
- Risers: copper tube, diameter 12.7 mm, thickness 0.7 mm

Other system specific important details are:

- Hot water pipe: 5 m long, ½ inch Galvanised iron (G.I.)
- Cold water pipe: 3 m long, ½ inch Galvanised iron (G.I.)
- Insulation on hot water pipe: 30 mm glass wool, 0.5 mm aluminium cover
- Support: 12.5 m of ½ inch angle iron for collector, 9 m of 1 inch angle iron for hot water tank

Material And Energy Balance

The detailed material and energy balances for different parts of the solar water heating system are shown in appendix-A7. Table 3.3.1 shows an overview of material and energy balances for this system. Requirement of iron for the support frame for collector and hot water tank and also the length of pipes are situation specific and may vary from study to study. Commonly found values have been considered for the balances. The life of solar water heating systems has been considered to be 15 years and due to hardness in water and typical environmental conditions of Indian cities replacement of copper tubes (risers), aluminium covers, glazing and 50% of insulation after every five years is considered as maintenance.

Table 3.3.1: Energy balance of solar hot water heating system

Component group	Energy content (MJ)	% of system
Collector	3603	36.26
Hot water tank	1540	15.50
Pipe work	529	5.33
Supports	294	2.96
Maintenance	3970	39.95
CED	9936	100.00

Collector and maintenance have the largest shares in the total CED. EYR_{prim} for such system ranges from 1.86 for Leh to 5.71 for Ahmedabad for a lifetime of 15 years. A sensitivity analysis has also been carried out for finding the variation in CED due to difference in the distances for transportation. It shows a possible variation up to 0.34% of the total CED for transportation by railways and 18.85% for the same by truck.

3.3.2 Electric Water Heating System

System Details

In absence of the solar water heating system, the requirement of electricity increases. This increase can be found by considering the efficiency of the electric heater. Table 3.3.2 gives the energy collected by the solar water heating system and the additional requirement of electricity in absence of such system with an average electric heater efficiency of 95%. Using the primary energy conversion factor of 0.35 for electricity mix, primary energy requirement for this case can be found

Table 3.3.2: Collected solar energy and equivalent electric heating requirement in Indian climatic zones

Climatic zone	Hot & dry	Moderate	Composite	Cold & sunny	Warm & humid	Cool & cloudy
Rep. City	Ahmedabad	Bangalore	Delhi	Leh	Madras	Srinagar
Solar Energy collected (GJ/a)	4.73	4.31	4,32	1,54	4,67	4,19
Equivalent electricity savings (kWh/a)	1383	1260	1263	450	1366	1225
Primary energy equivalent for electricity savings (lifetime) GJ	213.38	194.44	194.89	69.47	210.68	189.02
$EYR_{primary}$	21.48	19.57	19.61	6.99	21.20	19.02

3.3.3 Comparison

Tables 3.3.1 and 3.3.2 show that by investing 9.936 GJ of primary energy in the solar water heating system the primary energy consumption through the conventional electric route can be saved in a range from 69.47GJ to 213.38GJ for a lifetime of 15 years of the solar water heating system. This means, this regenerative technology returns about 7 to 21.5 times of the energy invested for making and maintaining it over its lifetime. These figures can also be considered as the primary energy yield ratio of the solar water heating system.

4 Germany

Due to the constraints like time, availability of information etc. this study has been restricted to few major types of power plants specially in the cases of wind energy and coal power plants.
A 1.5 MW type of wind energy converter and a 500 MW Hard Coal Power Plant have been analysed for their running in the typical operating conditions of the two countries as well as various Water Heating Systems.

The general figures and assumptions considered for Germany are:

- Electricity mix as follows [BMWi97]:
  - 31% nuclear
  - 26% hard coal
  - 25% brown coal
  - 9% gas
  - 4% hydro
  - 4% others
  - 1% wind
- Potential efficiency (Conversion from primary to end energy) is 35% [Koha97]
- Climatic conditions do not vary in Germany so that a detailed investigation has been dispensed.

4.1 Photovoltaic System v/s Hard Coal Power with power line connection

Photovoltaik is a technology that has been used in Germany in grid connected systems. Therefor a comparison should be made with respect to conventional power generating systems. Chapter 4.1 and 4.2 will deal with a coal power station and (to get an overall view) with the grid average for Germany.

4.1.1 Photovoltaic System

System details
All data for this system has been taken from investigations carried out by Fachhochschule Gelsenkirchen [Koha97, PuDe97].

The 1 MW photovoltaic power plant is located in Toledo, Spain and consists of three fields with 855 kW_{peak} for field 1 and 2 and 95 kW_{peak} for field 3. Solar modules in field 1 and 2 are mounted in fixed racks and can be rotated around one axis in field 2.
Field 1 is fitted with mono-crystalline cells that are fixed on oversize-modules, where modules have glued to the carrying structure with silicone.
Field 2 consists of laser grooved buried contact cells on standard modules, with an especially high cell-efficiency of 15,2%. These cells are known to have record efficiencies of 23% in the lab.[PuDe97]
Field 3 is similar to field 2 besides of the rotating longitudinal axis in north-south direction.
The system is theoretically considered to be situated in Germany. The yearly radiation output is consider to be 1000 kWh/m² and the expected lifetime is 25 years.
Though manufacturers do recycle material within their production processes a credit is not taken into account as no belastbares Zahlenmaterial is available. By doing this a conservative estimation is carried out energy wise.

Material and Energy Balance, Energy Output and Energy Yield Ratio
Table 4.1.1 gives an overview of the calculated figures for the power plant situated in Germany:
With a Primary Energy Conversion Efficiency for Hardcoal of 0.955 [Heit98] and an coal power plant efficiency of 0.43 (for the coal power plant used as a comparing bases) an potential efficiency of 0.41 can be obtained, that should be used to calculate the equivalent primary energy of the produced electricity as described in chapter 2.

Table 4.1.1: Photovoltaic Power Plant in Germany

	Unit	
CED_P	$GJ_{primary}$	63200
CED_U	$GJ_{primary}$	9500
CED_{total}	$GJ_{primary}$	72700
Gross Power Output	MWh/a	873
Total gross power output	GWh	21,825
$EYR,_{physical}$	-	1,1
$EYR,_{primary}$	-	2,6

It is obvious that with a supposed lifetime of 25 years more energy will be produced than is needed for manufacturing and use of the system.

4.1.2 Hard Coal Power Plant

System details
The hard coal power plant is a state of the art system with an electrical net efficiency of 43%, a net power output of 509 MW, a yearly plant load factor of 0.57 (5000 h/a) and an operating lifetime of 40 years. [Heit98]

Material and Energy Balance
The cumulated energy demand is calculated for production, utilisation and disposal of the plant. The tables for CED_P , CED_U and CED_D have been given in appendix-B. Table 4.1.2 shows an overall energy balance.

Table 4.1.2: CED of a Coal Power Plant in Germany [Heit98]

	Hardcoal power plant	
	[TJ]	[%]
power plant:		
production	2635	32%
utilization	5909	72%
disposal	-339	-4%
sum	8205	100%
fuel:		
hardcoal	905000	
total	913205	

Energy demand without considering hard coal results in a CED_U of 5.9 PJ, whereas the energy demand with hard coal taken into consideration increases to 905 PJ, increasing the total CED from 8.2 PJ to 913 PJ.

For disposal of the hard coal power plant the energy demand is negative as the energy content of recyclable materials has to be subtracted from the cumulated energy demand. Since, only a few materials have to be deposited the total amount comes to a credit of 339 TJ.

Energy Output
With a net efficiency of 43% and a load duration time of 5000 hours per year the net power output is 2545 GWh_{el}/a.
With an estimated operating life of 40 years a net energy of 101.8 TWh_{el} will be generated.

Energy Yield Ratio
Using the potential efficiency of 0.41 the energy yield ratios are obtained as follows:

$EYR_{net,physical} = 0.40$

$EYR_{net,primary} = 0.98$

These figures show, that the influence of energy demand for production and disposal can be neglected and that the „physical“ energy yield ratio for a conventional power generating plant is oriented towards the net efficiency of the plant.

