GLOBAL POTENTIAL OF RENEWABLE ENERGY SOURCES: A LITERATURE ASSESSMENT

BACKGROUND REPORT

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1 Introduction

This report provides a background on the methodology and results of the assessment of the long term (2050) global and regional technical potential of renewable energy sources. For renewable power also the cost distribution is assessed. The approach is based on a review of existing studies in combination with expert judgements. This analysis is done as part of the report *Opportunities for the rapid deployment of renewable energy in large energy economies* published by REN21. The report is prepared for the third Ministers Meeting in the Gleneagles Dialogue on Climate Change, in order to provide Ministers of participating countries an overview of opportunities to rapid deployment of Renewable Energy Sources (RES).

2 Approach and Definitions

2.1 General approach

This study is conducted with limited time and resources. Because of this no complete new integrated approach has been applied in which all sources are considered in the same way. The assessment is based on existing work. Where needed, additional assessments and recalculations were done using data found in the literature. The final results can be considered as a combination of literature review and expert judgement.

2.2 Renewable energy sources assessed

The technical potential and the cost of renewable energy sources at different cost categories was assessed for the renewable energy sources as presented in Table 1. As can be seen, the focus was mainly put on power and heat. For biomass energy the technical potential and costs of primary energy is reported as well as for biomass electricity. Renewable transport fuels are not included e.g. from biomass.

Table 1: Overview of types of renewable energy sources that have been included for the technical potential assessment

	Power	Transport fuel	Heat	Primary energy
Hydropower	Hydropower (small and large scale combined)			
Solar	PV CSP		Solar thermal	
Wind	Onshore Offshore			
Biomass	Biomass electricity from energy crops or residues			Energy crops, Residues: forest, waste and agricultural
Geothermal	Geothermal electric		Direct use	
Ocean	Wave Ocean Thermal Energy Conversion (OTEC) Tidal Osmotic			

2.3 Definition of potential

When focussing on the availability of renewable energy sources, it is important to define the type of potential that is considered. In the literature, various types of potentials are defined. There is no one single definition for the various types of potentials. We distinguish and define five types of potentials (see Figure 1).

- **Theoretical potential**: The highest level of potential is the theoretical potential. This potential only takes into account restrictions with respect to natural and climatic parameters.
- **Geographical potential**: Most renewable energy sources have geographical restrictions, e.g. land use land cover that reduce the theoretical potential. The geographical potential is the theoretical potential limited by the resources at geographical locations that are suitable.
- **Technical potential**: The geographical potential is further reduced due to technical limitations as conversion efficiencies, resulting in the technical potential.
- **Economic potential:** The economic potential is the technical potential at cost levels considered competitive.
- **Market potential**: The market potential is the total amount of renewable energy that can be implementation in the market taking into account the demand for energy, the compet-

ing technologies, the costs and subsidies of renewable energy sources, and the barriers. As also opportunities are included, the market potential may in theory be larger than the economic potential, but usually the market potential is lower because of all kind of barriers.

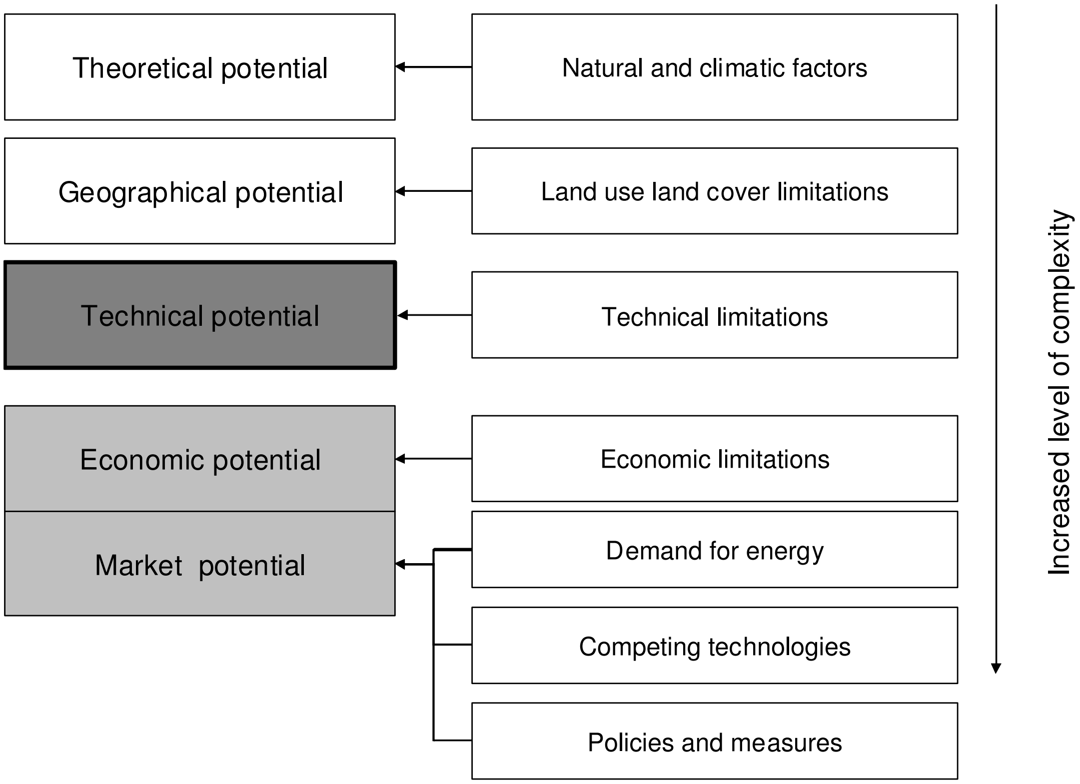

Figure 1: Categorisation of five types of potentials and their main important factors and limitations. In this study we focus on the technical potential

In this study we focus on the technical potential. We define the **technical potential** as: *the total amount of energy (final or primary) that can be produced taking into account the primary resources, the socio-geographical constraints and the technical losses in the conversion process.*

For **renewable electricity** we also analyse the **costs distribution**. The presented costs are levelised costs for the long term using a discount rate of 10%. The costs are expressed in US$/kWh[1]. The cost of renewable energy is expressed for different cost categories: < 3¢/kWh; < 5 ¢/kWh; < 10 ¢/kWh; < 15 ¢/kWh; < 20 ¢/kWh; and when applicable < 30 ¢/kWh.

It was decided to only include the cost distribution for renewable electricity because of the lack of data for renewable heat and renewable fuel.

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[1] Unless indicated otherwise, dollars for the year 2000 have been used

Because of the approach we have chosen, i.e. an assessment of different existing studies, the potential assessed per renewable energy source is not consistently defined for all renewable energy sources. As many literature sources did not report the limitations included it was not always possible to judge the type of potential assessed. However, by taking a large amount of literature sources for comparison, and adjust some of the figures we trust that in general the potential reported in this study can be considered a technical potential as defined above.

2.4 Regional aggregation

The technical potential and the cost distribution are analysed on the regional level as given in Table 2. When possible, the results are further disaggregated into more regions. A further disaggregation was not possible concerning the literature available.

Table 2: The world regions used and their most important characteristics (based on IMAGE regions, see Hoogwijk, 2004 and Price et al., 2006)

	Equivalent	Total land area (1000 km^2)	Total final energy$^\#$ consumption in 2002 (PJ)
North America	United States and Canada.	18750	93
OECD Europe		3720	72
Non-OECD Europe and FSU	Transition Economies; Eastern Europe and Central Asia	22990	39
Africa and Middle East	Africa plus Bahrain, Iran, Iraq, Israel, Jordan Kuwait, Lebanon, Oman , Saudi- Arabia, Syria, UAE, Yemen,	35520	44
Asia (excl. FSU)	South, East and Southeast-Asia	20960	100
Latin America	South-America, Central-America, Caribbean and Mexico	20300	24
Oceania	Australia, New Zealand and Pacific Islands	8380	31
World		13620	402

$^\#$electricity, heat/cooling and transport

Below, for each of the renewable energy sources an overview is presented of the current use, the main literature sources available; the assumptions made in this report and the main conclusions on the cost distribution per renewable energy source.