4.1.3 Comparison

The Cumulated Energy Demand has been calculated as the sum of CED_M, CED_U and CED_D.
Regarding the total CED the conventional power plant is dominated by the fuel. Its share is more than 100 times the quantity of all other parts.
In contrast to this the biggest share of CED for the photovoltaic system lies in the material and energy demand of manufacturing. About 87% of the total CED have to be procured for this part.
It becomes obvious that in comparison to the coal power plant the use of this photovoltaic system will produce more primary energy output than is needed for its production and utilisation, therefore it will save resources.
Table 4.1.3 summarizes the results:

Table 4.1.3: Energy Yield Ratio of Photovoltaic System and Hard Coal Power Plant

	Photovoltaic System	Hard Coal Power Plant
Net Physical Energy Yield Ratio	1.1	0.4
Net Primary Energy Yield Ratio	2.6	0.98

In addition to comparison of these figures it might also be interesting to have a look at the average supply of electricity by German grid.
This potential efficiency can be obtained by using the input of primary energy into electricity plants (i.e. coal, crude oil, gas, nuclear, ...), the factor of supply for fuels [GEMIS98], a factor of supply for power plant as recommended by [Wenz98] and the electricity output. It is the inverse of the factor of supply for electricity as quoted in chapter 2.
The calculation gives a potential efficiency of 0.34 (compare appendix B).

It has been stated earlier that the energy content for manufacturing of conventional power plant can be neglected in comparison to the energy input in form of fuels. Therefore the primary energy yield ratio of conventional systems becomes approximately the inverse of the efficiency of power conversion.
Comparing the calculated potential efficiency of 0.34 with the physical net energy yield ratio of the photovoltaic system it again becomes clear that more energy input is needed than output can be obtained. Of course the average of German power production is less effective than the state of art hard coal power plant that has been examined.

4.2 Photovoltaic System v/s Wind Energy Converter with power line connection

4.2.1 Wind Energy Converter

Use of wind energy in Germany has increased rapidly since 1990. Till 1997 installed power has grown to about 2000 MW. With this development Germany ranks first world-wide before U.S. and Denmark. 3 TWh of electricity have been produced in 1997 by wind energy that gives a corresponding share of 0.6% regarding overall electricity production.

System Details
For calculating the yearly energy output three sites have been selected: Coastal, near coastal and inland. A large WEC of 1.5 MW as produced in Germany has been chosen to be considered in this report. It has been found that the variation in energy yield ratio for different types (500kW and 1500kW) of WEC is within 10% only. [Pick98]

The features of the 1.5 MW WEC are as follows:
- Peak Output: 1.5 MW
- Hub height: 67 meter
- Rotorblade diameter: 66 meter
- Cut-in speed: 2.5 m/s
- Cut-out speed: 25 m/s

General assumptions used in this analysis are [Pick98]:
- Wind velocity distribution within a year and within a month follows Weibul´s distribution.
- The velocity profile of wind velocity with altitude is exponential in shape.
- All the components except the foundation are made at the plant situated in northern Germany.
- The machinery is transported by truck to the site.
- Lifetime of one plant is 20 years.
- Maintenance of rotor blades (coating) is required after 10 years.

Material and Energy Balance
For finding the material and energy balances the WEC has been divided in six parts as already stated in chapter 3.1.
Material and energy balances for each part are given in appendix-A3. Manufacturing factors have been assigned after the scheme given in chapter 3.1 to individual materials using the factors of [Wenz97].
Energy consumption for transportation has been taken into account as the wind energy converters are manufactured at the plant located in the northern part of Germany and are then transported to the sites:

Table 4.2.1: Estimated distances to sites of WEC

Site	Distance [km]
Coastal	400
Near coastal	600
Inland	1000

Table 4.2.2 gives the break-up of the CED including transportation ad maintenance. Major share of maintenance goes in coating of blades after ten years (as recommended by the manufacturer).
While calculating the energy for transportation, two additional blades for replacement in 20 years of lifetime have also been considered.

Table 4.2.2: Break-up of CED (incl. manufacturing-processes) of 1.5 MW WEC

	Coastal		Near coast		Inland	
Component group	Energy content (GJ)	%	Energy content (GJ)	%	Energy content (GJ)	%
rotor blades	1147	8,3	1147	8,3	1147	8,2
generator	2877	20,8	2877	20,9	2877	20,7
rest of machinery	1814	13,1	1814	13,2	1814	13,0
tower	3774	27,3	3774	27,4	3774	27,14
grid connection	1512	10,9	1512	11,0	1512	10,9
foundation	1493	10,8	1350	9,8	1350	9,7
assembly	402	2,9	402	2,9	402	2,9
transportation	599	4,3	710	5,1	821	5,9
maintenance incl. transportation	23	0,2	33	0,2	55	0,4
CED	13816	100,00	13795	100,00	13927	100,00

The CED of the WEC varies from 13795 to 13927 GJ. The tower has the biggest share of about 27% - 28%. Another important component group, due to a high content of energy-intensive materials, is the generator with a share of about 21%. The rest of machinery holds a share of about 13% while foundation and grid connection hold 10%-11%. For assembly, maintenance and transportation about 8% of the total CED are needed.

Energy Harvest and EYR:

Table 4.2.3: Yearly energy output of different sites

	site I (coastal)	**site II (near coastal)**	**site III (inland)**
$\bar{v}_N$ [m/s]	7,32	6,58	5,96
W_{el} [kWh/a]	4.086.320	3.204.400	2.497.550
W_{net} [kWh/a]	4.072.018	3.193.185	2.488.809
$W_{net, primary}$ [kWh/a]	11.634.337	9.123.385	7.110.883
EYR [-]	60,6	47,6	36,8

The energy output for the three sites has been taken from [Pick98].
For calculation of the energy payback the net harvest has been converted to equivalent primary energy. This has been done by using the primary energy conversion factor of average electricity (0.35).

4.2.2 Comparison

The photovoltaic system has a much lower value of EYR as compared to the wind energy converter. A value of 2.6 for the former is due to relatively low conversion efficiency and more energy intensity of materials. An EYR ranging from 36.8 to 60.6 is much higher than the corresponding value of 2.6 for photovoltaic system.

4.3 Solar Water Heating System v/s Oil + Natural Gas Water Heating System

4.3.1 Solar Water Heating System

By using additional absorber-systems for hot water heating a part of the fuel consumption of conventional systems can be substituted. Due to the low solar power density these systems are very material intensive. This investigation tries to find out, if a positive energy-balance can still be found when taking the energy demand of manufacturing of these materials into consideration.
Choice of reference-systems has taken into account the usability of solar-thermal systems in Germany as well as the bandwidth of different types of constructions used in Germany.

System Details
The application of solar-thermal power-generation has been divided into water heating for small houses (one to two families) and for big houses (multiple family houses), whereas the construction types are divided into flat-plate collectors and evacuated tube collectors (see appendix-B). These systems represent the most used ones on the German marked. The evacuated tube collector needs due to a high efficiency of about 20% a smaller area than the other systems. All other components aside from collectors are supposed to be of the same type.

Material And Energy Balance
Detailed investigation of used materials gives a total mass of collectors for the small systems of 130 kg (SOLVIS), 110 kg (SOLAR DIAMANT) and 90 kg (evacuated tube collector). For all cases the rest of the system increases the mass by another 90 kg.
The big systems collectors masses are 2900 kg (SOLVIS) and 2300 kg (evacuated tube collector), whereas the rest of the system weighs about 2400 kg.
Further details concerning the regarded plants and their material balances are included in [Wag95].

By using these material balances and data for the specific energy content of materials the CED_M can be obtained. As there is no data available for assembly of the components and installation of the systems an estimated energy demand of 10% of the material energy demand is chosen.
Furthermore it is supposed that no energy is required for disassembly and deposition or recycling of the systems.

Table 4.3.1: CED of solar hot water heating systems [Wag97b]

	absorber system for hot water heating of one- or two-family house			absorber system for hot water heating of multiple family house	
	small system			big system	
make	SOLVIS	Solar Diamant	evacuated tube c.	SOLVIS	evacuated tube c.
area [m²]	6,15	5,76	5	98,4	78
CED_M [GJ]	11,45	9,79	6,83	231,2	130,7
$CED_{assembly}$	10%	10%	10%	10%	10%
CED_U [GJ]	5%	5%	5%	5%	5%
CED_D [GJ]	not taken into account				
CED_{total} [GJ]	13,2	11,3	7,9	267,0	151,0

Energy Output and EYR

The following parameters are determinant for the gained heat:

- meteorological circumstances
- technical condition of plant
- optimised layout of plant
- operating method
- behaviour of user

To cover a wide spectrum of influences a variety of parameters has been selected, as can be seen from appendix B.

As the solar systems partly substitute conventional systems the generated heat is thought to be produced through oil- or gas-heating. This philosophy has been described in [Wag95] in detail. Consequently the primary energy equivalent of the heat that is gained per square-meter of the solar systems is calculated by dividing the heat by a corresponding efficiency. This efficiency takes into account the efficiency of energy conversion of the systems and of the process chain of oil and gas.

As the duty to heat warm water in summer is very low, the efficiency in this period is much lower compared to the overall efficiency. Measurements show that lowest efficiencies can be about 50%. [Croy94]

For calculation the efficiencies η_{conv} as used in [Wag95] are:

Table 4.3.2: Efficiencies for calculating primary energy equivalent

one- and two-family houses	60 %
multiple-family houses	60 % with one boiler

The primary energy yield ratio as a ratio of substituted primary energy to total cumulated energy is obtained from [Wag97b]:

Table 4.3.3: Energy savings of solar hot water heaters

small system	
SOLVIS	14,0 to 25,1
SOLAR Diamant	15,3 to 27,5
evacuated tube collector	19,0 to 34,2
big system	
SOLVIS	11,1 to 19,9
evacuated tube collector	15,5 to 27,9

4.3.2 Comparison

From calculation of these figures the succeeding results can be obtained:

- Solar hot water heaters are 11,1 to 34,2 times more energy efficient than conventional systems. Speaking of resource preservation the installation of flat plate and evacuated tube collectors is useful.
- Energy yield ratios will not become lower than one, even when worst-case-scenarios are considered.
- The choice of a type of collector and its material is highly influential on the energy yield ratio.
- The choice of efficiency of the substituted conventional system is also worth mentioning: The worse the efficiency the higher the energy yield ratio. [Wag97b].

Electrical water heating systems have an efficiency of 95%. With respect to the potential efficiency of the German electricity mix a primary energy efficiency of 33% can be obtained. Again the conventional system is much less energy efficient than the solar systems.

5 Remarks and Conclusions

Findings revealed by the calculations, results and conducted studies are summarised below:

1. A general tendency in the results of all the scenarios is clearly in favour of renewable energy technologies, as they are more energy efficient, provided all energy inputs are considered including the consumption of fuels. The authors think that the system boundary should also include the energy demands of the utilisation-phase as the purpose of this study is to find the total load on the limited energy resources.

2. It has been felt that the scenarios can't be compared among themselves and one single renewable energy technology can't be said to be the best, as the availability and hence the suitability of renewable energy sources varies from place to place. However, comparing the best places for each renewable energy source, it was found that the wind energy converters tend to be most energy efficient than the respective conventional energy option, followed by solar water heating systems and photovoltaic systems respectively. Diagrammatic presentation of the results can be seen in Appendix- A11 and B for comparison.

3. Neither the electricity mix of India and Germany, nor the process chain details for supply of fuels are similar due to the differences in availability of resources. Incidentally, the average potential efficiencies for the two countries are found to be almost the same. Concerning the Indian electricity mix, the effect of a dominating yet less efficient share of coal based power generation is balanced by the high efficiency of hydro power having a relatively small share. In German electricity mix, a relatively high share of nuclear power governs the overall efficiency to the level of 35%.

4. The average cumulated annual solar radiation in Germany ranges from 900 to 1200 kWh /m² whereas in India it is in the range of 1800 to 2700 kWh/m². The annual mean ambient temperatures in the two countries have a difference ranging from 5 to 20°C. The spectrums of wind energy potentials are overlapping, the best site for India have an output more than the best site of Germany, but the near coastal and inland sites of Germany are much better for wind energy when compared to similar sites in India. These differences don't permit to make a single generic statement regarding the technologies and also regarding the two countries.

5. The energy collected by direct solar energy technologies is much higher for India, however balances show that the cumulated energy demands of these systems are also higher than the values for Germany due to various reasons like difference in system layout, design specifications, maintenance requirements etc.. This has restricted the energy payback and energy yield ratios from being much different for the two countries as they could be for the identical system specifications.

6. As the maintenance requirements of the technologies are generally situation specific and probabilistic in nature, it is suggested that a sensitivity analysis for individual sites should be done based on past data and previous experiences in future research.

7. The sensitivity analysis for transportation shows that there can be considerable difference in the total energy demand with different modes of transportation. The sensitivity analysis for solar water heating systems shows up to 18.8% variation possibility in India due to large distances. The effect of mode of transportation may even overshadow the distance as in case of wind energy converters. Due to the selection of different modes, the effect of distance on the final value of CED is not significantly different for the two countries.

8. It has been observed that for a higher ratio of cumulated energy demand to weight, the sensitivity for mode and distance is low and an average value can be considered for such cases. This can be understood by looking at the sensitivity analysis results for photovoltaic and solar water heating systems.

9. The results for the hard coal power plant show that the EYR for large capacity fossil fuel based power plants with a long lifetime are primarily governed by the plant efficiencies. For smaller capacities and lifetime energy demands besides of fuel consumption may have a considerable effect on the EYR. Furthermore, the energy yield ratio in terms of physical energy (normally electricity) makes more sense than the same in terms of primary energy. In case of a good plant, the former should be as close as possible to the plant efficiency and the later, close to one.

10. While examining wind profiles for various stations in India, it was noticed that choosing a higher height may not always be useful. At one of the stations considered here, in few months, the average wind velocity at 20 meter height is found to be less than at 10 meter height. This may happen due to presence of very typical geographical conditions like temperature inversions. Hence, a separate investigation for finding the most suitable type of wind energy converter is proposed for the future research.

11. One reason for the difference in primary energy savings from solar water heating system and photovoltaic systems is the high energy content of silicon wafers, low conversion efficiency of the later is another reason for the difference. Efforts are being done to improve both that may improve the suitability of photovoltaic systems in future.

12. Due to relatively high ambient temperature the efficiency of solar water heating systems in India is much higher than in Germany. However the state of art is an important reason for a much high overall efficiency of photovoltaic systems in Germany as compared to India.

13. The photovoltaic charging system in India since designed on the basis of minimum daily radiation value remains under-utilised in the high radiation days, on the other hand the solar water heating system since working in combination with auxiliary electric water heater remains fully utilised throughout the year. This difference of system utilisation has consequently, increased the difference in the primary energy savings from the two technologies.

The calculations of Cumulated Energy Demand and Energy Yield Ratio are not very accurate like economic cost and benefit analysis, where decimal figures have to be exact. Nevertheless the results show clear tendencies that can be utilised in making preferences.

Furthermore, the selection of appropriate technologies will also depend on other factors than Cumulated Energy Demand and Energy Yield Ratio (i.e. emissions, cost of energy supply, social implications), therefore a comprehensive analysis of the energy options is suggested.