2.5 Data sources and uncertainties

A large amount of literature sources was used, e.g. studies that focused on all or many sources, for instance the world energy assessment (UNDP/WEC, 2000) and Hoogwijk, 20004, and studies that only focus on one source (for instance Hofman et al, 2002, Fellows, 2001). Where possible the technical potential and the cost distribution assessed here are based on a combination of sources. However, often we preferred to refer to one literature source as for this source the methodology was consistent, next to the technical potential also costs are reported in a consistent manner or because the results are easily compared to other sources.

Assessing a technical potential for the long term is subject to various uncertainties. The distribution of the theoretical resources is not always well analyses, e.g. the global wind speed or the productivity of energy crops. The geographical availability is subject to issues as land use change, subjective factors on where technologies can be installed and accessibility of resources, e.g. for geothermal. The technical performance will develop on the long term and the rate of development can vary significantly over time. The economic factors as future investment or O&M costs, and the distribution of the resources are subject to factors as learning by doing, economies of scale, R&D expenditures. Next to these inherent uncertainties we add one additional uncertainty by using different studies. There is a discrepancy in the used type of potentials and costs between the studies.

3 Approach and results

3.1 Hydropower

3.1.1 Technical potential

Hydropower is by far the largest renewable energy source currently used. Its current (2002) use is estimated at 2640 TWh/y (WEC, 2004). It is generated by mechanical conversion of the potential energy of water in high elevations. The availability of hydropower depends therefore on local and geographical factors as the availability of water and the height difference for runoff water. Various studies have indicated the technical potential of hydropower at a regional level. Most of the sources refer to the World Atlas and Industry Guide, (1998), e.g. UNDP/WEC, 2000; WEC, 2001. The total global technical potential is estimated at around 50 EJ/y, (UNDP/WEC, 2000; Bartle, 2002; Johansson, 2004; Bjornsson et al, 1998). Lako et al., 2003 and the recent IPCC Fourth Assessment report, (IPCC, 2007) present much lower numbers at around 25 EJ/y. The regional distribution is slightly different but in the same order of magnitude among all studies. The largest difference between the regional distribution of e.g. WEA and Lako et al., 2003 is in OECD Europe where the latter indicates a much lower technical potential, around 1800TWh/y in WEA compared to around 600 TWh/y by the other two sources. To be consistent with the economic data, we have used data from World Energy Assessment on the technical potential at a regional scale. The World Energy Assessment considered this estimate still conservative as the potential in many developing countries are weakly assessed. However, according to other sources, it might also be more limited. This indicates the uncertainty in the results.

3.1.2 Electricity Costs

The World Energy Assessment also presents the economically accessible potential of hydropower. This is done by looking in more detail to the local situation and the availability and accessibility of hydropower. However, the definition of economic accessible is not given, nor is the related costs. Various sources indicate that the costs for hydropower range between 2 – 8 ¢/kWh for the present situation and will slightly increase over time (NEA/IEA/OECD, 2005, IPCC, 2007). In addition, a detailed cost supply curve for the EU is available (Ragwitz et al., 2003) indicating that the costs in the EU range from 3.6 – 12.4 €c/kWh.

For this assessment it was therefore assumed that the currently produced hydropower is produced at the lowest costs, 5 ¢/kWh, that the economic potential is available ate at cost under 10 ¢/kWh and that the total technical potential is available up to costs of 15 ¢/kWh.

3.1.3 Results

Figure 2 provides the cost distribution for hydropower at a regional level. High potentials can be found in Asia and Latin America. OECD Europe has relatively a high share of low cost resources compared to other regions.

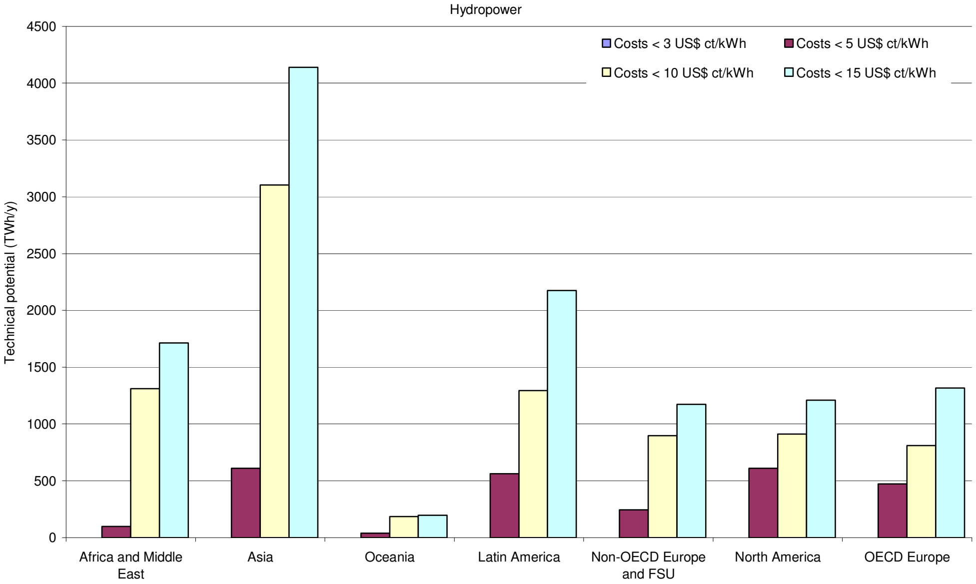

Figure 2: Cost of hydropower for different cost categories

3.2 Biomass energy

3.2.1 Technical potential

The use of biomass energy is currently increasing, both for the application of heat, e.g., by means of CHP, as well as for transport fuels and electricity, e.g. by means of co-firing. Its current installed electric capacity is estimated at 48 GW (Greenpeace, Erec, 2007). And its total current (2004) use including heat and transport fuels is estimated at around 50 EJ/y (IPCC, 2007).

Biomass resources are available from large range of different feedstock (Figure 3). Here we distinguish dedicated energy crops and residues from agriculture, forestry, food industry and waste. The category energy crops includes short rotation forestry, the category residues is not further, due to lack of data. The primary biomass can be converted to all energy applications; heat, electricity and transport fuel. In this report we specify the technical potential and costs of primary biomass (residues and energy crops) and the costs and technical potential of biomass electricity.

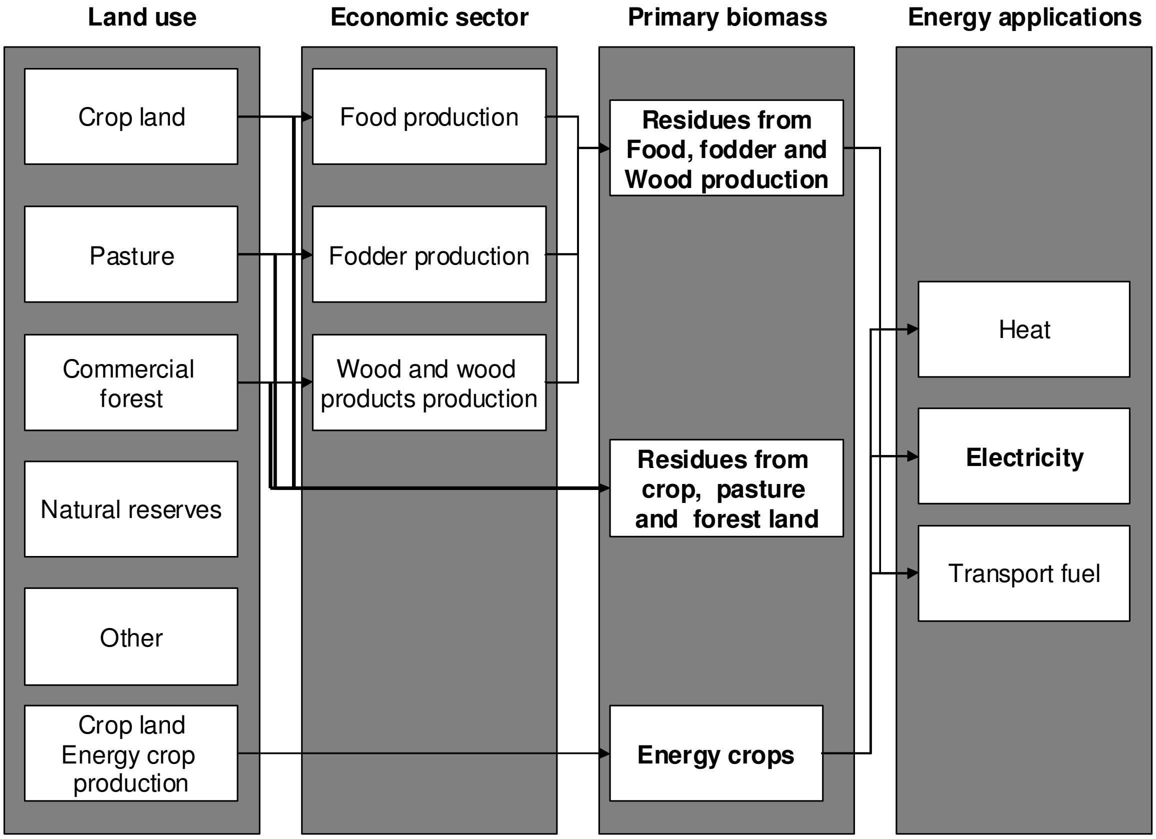

Figure 3: Schematic representation of the type of primary biomass feedstock and the conversion to energy applications.