Appendix A: India

A1 Climatic Zones of India

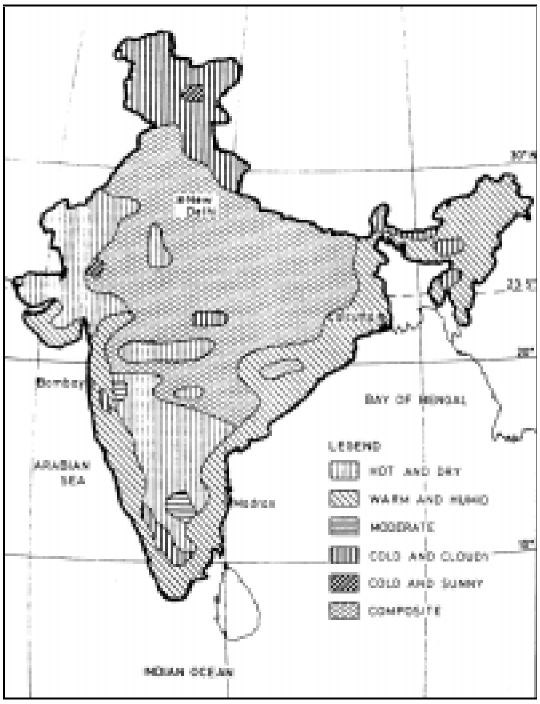


Figure A1.1: Climatic zones of India

Table A1.1: Representative cities of Indian climatic zones

Climatic zone	Representative city	Cumulative annual solar radiation [GJ]	Annual average temperature [°C]
Hot & dry	Ahmedabad	9.89	28.0
Warm & humid	Madras	9.83	28.6
Moderate	Bangalore	9.23	23.6
Cool & cloudy	Srinagar	8.88	13.4
Cold & sunny	Leh	6.22	05.5
Composite	Delhi	9.12	25.3

A2 Wind data for selected sites in India

Table A2.1: Wind data for Rameswaram (Location: Coastal, climatic zone: warm & humid)

Month	Wind velocity (10m) Km/hr	Wind velocity (20m) Km/hr	Air density at MSL	Shape parameter	Size parameter Km/hr
January	24.04	25.79	1.172	2.9	28.6
February	20.54	22.21	1.168	3.0	24.0
March	16.15	18.12	1.158	2.9	19.7
April	15.36	19.28	1.149	1.9	20.5
May	21.38	27.59	1.139	3.0	29.5
June	26.79	33.35	1.144	3.8	35.3
July	21.81	27.44	1.145	3.0	29.3
August	18.01	23.33	1.144	2.9	25.2
September	19.06	24.39	1.150	2.5	26.6
October	15.87	19.23	1.154	2.1	20.7
November	21.86	23.60	1.163	3.2	25.5
December	25.16	27.04	1.170	3.8	28.8
Annual	20.50	24.29	1.155	2.6	26.4

Table A2.2: Wind data for Bamanbore (Location: Near coastal, Climatic zone: hot and dry)

Month	Wind velocity (10m) Km/hr	Wind velocity (20m) Km/hr	Air density at MSL	Shape parameter	Size parameter Km/hr
January	8.94	11.60	1.174	2.4	13.0
February	9.45	11.78	1.163	1.5	11.1
March	12.48	14.02	1.145	1.6	13.2
April	15.32	16.85	1.127	2.0	17.4
May	21.45	22.92	1.116	3.3	24.5
June	20.57	22.53	1.115	3.1	24.4
July	23.36	25.49	1.122	3.3	27.2
August	16.49	18.19	1.129	2.5	18.8
September	11.55	13.09	1.133	2.4	13.7
October	8.10	10.03	1.135	2.1	10.1
November	8.67	11.06	1.154	2.1	11.9
December	10.25	12.94	1.172	2.1	13.1
Annual	13.47	15.47	1.140	2.0	17.2

Table A2.3: Wind data for Sultanpet (Location: Inland, climatic zone: moderate)

Month	Wind velocity (10m) Km/hr	Wind velocity (20m) Km/hr	Air density at MSL	Shape parameter	Size parameter Km/hr
January	10.73	11.67	1.128	3.7	13.3
February	11.36	11.82	1.120	1.9	11.4
March	13.05	12.88	1.111	1.9	14.4
April	16.92	16.63	1.103	2.1	19.1
May	23.87	23.58	1.102	2.9	26.0
June	30.54	29.87	1.109	4.0	32.3
July	30.73	30.00	1.113	4.3	31.9
August	31.48	31.36	1.113	4.2	33.5
September	26.54	25.68	1.112	3.0	28.1
October	14.14	13.29	1.114	1.8	16.2
November	10.06	10.34	1.121	1.4	10.2
December	9.60	10.29	1.128	2.6	11.3
Annual	19.09	18.96	1.115	2.0	21.5

A3 Material balance for 1.5 MW wind energy converter

Table A3.1: Material and energy balance for 1.5 MW WEK

Component	Material (actual)	Material (chosen)	Quantity	Unit	Specific CED [MJ/unit]
Rotor blades	Aluminium	Aluminium (primäres) - Deutschland	33	kg	225,3149
	Fibre glass	Glasfasern (GF)	2188	kg	50
	Epoxy resin	Epoxidharz	1516	kg	80
	Hardener	Härter	525	kg	61
	Polyamide	PA 6	76	kg	177,2
	Polyethene	LDPE	228	kg	88,6
	PVC-foam	Polyvinylchlorid; PVC	279	kg	66,8
	PVC	Polyvinylchlorid; PVC	131	kg	66,8
	Paint	Lack	184	kg	125
	Rubber	Gummi	55	kg	117
	Others	Sonstige	169	kg	.
Sum			5384	kg	
Generator	Steel sheet	Elektroblech	17927	kg	82
	Copper	Kupfer, Primär (schlechtester Fall)	8988	kg	83,9
	Paint	Lack	150	kg	125
	Steel (no alloy)	Stahlschiene	13258	kg	18,362
	Steel (galvanised, low grade)	Stahl, niedrig legiert, elktrolytisch verzinkt	105	kg	35,2
	Steel (alloy, high grade)	Stahl, hoch legiert	14	kg	42
	Others	Sonstige	248	kg	
Sum			40690	kg	
Rest of machinery	Steel (no alloy)	Stahlschiene	10780	kg	18,362
	Steel (alloy, low grade)	Stahl, niedrig legiert	9101	kg	31
	Steel (galvanised, low grade)	Stahl, niedrig legiert, elktrolytisch verzinkt	1224	kg	35,2
	Cast steel	Stahlguß	3708	kg	61,8
	Cast iron	Gußeisen	21027	kg	17,6
	Aluminium	Aluminium (primäres) - Deutschland	127	kg	225,3
	Copper	Kupfer, Primär (schlechtester Fall)	293	kg	83,9
	Fibre glass	Glasfasern (GF)	924	kg	50
	Unsaturated polyester resin	Polyesterharz, ungesättigt (UP)	2159	kg	78

Table A3.1: (contd.)

	Electronics	allgemeine Elektronik	120	kg	235
	Paint	Lack	504	kg	125
	Others		1624	kg	
Sum			51591	kg	
Tower	Steel	Stahlschiene	144182	kg	18,362
	Galvanised steel	Blech (elektrolytisch verzinkt)	4695	kg	22,92
	Paint	Lack	4217	kg	125
Sum			153094	kg	
Grid connection	Galvanised steel	Blech (elektrolytisch verzinkt)	715	kg	22,92
	Steel (alloy, low grade)	Stahl, niedrig legiert	927	kg	31
	steel (alloy, high grade)	Stahl, hoch legiert	630	kg	42
	Steel sheet	Elektroblech	1300	kg	82
	Steel (for construction)	Betonstabstahl	741	kg	30,1
	Iron	Stahlschiene	1042	kg	18,362
	Copper	Kupfer, Primär (schlechtester Fall)	6119	kg	83,9
	PVC	Polyvinylchlorid; PVC	747	kg	66,8
	Gear oil	Getriebeöl	940	kg	39,4
	Rest of electrics	Elektrik, allgemein	1065	kg	100
	Electronics	allgemeine Elektronik	1283	kg	235
	Light weight concrete	Leichtbeton LB25	12000	kg	2,3
	Others		225	kg	
Sum			27734	kg	
Foundation (shallow): for near coastal and inland site					
	Normal concrete	Normalbeton B25	828000	kg	0,7
	Steel (construction)	Betonstabstahl	24000	kg	30,1
	PVC	Polyvinylchlorid; PVC	166	kg	66,8
Sum			852166	kg	
Foundation (deep): for coastal site					
	Normal concrete	Normalbeton B25	575000	kg	0,7
	Steel (construction)	Betonstabstahl	26300	kg	30,1
	Steel (no alloy)	Stahlschiene	13243	kg	18,362
	PVC	Polyvinylchlorid; PVC	166	kg	66,8
Sum			614709		