The total available primary biomass resources from both groups of feedstock depend on (see Figure 4):

1. The **land available** as a function of the amount of forestry and agricultural products produced and other competing land use functions as natural reserves and urban areas;
2. The **biomass produced** on this land as a function of the quality of the land, the climatologic conditions and the management practice.

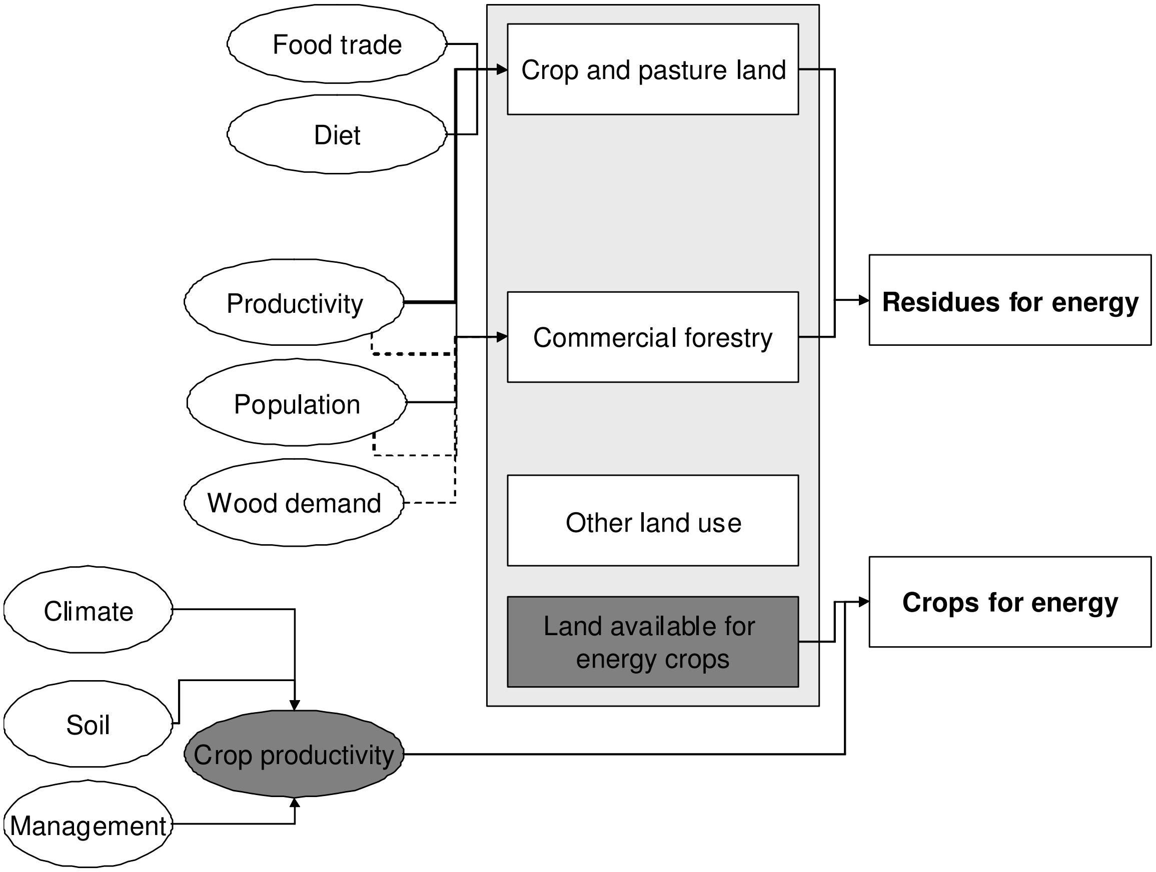

Figure 4: Schematic representation of main parameters influencing the potential of primary biomass: residues and energy crops

Most of the studies that have been considered here have incorporated all the parameters mentioned above. However, understandable, there is a large variation between the assumptions on the future land use changes and land use management practices. Table 3 indicates the ranges of the biomass as found in various literature sources allocated to the regions we have here. There are some more extreme values on the potential found in the literature, see e.g. Berndes et al., 2003, Hoogwijk, 2003, but we consider the type of potential assessed in these studies rather a theoretical potential and do not include these figures in this overview.

Studies that have been taken into account are: Berndes, et al., 2003; Yamamoto et al., 2001; Williams 1995; Hall et al., 1993; Hoogwijk, 2004; EEA, 2006; ASES, 2007; FAO/RWEDP, 2000. The ranges of biomass energy potential are based on the ranges from these studies. The type of potential that is assessed in these studies are all the technical potential in the sense that all parameters are included. However as can be seen from Figure 4 many assumptions are required that result in more optimistic or pessimistic figures for the technical potential, being more theoretical or more realistic. We have therefore taken the average of these studies.

Table 3: An estimate of the ranges of the biomass energy potential as found in the literature and the values that are used in this report (EJ/yr)

	Residues			Energy Crops		
	Low	High	Assumed	Low	High	Assumed
Africa and Middle East	4	11	7	15	69	38
Asia	13	32	23	25	96	53
Oceania	1	1	1	0	32	16
Latin America	2	25	15	2	66	34[a]
Non-OECD Europe and FSU	3	7	5	48	112	80
North America	7	36	17	15	60	38
OECD Europe	2	5	5	9	15	12
World	*32*	*117*	*73*	*162*	*450*	*271*

A very recent study by Doornbosch and Steenblik 2007 arrives at much lower estimates for the potentials from energy crops (~110 EJ/year), with relatively high potentials estimated for Latin America and Africa, but low estimates for Europe and North America and negative potentials estimates for Asia. They have included also considerations in terms of water stress to determine the estimate for land availability and productivity and include the shortage of food production resulting in negative potentials. The estimates for technical potentials from residues by Doornbosch and Steenblik (135 EJ/year) are higher than the high estimates used in this study. There seem to be a difference in categorization for this these numbers are not included. The overall estimate by these authors (245 EJ/year) is, thus, somewhat higher than the low estimates in the earlier studies considered here but the focus is more on residues and the regional availability is considered much lower in Asia including Central Asia. This study is not included in the overview as also some social and environmental constraints are included in their considerations. However it does indicate the in reality the potential for energy crops can be expected much lower than the technical potential estimated by the other studies.

3.2.2 Costs of primary biomass

Whereas there is a large number of studies available assessing the technical potential of primary biomass on a global scale, limited studies are available assessing costs on a global scale. On a regional scale cost data are available for OECD Europe, Eastern Europe and the US, e.g. van Dam 2007; Siemons, 2004; Milbrandt, 2005.

The cost of biomass from energy crops on a global scale depend on local climate and soil conditions has been assessed for four different scenarios by Hoogwijk, 2004. Here, the results from these scenarios have been taken, assuming that all the biomass crops potentials are used for electricity, the standard process being a woody short rotation crops conversion to power in BIGCC plants. The cost estimates of the energy crops for the four scenarios are presented in Table 4

Table 4: The cost estimates of the energy crops for the four scenarios in $/GJ for different cost levels

	A1			A2			B1			B2		
	< 2	< 5	< 10	< 2	< 5	< 10	< 2	< 5	< 10	< 2	< 5	< 10
Africa and Middle East	64	75	76	22	25	26	40	44	44	7	9	9
Asia	37	89	92	15	24	25	59	73	73	4	36	38
Oceania	33	35	35	17	18	18	28	29	29	24	25	25
Latin America	19	88	88	7	18	18	32	68	68	8	36	36
Non-OECD Europe & FSU	85	97	102	48	56	56	75	78	78	68	70	71
North America	29	50	53	15	29	31	36	45	46	38	51	51
OECD Europe	3	12	12	6	12	13	3	9	9	7	15	16
World	271	446	458	129	183	188	272	346	348	155	243	246

For residues, no global cost supply curve is available. On regional level, cost curves are estimated (e.g., Ragwitz, 2003; Milbrandt, 2005) and also residue costs have been presented (e.g. Siemons, 2004; USDA/USDOE, 2005). When cost ranges for residues were available on a regional scale, these were used. For the remaining regions an estimate was made on the cost range based on variation in transport costs and the type of residues available in these regions, e.g. if the low cost residue bagasse is available. This resulted in cost ranges for residues as presented in Table 5.

Table 5: Overview of cost range of biomass residues at a regional level

Name of region	Cost range	
	$/GJ	
	Low	High
Africa and Middle East	0.5	3.3
Asia	0.5	3.3
Oceania	0.8	6.4
Latin America	0.6	3.4
Non-OECD Europe and FSU	1.4	8.5
North America	0.6	10.4
OECD Europe	0.9	10.5

3.2.3 Cost of biomass electricity

Biomass can be converted to electricity in various ways. Co-firing in coal plants is currently applied at a large scale. Biomass only combustion plants are also available. For the long term it is assumed that gasification in a combined cycle would be the most efficient way for biomass electricity production. This technology is assumed here. The assumptions on the conversion and costs are presented in Table 6. For the energy crop or residue costs of 2 $/GJ these assumptions result in a biomass electricity costs of 5.5 ¢/kWh.

Table 6: Overview of main assumptions for the cost and conversion to biomass electricity

	Value	Unit
Type of technology	BIGCC	
Conversion efficiency	56	%
Typical scale	500	MW
Specific investment costs	1200	$/kW
O&M costs	4	% of total investment costs
Lifetime	20	Years
Discount rate	10	%

3.2.4 Results

Figure 5Figure 6 show the main results at regional level for electricity produced by energy crops (Figure 5) and residues (Figure 6). Large potentials can be found in non OECD and Former USSR. The cost distribution in the regions does not vary significantly mainly because the global studies included here provide limited regional variation in key parameters except productivity.

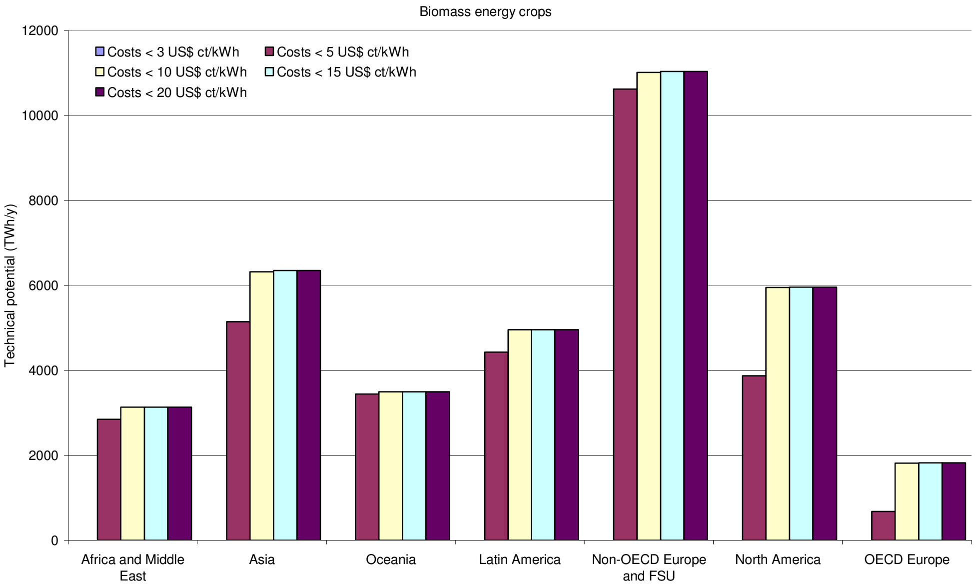

Figure 5: Cost of biomass electricity from energy crops for different cost categories

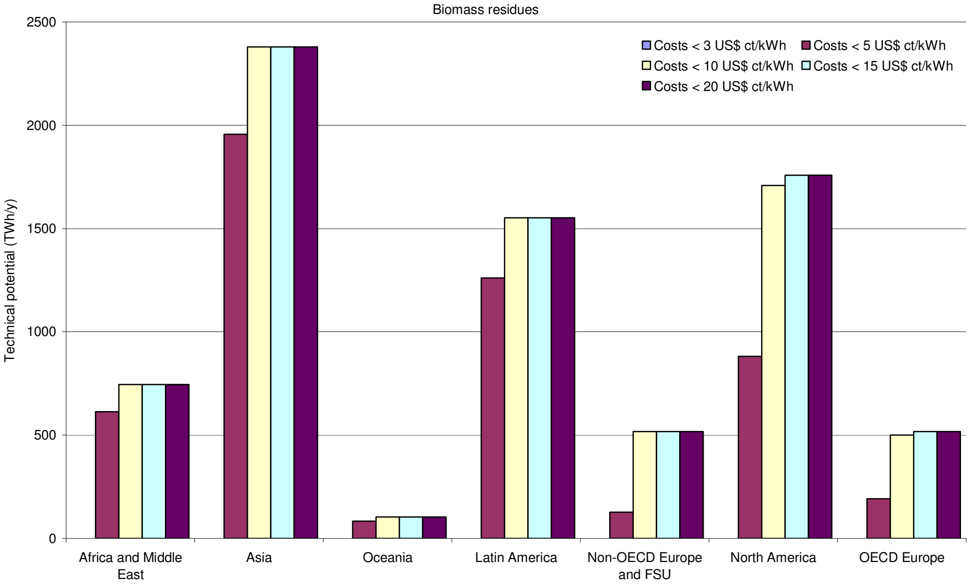

Figure 6: Cost of biomass electricity from residues for different cost categories

3.3 Wind onshore

3.3.1 Technical potential

The use of wind power is increasing rapidly over time. Currently, there is about 74 GWe installed capacity over the world and a further increase is expected. The technical potential of wind onshore depends on wind resources, land available for the installation of wind turbines and the amount and rated power of wind turbines installed per unit of land area (horizontal power density). A typical wind turbine for onshore production is at present around 2 MW of size and has a hub height of around 80 m. With increasing turbine sizes, the hub heights increase and apart from cost reduction, this also gives access to higher wind speeds.

On a global scale there are various studies that have assessed the technical potential of wind energy onshore, e.g. Hoogwijk et al., 2004, WEC, 1993, UNDP/WEC 2000, Fellows, 2000. Although all use a similar approach, there are some minor differences between the approaches. The results obtained by Hoogwijk, et al., 2004 are used here because it is the only study covering the globe, and the results and estimates can be easily converted using more recent numbers. The main assumptions for this estimate are given in Table 7. The wind speed is converted to output in terms of full-load hours using a linear relation. The land available depends on land use change. A suitability factor was applied for each land use type, e.g. assuming tropical forest to be excluded, high availability for agricultural and grassland area and limited availability for regular forest areas. In addition, urban areas and natural reserves have been excluded. At these suitable areas, a power density of 4 MW/ km^2 was assumed. The output of a wind turbine was calculated assuming a wind turbine with a size of 1 MW. Here we assume that in 2050 the wind turbines have on average a higher capacity and therefore a higher hub height (100 m). This results in higher wind speeds and therefore an increased output when assuming a roughness length of 0.1 m of 10%.