A4 Energy demand for transportation of wind energy converters

Table A4.1: Specific CED for various transportation modes

Mode of transportation	Energy demand [MJ/T*Km]
Ship (sea):	0.15
Railways:	0.10
Truck(<3T):	5.50

Table A4.2: CED_T of 1.5 MW WEK for India

	coastal (Rameswaram)	near coastal (Bamanbor)	inland (Sultanpet)
Weight [kg]	289261	289261	289261
Distance by ship [km]	17000	15000	17000
Distance by railway [km]	200	200	300
Energy for ship [MJ]	737615.55	650837.25	737615.55
Energy for railway [MJ]	5785.22	5785.22	8677.83
Total energy [MJ]	743400,77	656622.47	746293.38

A5 Power curve for 1.5 MW wind energy converter

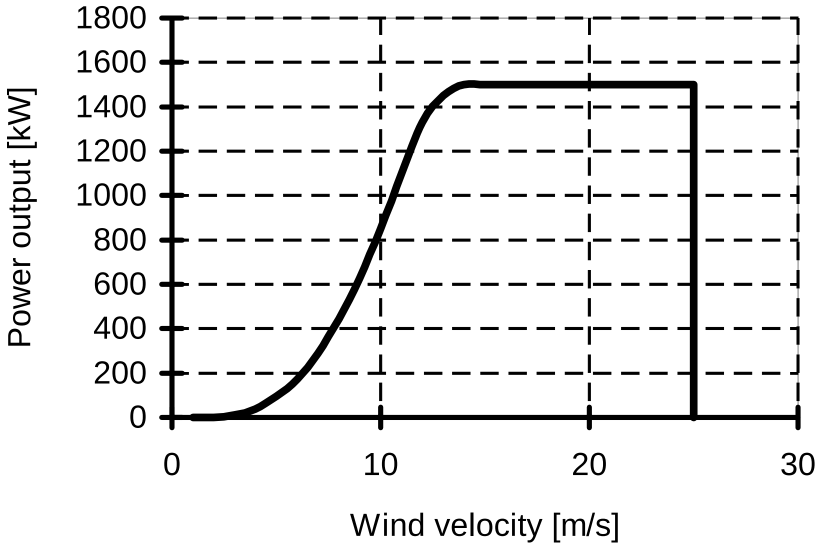


Figure A5.1: Power curve for 1.5 MW WEC (Type E-66)

A6 Calculation of PV module area requirement in the six climatic zones

Table A6.1: Calculation of required number of PV modules in Indian climatic zones

Climatic zone	Hot & dry	Moderate	Composite	Cold & sunny	Warm & humid	Cool & cloudy
Rep. City	Ahmedabad	Bangalore	Delhi	Leh	Madras	Srinagar
Minimum daily radiation [kWh/m²]	5,16	6,20	4,22	3,50	6,24	3,52
Output [kWh/m²]	0,258	0,31	0,211	0,175	0,312	0,176
Reqd. Output [kWh]	1,00	1,00	1,00	1,00	1,00	1,00
Reqd. Area[m²]	3,87	3,23	4,74	5,71	3,21	5,68
Modules reqd.[no.]	9,69	8,06	11,85	14,29	8,01	14,20
Std.modules*	10	9	12	15	9	15

* Std. modules: as available in market (produced by CEL, India)

A7 Material and energy balance for solar water heating system

Table A7.1: Material and energy balance for solar water heating system in India

Component	Sub component	Material (actual)	Material, (chosen)	Quantity	Unit	Specific ced [MJ/unit]	CED (material) [MJ]	Manu. factor	CED [MJ]	Percentage of plant
Collector	Absorber	Copper	Kupfer, Primär (schlechtester Fall)	7,14	kg	83,9	599,046	0,1	658,9506	6,63
	Cover	Glass	Flachglas	22	kg	14,96	329,12	0	329,12	3,31
	Risers	Copper	Kupfer, Primär (schlechtester Fall)	3,98	kg	83,9	333,922	0,15	384,0103	3,86
	Headers	Galvanised iron	Stahl, niedrig legiert, elktrolytisch verzinkt	3,76	kg	35,2	132,352	0,15	152,2048	1,53
	Insulation	Glass wool	glaswoole	4,28	kg	33,1	141,668	0	141,668	1,43
	Base & frame	Aluminium	Aluminium (primäres) - Deutschland	7,69	kg	225,3	1732,557	0	1732,557	17,44
	Insulation cover	Aluminium	Aluminium (primäres) - Deutschland	0,65	kg	225,3	146,445	0	146,445	1,47
	Sealant	Rubber	Gummi	0,5	kg	117	58,5	0	58,5	0,59
	Sum			50	kg		3473,61		3603,4557	36,26
Hot water tank	Body	Steel (high grade)	Stahl, hoch legiert	11,21	kg	42	470,82	0,15	541,443	5,45
	Insulation	Glass wool	glaswoole	7,36	kg	33,1	243,616	0	243,616	2,45
	Insulation cover	Aluminium	Aluminium (primäres) - Deutschland	3,35	kg	225,3	754,755	0	754,755	7,60
	Sum			21,92	kg		1469,191		1539,814	15,50

Table A7.1: (contd.)

Pipe work	Pipe	Galvanised iron	Stahl, niedrig legiert, elktrolytisch verzinkt	5,05	kg	35,2	177,76	0,15	204,424	2,06
	Hot pipe insulation	Glass wool	glaswoole	3,55	kg	33,1	117,505	0	117,505	1,18
	Insulation cover	Aluminium	Aluminium (primäres) - Deutschland	0,92	kg	225,3	207,276	0	207,276	2,09
	Sum			9,52	kg		502,541		529,205	5,33
Supports	For collector	Iron (no alloy)	Stahlschiene	4,97	kg	18,362	91,25914	0,15	104,948011	1,06
	For hot tank	Iron (no alloy)	Stahlschiene	8,97	kg	18,362	164,70714	0,15	189,413211	1,91
	Sum			13,94	kg		255,96628		294,361222	2,96
Maintenance	Insulation	Glass wool	glaswoole	15,19	kg	33,1	502,789	0	502,789	5,06
	Insulation cover	Aluminium	Aluminium (primäres) - Deutschland	8,54	kg	225,3	1924,062	0	1924,062	19,36
	Risers	Copper	Kupfer, Primär (schlechtester Fall)	7,96	kg	83,9	667,844	0,15	768,0206	7,73
	Cover	Glass	Flachglas	44	kg	14,96	658,24	0	658,24	6,62
	Sealant	Rubber	Gummi	1	kg	117	117	0	117	1,18
	Sum			76,69	kg		3869,935		3970,1116	39,95

A8 Specifications of inverter-accumulator system

- Inverter input: AC 300 VA , 200-250 V
- Inverter input: DC 10-15 V (in 12 V system), 20-30 V (in 24 V system)
- Output: AC voltage 230 (10% variation), Frequency 50 Hz (0.5% variation)
- Efficiency: 90%
- Power factor: 0.85
- Accumulator capacity: 10 Ah