The basis of the estimate by Hoogwijk et al., 2004 is the Climate Research Unit (CRU) meteorological data. This database is not specifically constructed for wind energy analyses. The CRU data, however, is currently the only set of globally available data. The CRU wind data are obtained from measurements at 10 m height and extrapolated to hub height. In general higher resolution assessment with correction for terrain, obstacles and roughness will give higher wind energy resource potentials. This was demonstrated for Mexico, Vietnam, North Africa and North China Morroco, Egypt, Madagascar, Mongolia, North and Northwestern China (Hamlin 2007). The respective regional estimates for East Asia are, therefore, very conservative although, for some places, e.g. Honduras, higher resolution data give lower estimates.

3.3.2 Electricity Costs

The future costs of wind onshore are mainly (around 80%) determined by the turbine costs. They therefore depend on the development of wind turbines, the output per turbine or per unit of land area, the size of the wind turbines and the specific investment costs. For the cost distribution, also the data from Hoogwijk 2004 are used for the longer term. The assumptions that have been made are presented in Table 7. The specific investment cost is calculated exogenously in the model based on a scaling factor of 0.3, a wind turbine in 2050 of 3 MW and a reference turbine of 800 kW with a specific investment cost of 1000 $/kW. In addition it is assumed that wind turbines are 80% of the total investment costs.

Table 7: Main assumptions for the technical potential and the cost of wind onshore at a regional level.

	Suitable area (Mha)	Average wind speed (m/s)	Average power density on total area (MW/km^2)[a]	Turbine size (MW)	Specific turbine investment costs ($/kW)	O&M costs (% of total investment costs)
Canada	199	4.1	1.08	3	585	3
USA	248	4.3	1.02	3	585	3
Central America	29	3.3	0.4	3	585	3
South America	82	3	0.26	3	585	3
Northern Africa	55	2.9	0.42	3	585	3
Western Africa	4	1.8	0.01	3	585	3
Eastern Africa	38	2.6	0.28	3	585	3
Southern Africa	3	2.2	0.03	3	585	3
Western Europe	47	4.3	0.58	3	585	3
Eastern Europe	6	3.1	0.22	3	585	3
Former USSR	206	3.4	0.47	3	585	3
Middle East	47	3.1	0.33	3	585	3
South Asia	15	2.3	0.12	3	585	3
East Asia	25	2.4	0.1	3	585	3
South East Asia	0	2	0.01	3	585	3
Oceania	199	3.6	0.91	3	585	3
Japan	1	3.3	0.08	3	585	3
Global	**1204**			3	585	3

[a] This refers to the average installed capacity per total km2 (based on 4 MW/km2 on suitable land areas). To get to the amount of power generated, the power density per grid cell is multiplied by the amount of load hours, which depends on the wind speed in the grid cell.

3.3.3 Results

Figure 8 shows the results of the costs and potential for onshore wind at a regional level. It can be seen that North America has a significant potential. Resources at lowest costs can be found in OECD Europe and Latin America.

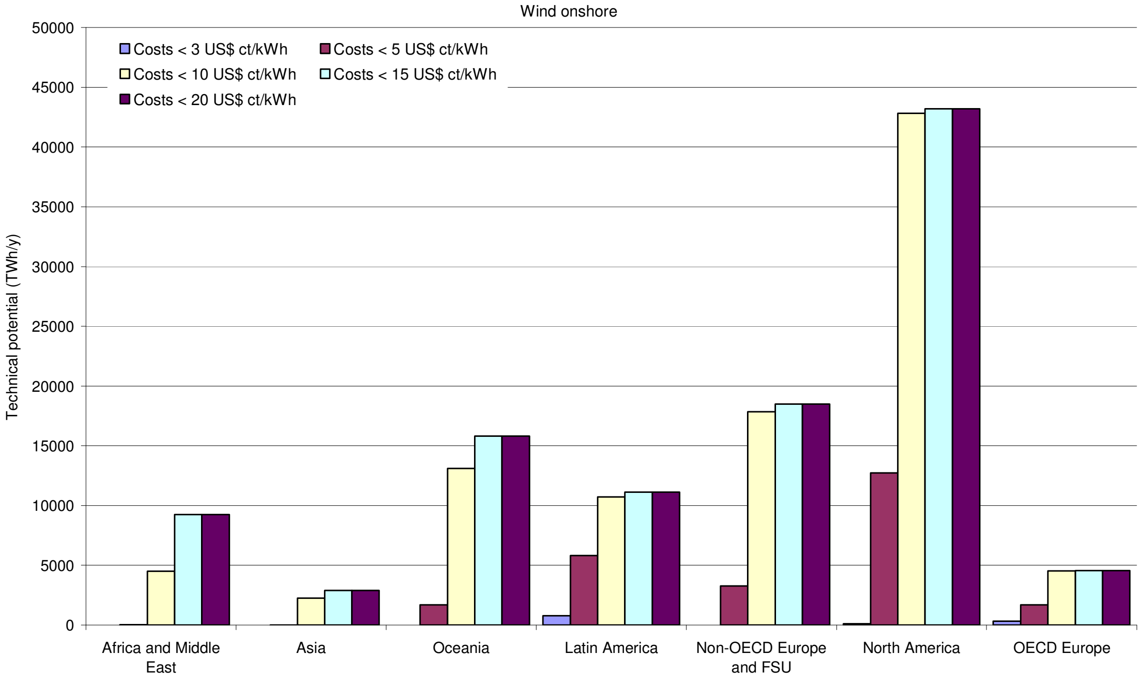

Figure 7: Cost of onshore wind electricity for different cost categories

3.4 Wind offshore

3.4.1 Technical potential and Electricity Costs

Offshore wind power is one of the upcoming renewable energy technologies. By far most of the over 1000 MW currently installed capacity is located in OECD Europe. Technical potential of wind offshore depends on the wind resources offshore, the competition for other functions at sea (e.g. fishery, oil and gas extraction, natural reserves) and the depth of the sea close to the shore. The distance to the shore that is included in most potential assessments is around 40 km and a representative depth that is used as a maximum is around 40 m.

Various studies have assessed the technical potential for offshore wind (e.g. Leutz, et al., 2001, Fellows 2000, Siegfriedsen et al., 2003). However, only Fellows, 2000 presents the assessments on a global level (except Norway and Canada) including cost estimates for the timeframe to 2020. For use in this study, data for Canada have been added (Tampier, 2004) and the data have been corrected for the technological development for 2020 to 2050. This was done by increasing the potential figures from the year 2020 with 30%. This can largely already be achieved by e.g. increasing the power density from 8 MW/km^2 to 10 MW/km^2. The main assumptions from the original study are represented in Table 8.

Table 8: Main assumptions on the technical performance and costs of offshore wind energy. Please note, the total output and costs has been corrected for the longer term

	Value assumed by Fellows, 2000	Unit
Power density	8	MW/km^2
Turbine size	2	MW
Hub height	60	m
Wind farm efficiency	90	%
Distance to shore	5 – 40	km
Maximum depth	40	m
Specific investment costs (pending on the depth)	1433-2324	$/kW

The factor of 1.3 is based on an assumed increase in turbine size and therefore in wind speed at higher hub height and a larger power density. The latter can be assumed because the current power densities are already exceeding the level assumed by Fellows. In addition, it was assumed that the cost can be reduced by 40% because of economies of scale and learning by doing and the increased output per wind farm. The factor 40% is also according to the annual cost reductions assumed by Fellows, 2000. Table 9 provides an overview of planned and installed European offshore wind farms to show that current wind farms have already lower investment costs and higher power density than assumed by Fellows, 2000.

Table 9: Overview of some planed or installed European offshore wind farms. *Source: Van Hulle et al., 2004; IEA, 2005b.*

Name project	Country	Total wind farm area (km^2)	Nr of WT	WT rated power (MW)	Power density (MW/km^2)	WT rotor diameter (m)	Costs M€/MW
Horns Rev	DK	20	80	2	8	80	1.9
Roedsand	DK	23	72	2.3	7	82.4	
C-power	BE	14	60	3.6	15	104	
DOWEC	NL	45	80	6	11	129	
North Hoyle	UK	5.4	30	2	11	80	1.8
Nysted	DK		72	2.3			1.7
Srcoby Sands	UK		30	2			1.8

3.4.2 Results

Figure 8 shows the main results for the technical potential and the cost distribution. High potentials are found in OECD Europe and Latin America. According to the literature included in our assessment, the latter also has high shares of low costs potentials un explored at this moment.