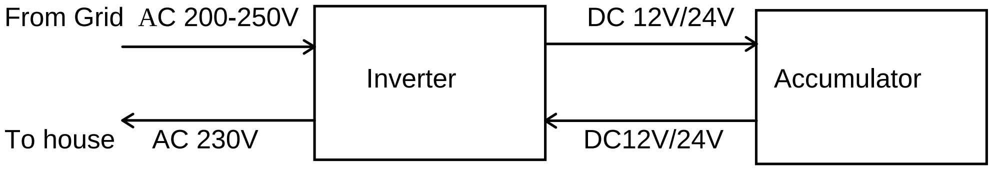


Figure A8.1: Typical stand-bye inverter-accumulator system used in Indian houses

A9 Material and energy balance for photovoltaic modules

Table A9.1. Material and energy balance for Indian PV module (35W;0,4 m²)

Component	Sub component	Material (actual)	Material (chosen)	Quantity	Unit	Specific CED [MJ/unit]	CED (material) [MJ]	Manu. factor	CED [MJ]	Percentage of total
PV module	Wafer	Mono-crystalline Si	Mono-crystalline Si	35	watt peak	119,93	4197,55	0	4197,55	82,08
	Frame	Aluminium	Aluminium (primäres) - Deutschland	0,96	kg	225,3	216,288	0,1	237,9168	4,65
	Glass cover	Glass	Flachglas	3,24	kg	15	48,6	0	48,6	0,95
	Electricals			1	kg	100	100	0,16	116	2,27
	Processing			35	watt peak	9,03	316,05	0	316,05	6,18
Support		Steel	Stahlschiene	4,76	kg	18,36	87,3936	0,15	100,50264	1,97
Maintenance	Cover	Glass	Flachglas	6,48	kg	15	97,2	0	97,2	1,90
Sum									5113,81944	100,00

A10 Material and energy balances for coal power plant

Table A10.1: CED_P of hard coal plant production

Component	CED_P [TJ]
Structural components	677
Machine parts	1152
Electro technical parts	222
Operational materials	584
Total	2635

Table A10.2: CED_U of hard coal plant utilisation in India

Component	CED_U [TJ]
Additional fuel (fuel oil)	3800
Operational material including transportation	1659
Service & maintenance	7
Waste handling	443
CED_U (without hard coal)	5909
Hard coal	1014758
CED_U (with hard coal)	1020667

Table A10.3: CED_D of hard coal plant disposal

Component	CED_D [TJ]
Demolition and transportation	90
Deposition/thermal usage	-16
Credits	-413
Total	-339

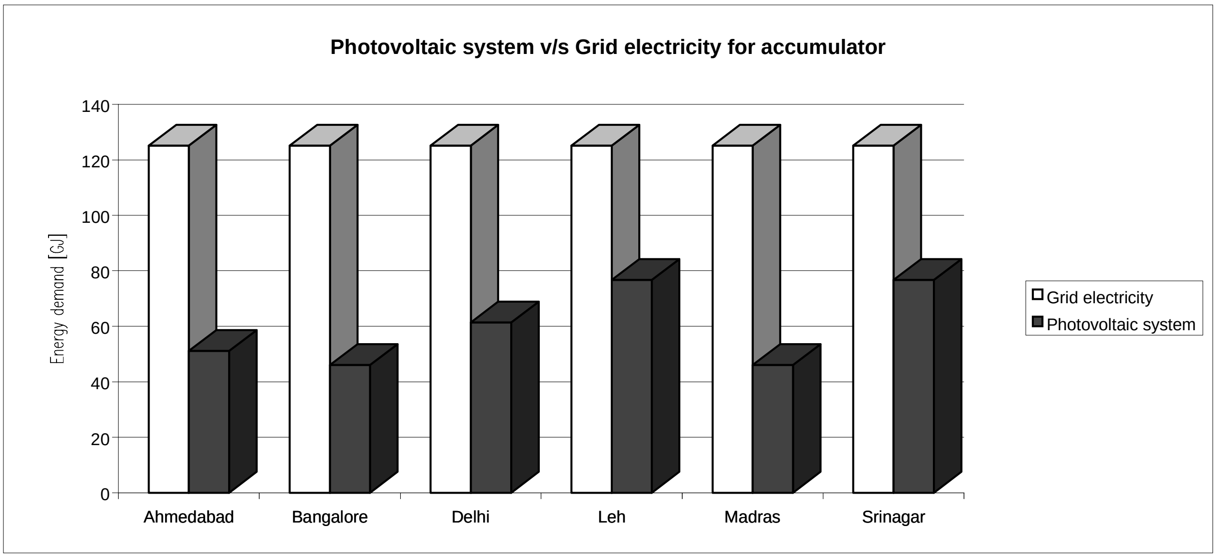
- The CED_P of the structural components amounts to 677 TJ. Within this section about 47% belong to the component steel building.

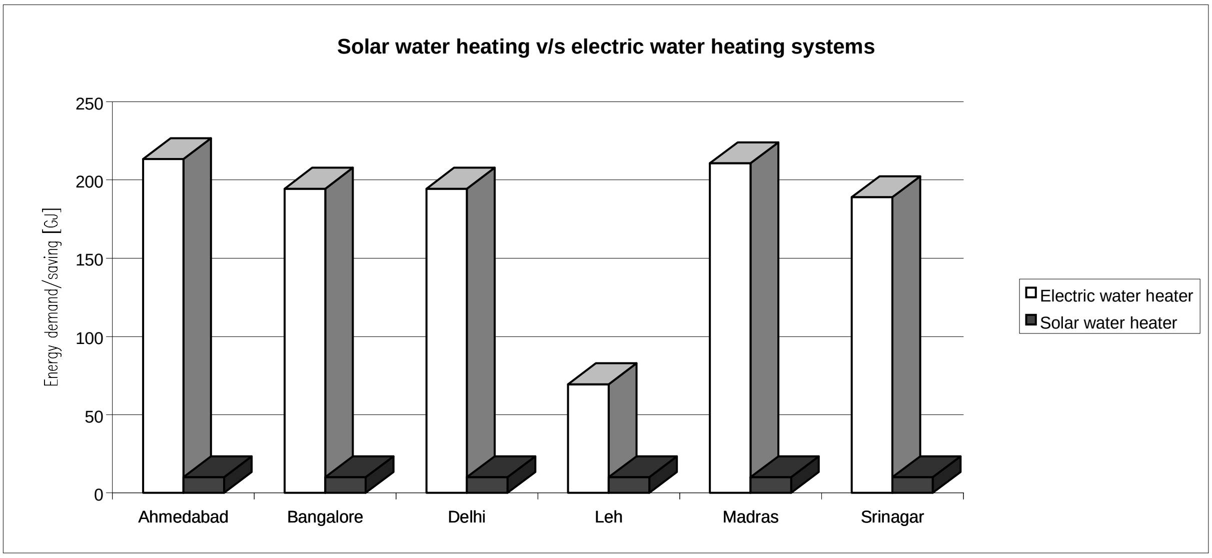
- The CED_P for the machine parts comes to a total of 1152 TJ, where boiler unit (50%) and flue gas purification system (19%) hold the bigger share.

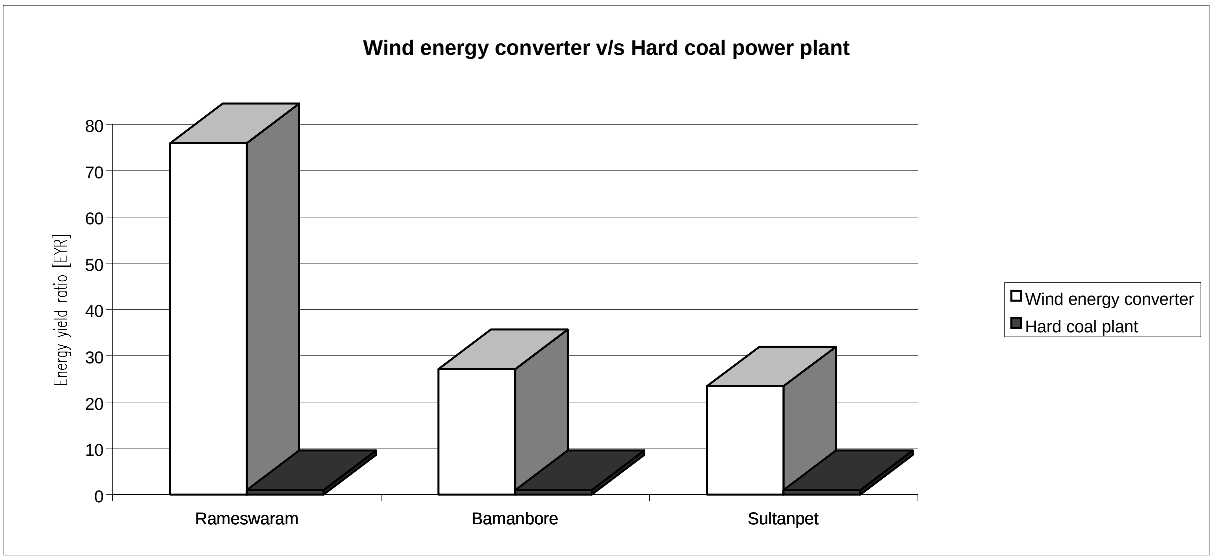
- The CED_P of the electro-technical parts (222 TJ) is about 8% of the total CED_P of the plant.