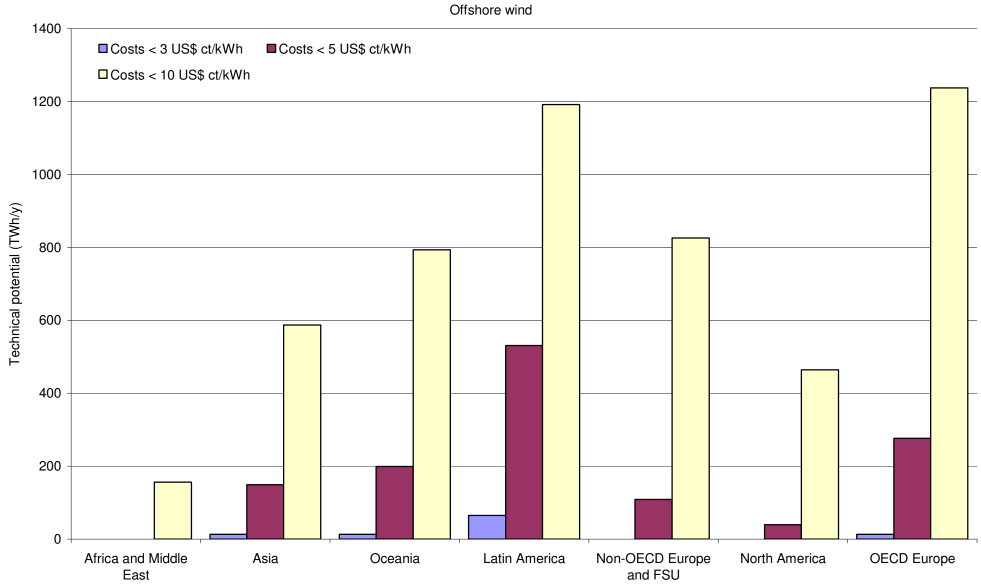

Figure 8: Cost of wind electricity for different cost categories

3.5 Solar PV

3.5.1 Technical potential

The total currently installed PV capacity is 1.7 GWe worldwide (2005) (REN21, 2006). This is limited compared to other renewable energy sources as hydropower or wind. However, the technical potential of solar PV is large as per unit of area the output of solar PV is relatively high compared to other renewable energy sources. The technical potential depends on the land area available and the solar irradiation. On a global scale two studies are available that assess the technical potential of solar PV for both centralized and decentralized applications on the longer term and include the costs of solar PV, Hofman et al., 2002 and Hoogwijk, 2004. In addition, global numbers are presented in the World Energy Assessment (UNDP/WEC, 2000) and by Johansson et al., 2004.

Both Hofman et al. and Hoogwijk consider the technical potential at grid cell level based on solar irradiation, land use exclusion factors and assumptions on future efficiencies. Hofman et al. focus on the year 2020 and do not include all countries. Hoogwijk focuses on the longer term, i.e. 2050. Hoogwijk is slightly more optimistic on the future potential of solar PV, partly because higher efficiencies have been assumed, a higher land use suitability factor is used and no land area is excluded because of limited solar radiation, and it was assumed that the area is completely used for solar modules, e.g. no space factor was included. The figures presented here are based on the data from Hoogwijk but have been corrected with a factor of 0.6 to correct for the more optimistic assumptions compared to other studies, e.g. as no space factor was applied. As a result, the numbers are comparable to values from World Energy Assessment (UNDP/WEC, 2000) and assumptions by Hofman et al., 2002 but are based on the regional distribution based on detailed irradiation data. The original assumptions are presented in Table 10.

3.5.2 Cost of Electricity

The costs of solar PV are also estimated by Hoogwijk, 2004. The cost distribution is assumed to be only a function of the solar irradiation. All technical parameters and costs are assumed to be equal among all regions. The assumptions are presented in Table 10.

Table 10: Main techno-economic assumptions of solar PV scale by Hoogwijk, 2004. Note: these data have been corrected in this study

	Land area	Average irradiation	Average land use factor for centralised PV	Conversion efficiency	Performance factor	Specific investment costs
	Mha	W/m2	%	%	%	$/Wp
Canada	950	93.6	0.50	25	90	1
USA	925	127.4	0.92	25	90	1
Central America	269	175.9	1.38	25	90	1
South America	1761	152.4	0.84	25	90	1
Northern Africa	574	203.1	4.50	25	90	1
Western Africa	1127	184.1	2.10	25	90	1
Eastern Africa	583	195.3	2.71	25	90	1
Southern Africa	676	180.2	2.1	25	90	1
Western Europe	372	108.8	0.69	25	90	1
Eastern Europe	116	124.4	0.63	25	90	1
Former USSR	2183	95.8	0.92	25	90	1
Middle East	592	198.1	3.32	25	90	1
South Asia	509	193	1.92	25	90	1
East Asia	1108	149.4	2.14	25	90	1
South East Asia	442	158.6	0.51	25	90	1
Oceania	838	188.5	3.32	25	90	1
Japan	37	126.4	0.23	25	90	1
Global	**13062**		**1.69**	25	90	1

3.5.3 Results

Figure 9 provides the costs and technical potential of Solar PV based on the studies assessed in this report. Limited cost distribution is assessed and as expected one region, i.e. Africa has by far the largest resources available.

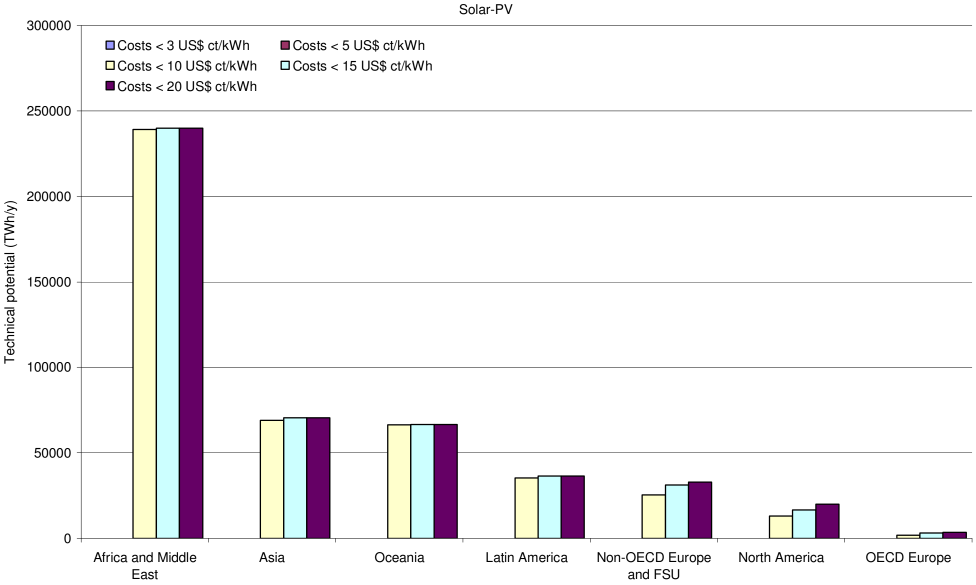

Figure 9: Cost of electricity from Solar PV for different cost categories

3.6 Solar CSP

3.6.1 Technical potential

Concentrating solar power (CSP) plants are categorized according to whether the solar flux is concentrated by parabolic trough-shaped mirror reflectors, central tower receivers requiring numerous heliostats, or parabolic dish-shaped reflectors. The receivers transfer the solar heat to a working fluid, which in turn transfers it to a thermal power conversion system based on Rankine, Brayton, combined or Stirling cycles. Currently, about 600 MWe has been installed worldwide, but various large projects are under construction (Molenbroek, 2006).

The technical potential for concentration solar power on a global scale is only assessed by Hofman et al., 2002. The data cover most of the world, expect Canada, Norway and Switzerland. However, it is expected that the potential for CSP is limited in these three countries. The technical potential for solar CSP for North Africa and the Mediterranean countries is assessed by the German Aerospace Center (DLR) (2005). The technical potential in this study is much higher compared to what has been assessed by Hofman et al., 2002 for these regions (about a factor 20). This is mainly caused by the assumption on the land availability. Both studies have excluded land use functions as urban area, mountainous areas and natural reserves. Furthermore, both studies have limited the areas to areas with high direct irradiation only. In addition to this, Hofman et al., have also excluded agricultural and forestry areas and have assumed that due to socio-geographical reasons, the remaining land area is available for 5%.

To be consistent with the assessments for the other renewable energy sources, in which socio-geographical considerations have been taken into account, it was decided to use the data from Hofman as a basis. However, we have assumed a slightly higher figure on the technical potential for the year 2050 (increase with a factor of 4) because of increased efficiency (e.g. from 18% in 2020 to about 25% in 2050) and because the data by Hofman had been corrected for the capacity factor which we consider not needed. In addition, one may consider a larger availability of areas as the assumption of 5% land area available after already excluding most constraint areas was considered conservative compared to other studies.

The overall assumptions on the technical and economic assumptions are presented in Table 11.

3.6.2 Cost of Electricity

The cost of electricity generated from CSP is assessed to be lower than solar electricity from PV. For the analysis here we have used the cost curves on a regional level as assessed by Hofman et al., 2002, corrected for the longer term. The main assumptions are reported in Table 11. However, for the final figures we incorporated feedback from experts who asserted that the costs of CSP are underestimated and that current projects have cost of around 15 cents per kWh. To take this feedback into account we moved 80% of the potential in the cost category < 5 US$ct/kWh to the category 5 to 10 ct US$/kWh and 20% of the potential in the cost category 5 to 10 ct US$/kWh to the cost category 10 to 15 ct US$/kWh.

Table 11: Overall assumptions on conversion efficiency and costs for CSP in 2020 by Hofman et al. Please note that we have assumed slightly higher factors here for the conversion.

	Value	Unit
Total efficiency	18	%
Investment costs	745- 1120	$/kW
O&M costs	2	% of total investment costs
Space factor	0.28	

3.6.3 Results

Figure 10 shows the costs and potential for Solar CSP at a regional level. As direct irradiation is important, this is mainly found in Africa and this region has by far the largest and together with Oceania the lowest costs.

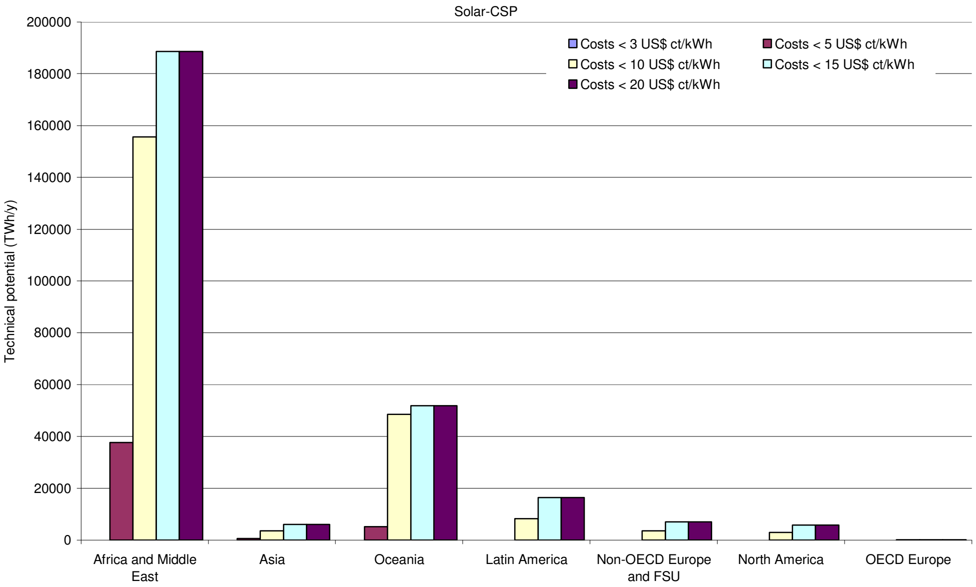

Figure 10: Cost of electricity from Solar CSP for different cost categories

3.7 Solar heating

3.7.1 Technical potential

The potential of solar energy for heating purposes is virtually endless. The mostly used application is passive use in the built environment, the use of solar energy for drying agricultural products and the use of solar water heating. It is difficult and not relevant to assess the total technical potential, as this is mainly limited by the demand for heat. Because of this, the technical potential is not assessed in the literature. However, in order to provide a reference, in this study we have made a rough assessment on the technical potential of solar water heating by taking the assumed available roof area for solar PV applications from Hoogwijk, 2004 and the irradiation for each of the regions. The total potential for solar water heating has been recalculated from the efficiencies assumed in this study. The efficiency for solar water boilers is assumed to be 60% in 2050. The results are summarised in Chapter 4

3.8 Geothermal

3.8.1 Technical potential

Worldwide more than 58 countries are operating in the geothermal sector (Fridleifsson, 2003). Geothermal energy contributed 49 TWh/y for electricity and 51 TWh/y for direct use in 1999.

In comparison to most other renewable resources, geothermal energy has the advantage that the source is consistently available without any restriction. Depending on the temperature of each system, the subsequent geothermal energy utilisation can be divided into two main sectors – direct use and electricity generation. For direct use, e.g. space heating/ cooling, industrial use or balneology, low temperature resources are sufficient. These can be found in many countries at shallow depths. As a consequence of the easy accessibility many countries benefit from this source (see Table 12). However, most of the direct use is only interesting if the resources are situated close to the application. Long distance transportation is an alternative solution, which can be handled with good isolation material.

In contrast to direct use, high temperature sources (above 150 ^{0}C) are required for high-output power generation. These sources are less easily available and an efficient use demands thorough geoscientific investigations (multi-method approach) before designing a power plant. Table 12 is in addition to the direct use representing a ranking of the countries involved in electricity generation from geothermal resources.

Table 12: Direct use and electricity generation of geothermal energy worldwide for 2005. Based on data from IGA, International Geothermal Association (2007)

	Direct use [MWt]	Capacity factor	Electricity (MWe)
Australia			0,2
Austria	352	0,20	1
Canada	461	0,18	
China	3687	0,39	28
Costa Rica			163
Czech Republic	205	0,19	
Denmark	821	0,17	
El Salvador			151
Ethiopia			7
Finland	260	0,24	
France	308	0,53	15
Georgia	250	0,80	
Germany	505	0,18	0,2
Guatemala			33
Hungary	694	0,36	
Iceland	1791	0,42	322
Indonesia			797
India	203	0,25	
Italy	607	0,39	790
Japan	413	0,40	535
Kenya			127
Mexico			953
Netherlands	254	0,09	
New Zealand	308	0,73	435
Nicaragua			77
Norway	450	0,16	
Papua New Guinea			39
Philippines			1931
Poland	171	0,16	
Portugal			16
Russia	308	0,63	79
Slovak Republic	188	0,51	
Sweden	3840	0,30	
Switzerland	582	0,23	
Thailand			0,3
Turkey	1177	0,53	20
USA	7817	0,13	2544

The global useful accessible resource base for electricity production is estimated at 12000 TWh/y (43 EJ/y) (Björnsson et al., 1998). The global potential for direct use is much larger. At present the World Energy Assessment has estimated the global total potential for direct use that could become accessible within 40 – 50 years at 5000 EJ/y. It is unclear whether this figure is more theoretical or also includes geographical constraints.

3.8.2 Cost of electricity

A number of literature sources report a cost range for geothermal power generation of 2-10 ¢/kWh (see Fridleifsson, 2001; IEA, 2005; Stefansson and Fridleifsson, 1998; Bjornsson et al., 1998; UNDP/WEC, 2000). Fridleifsson (2001) expects future costs for geothermal power generation to be in the range of 1-8 US$ct/kWh. In the cost assessment for geothermal power generation, it is assumed that 10 % of the technical potential can be achieved at costs below 5 ¢/kWh in 2050 and that the rest of the potential can be achieved at costs between 5-10 ¢/kWh.

3.8.3 Results

Figure 11 shows the cost and potential at a regional level. Asia and Latin America have the largest potential and also the largest potential at costs below 5 ¢/kWh according to the literature assessed in this study.