- Not only usage of operational materials, such as electricity consumption on the building site, fuel oil for trial runs of several machines and lubricants, but also energy consumption for transportation and excavation were taken into account and have a share of 22% (584 MJ).

A11 Energy demand and saving of considered plants







Appendix B: Germany

B1 Hard Coal Power Plant

B2 Solar Water Heating System

B3 Potential Efficiency of German Electricity Mix

B4 Process Chain Analysis

B5 Energy yield ratio and saving of considered plants

B1 Hard Coal Power Plant

The cumulated energy demand is calculated for production, utilisation and disposal of the plants.

The production of the power plant is divided into the sections:

- structural components
- machine parts
- electrotechnical parts
- operational materials

The cumulated energy demand for production of the plant is given in table B1.1:

Table B1.1: CED_P of Coal Power Plant (compare table A.XXX)

section	$ced_{production}$ [TJ]
structural components	677
machine parts	1152
electrotechnical part	222
operational materials	584
total	2635

All in all a ced_P of 2635 TJ can be calculated.

With a net efficiency of 43% and a load duration time of 5000 hours per year the net power output is 2545 GWh_{el}/a.

With an estimated operating life of 40 years a net energy of 101,8 TWh_{el} will be generated.

Concerning the utilisation of the power plant the energy demand of the following materials and operation is taken into account:

Table B1.2: CED_U of Coal Power Plant (compare table A.XXX)

section	$ced_{utilisation}$ [TJ]
additional fuel (fuel oil)	3800
operational materials incl. transportation	1659
service and maintenance	7
transport of waste	443
$ced_{utilisation}$ (without hardcoal)	5909
hardcoal	905000
$ced_{utilisation}$ (incl. hardcoal)	910909

Looking at the energy demand disregarding hard coal results in a ced_u of 5909 TJ, whereas the energy demand with hard coal taken into consideration increases to 911 PJ.

As for disposal of the hard coal power plant the energy content of recyclable materials is subtracted from the cumulated energy demand. As only a few materials have to be deposited the total amount comes to a credit of 339 TJ.

Table B1.3: CED_D of Coal Power Plant (compare table A.XXX)

section	$ced_{disposal}$ [TJ]
demolition of buildings and transport of waste	90
deposition / thermal usage	-16
credits	-413
total	-339

B2 Solar Water Heating System

Table B2.1: Overview of selected solar systems

	absorber system for hot water heating of one- or two-family house			absorber system for hot water heating of multiple family house	
	small system			big system	
type	flat plate collector	flat plate collector	vacuum tube collector	flat plate collectors	vacuum tube collector
make	SOLVIS F60	Solar Diamant	Klöckner	SOLVIS	Klöckner
remark	casing from aluminium	casing from glass fibre reinforced plastic	heat-pipe-system	casing from aluminium	heat-pipe-system
area [m²]	6,15	3 x 1,92	50 x 0,1	100	78

Table B2.2: CED of solar hot water heating systems [Wag97b]

Bandwidth of generated heat		
small system	900 MJ/(m²a) = 250 kWh/(m²a)	1620 MJ MJ/(m²a) = 450 kWh/(m²a)
	low efficiency due to: • oversized system layout • unefficient insulation • components of average quality • low radiation	high efficiency due to: • optimised system layout • efficient insulation • high quality components • high radiation
big system	900 MJ/(m²a) = 250 kWh/(m²a)	1620 MJ MJ/(m²a) = 450 kWh/(m²a)
	low efficiency due to: • poor fine-tuning concerning user profile • oversized system layout • unefficient insulation • components of average quality • low radiation	high efficiency due to: • optimised system layout • efficient insulation • high quality components • high radiation

Table B2.3: CED and EYR of hot water heating systems [Wag95]

	small system			big system	
	SOLVIS	Solar Diamant	evac. t. coll.	SOLVIS	evac. tube coll.
area [m²]	6,15	5,76	5	98,4	78
CED, M [GJprimary]	11,45	9,79	6,83	231,2	130,7
CED, assembly [factor]	1,1	1,1	1,1	1,1	1,1
CED, U [factor]	1,05	1,05	1,05	1,05	1,05
CEDtotal [GJprimary]	13,2	11,3	7,9	267,0	151,0
produced energy, min [MJ/m²a]	900,00	900,00	900,00	900,00	900,00
produced energy, max [MJ/m²a]	1.620,00	1.620,00	1.620,00	1.620,00	1.620,00
produced energy, min [MJ/20a]	110.700,00	103.680,00	90.000,00	1.771.200,00	1.404.000,00
produced energy, max [MJ/20a]	199.260,00	186.624,00	162.000,00	3.188.160,00	2.527.200,00
lifetime [a]	20	20	20	20	20
eyr, min, physical	8,4	9,2	11,4	6,6	9,3
eyr, max, physical	15,1	16,5	20,5	11,9	16,7
eyr, min, primary	14,0	15,3	19,0	11,1	15,5
eyr, max, primary	25,1	27,5	34,2	19,9	27,9

B3 Potential Efficiency of German Electricity Mix

The following data has been taken into account:

Table B3.1: Potential Efficiency of electricity production in Germany [Wenz98]

Input	Electricity Plants [$MJ_{secondary}$]	factor of supply for fuels	factor of supply for power plants	Input [$TJ_{primary}$]	percentage
Coal	2.751.565	1,05	1,005	2.903.589	58,2%
Petroleum Products	72.013	1,08	1,002	77.930	1,6%
Gas	334.944	1,058	1,001	354.725	7,1%
Nuclear	1.423.512	1,04	1,004	1.486.374	29,8%
Hydro	71.176	1	1,045	74.379	1,5%
Geothermal/ Solar etc.	18.422	1	1,067	19.656	0,4%
Combustible Renewables & Waste	69.082	1	1,008	69.635	1,4%
	4.740.714			4.986.287	100,0%
	Electricity Plants [TJ_{end}]				
Output					
Electricity	1.921.741				
Own Use (Electricity)	138.164				
Distribution and Transfer Losses (Electricity)	103.414				
net:	1.680.163				
PE:	0,34				

B4 Process Chain Analysis

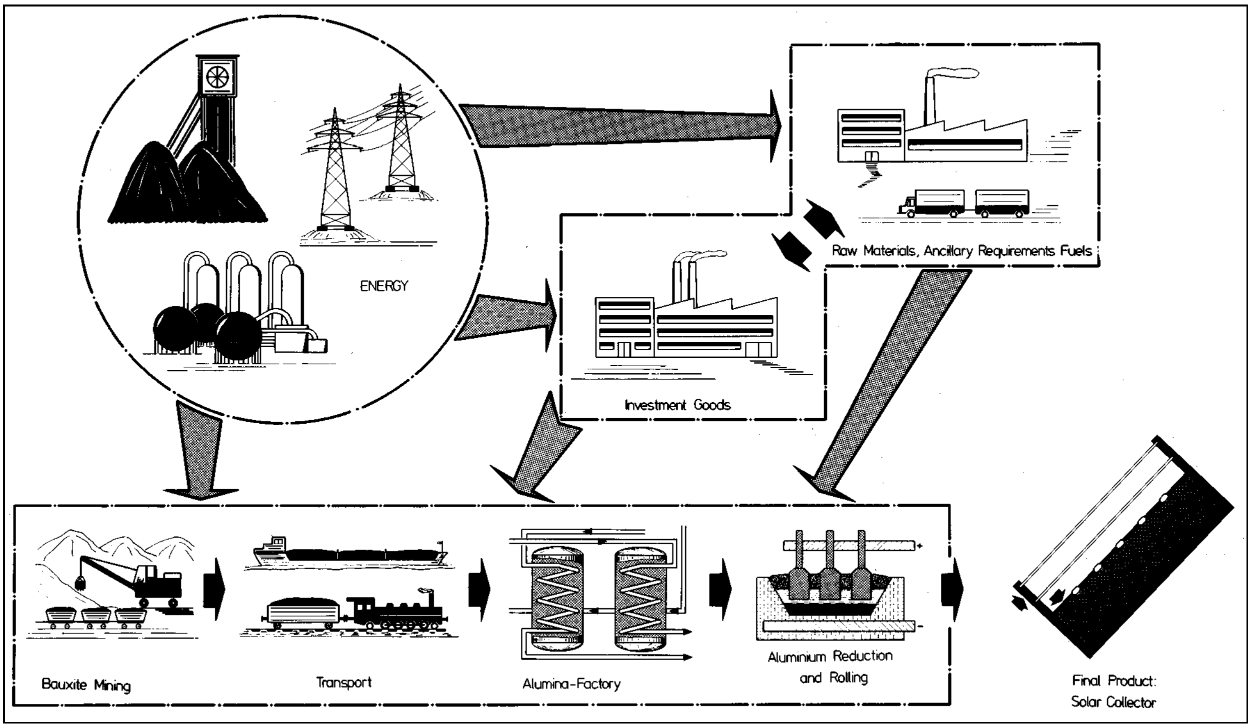
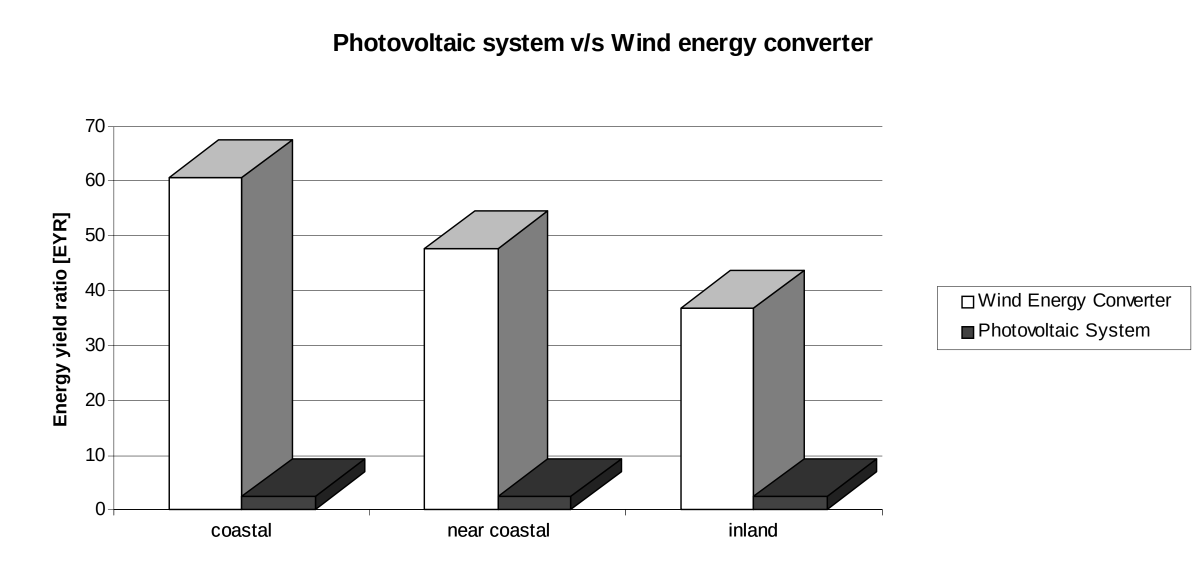
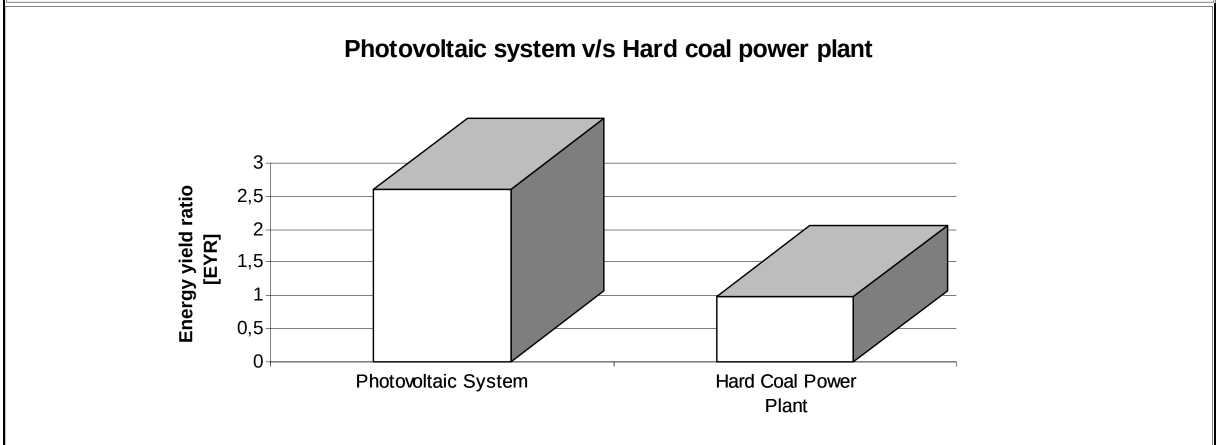
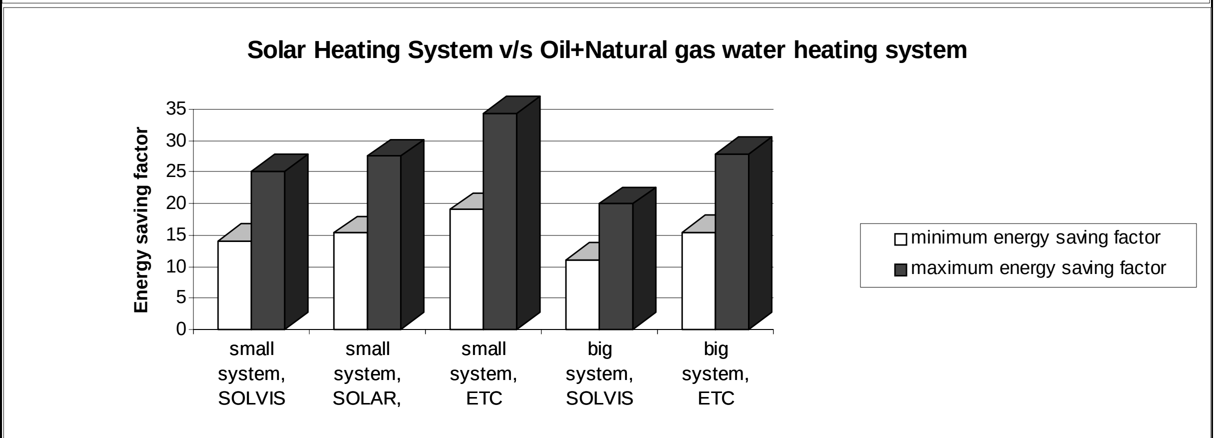


Figure B4.1: Example of Process Chain Analysis

B5: Energy yield ratio and saving of considered plants







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