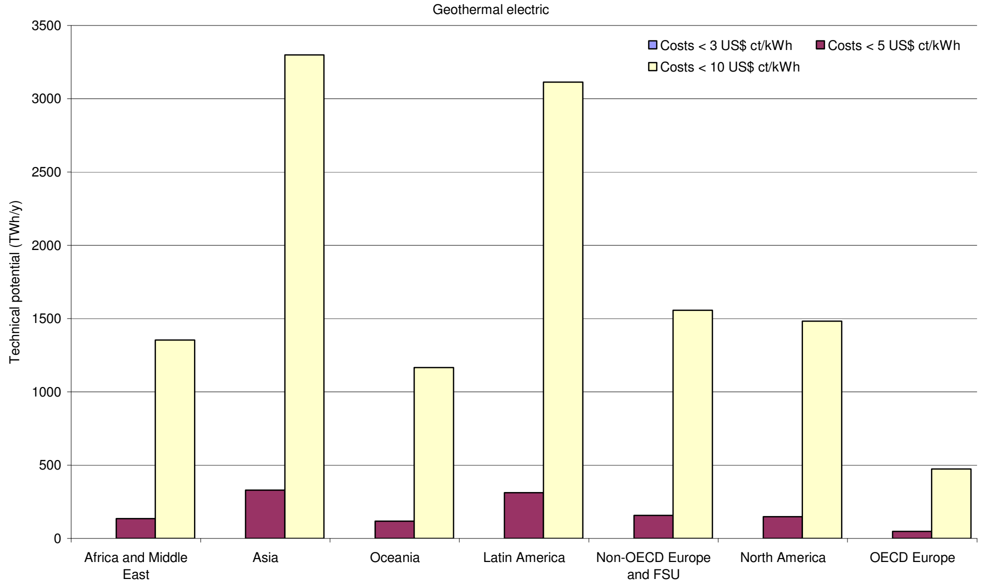

Figure 11: Cost of geothermal electricity for different cost categories

3.9 Ocean energy

The energy that can be extracted from the ocean is divided into OTEC (Ocean Thermal Energy Conversion), wave, tidal and osmotic. The World Energy Assessment presents a total theoretical annual potential of 7400 EJ/y (UNDP/WEC, 2000) of which by far the largest share is from OTEC. Below each of the technologies is described separately. The regional distribution is taken from the area of ocean for each of the regions.

3.9.1 OTEC

Ocean thermal energy conversion (OTEC) produces electricity from the natural thermal gradient of the ocean, using the heat stored in warm surface water to create steam to drive a turbine, while pumping cold, deep water to the surface to recondense the steam.

In total, it is estimated that about 10 TW of power could be provided by OTEC without affecting the thermal structure of the ocean (Pelc and Fujita, 2002). Converting this to annual values this is about 300 EJ/y.

The current cost of electricity generation from OTEC varies between 8 and 24 ¢/kWh (Pelc and Fujita, 2002). Since OTEC is still in the development phase, we assume that only 50 kWh can be achieved at costs below 10 ¢/kWh and 5% of the technical potential at costs below 20 ¢/kWh in 2050.

3.9.2 Wave energy

Worldwide, wave energy could potentially provide up to 2 TW of electricity (Pelc and Fujita, 2002). This can be converted into about 20 EJ/y of final energy. One of the richest nations in terms of potential for wave energy is the UK, where wave energy devices are estimated to be able to contribute more than 50 TWh/yr (Pelc and Fujita, 2002).

The economics of wave energy power, though not yet competitive with fossil fuels, are promising, and the situation is improving with more advanced technology. Costs have dropped rapidly in the last several years, and now companies are aiming for less than 10 ¢/kWh, to as low as 5 ¢/kWh, for the latest designs (Pelc and Fujita, 2002). EU-OEA (2007) mentions that the cost of wave energy depends on the local wave climate. They expect cost per kWh to be in the order of 10 to 23 ¢t/kWh in 2020[2].

Based on the above considerations, we assume that 25% of the technical potential can be achieved at costs below 10 ¢/kWh in 2050 and 75% of potential is can be achieved at costs below 20 ¢/kWh in 2050

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[2] Converted from 10 – 25 €c/kWh

3.9.3 Tidal energy

Total worldwide potential is estimated to be about 500–1000 TWh/yr (1.8 – 3.6 EJ/y), though only a fraction of this energy is likely to be exploited due to economic constraints (Pelc and Fujita, 2002). This value is about a factor 20 lower compared to the values presented as theoretical potential in the World Energy Assessment.

Fridleifsson (2001) estimates current and future costs for tidal to be between 8-15 ¢/kWh. IEA (2005) estimates that cost in 2050 are around 9 ¢/kWh. Based on these literature sources we assume that 75% of the technical potential can be achieved at costs below 10 ¢/kWh in 2050 and the remaining potential at costs below 20 ¢/kWh.

3.9.4 Osmotic power

The global discharge of fresh water to seas is about 44.500 km^3 per year. If it is assumed that 20% of this discharge can be used for osmotic power production, the global potential is roughly 2000 TWhe (7 EJ/y). This is about 10% of the theoretical potential assessed in the World Energy Assessment (UNDP/WEC, 2000).

Present cost estimates made by Statkraft[3] show that osmotic power generation can be developed to be cost competitive with renewable power sources such as bio power and tidal power when commercialized around 2015. We assume that 50% of potential can be achieved at costs below 10 ct/kWh and the other 50% at costs below 20 ¢/kWh in 2050

3.9.5 Results

Figure 12 shows the aggregated results for ocean energy. It can be seen that next to Asia, North America also has a large potential.

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[3] http://192.107.92.31/test/owemes/35.pdf

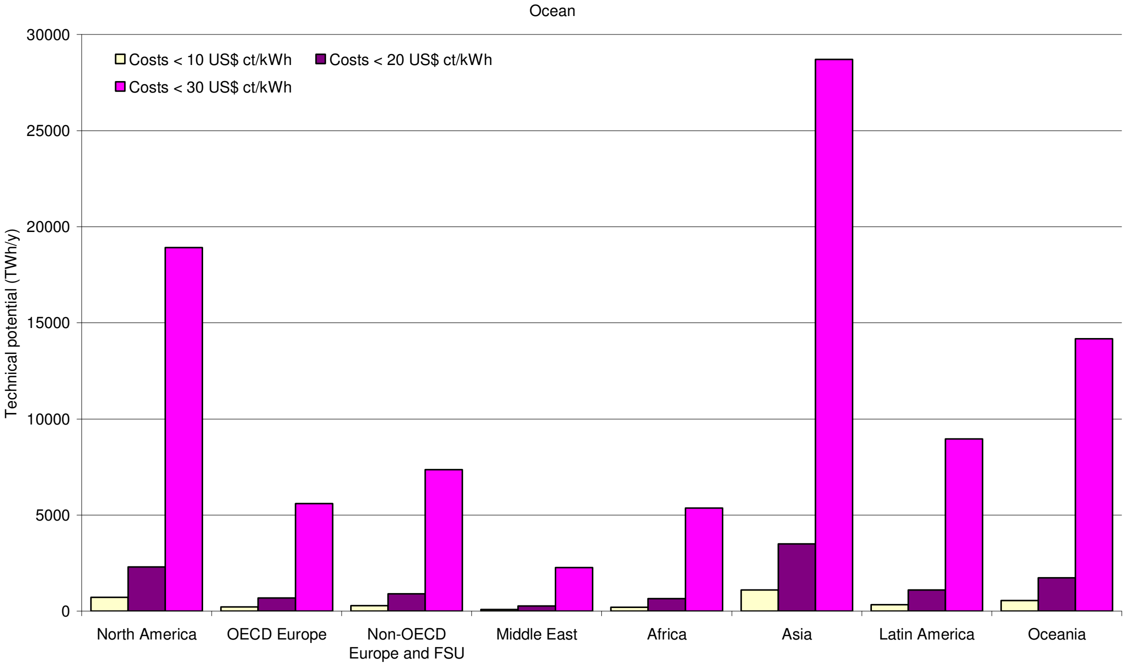

Figure 12: Cost of ocean electricity for different cost categories

4 Summary of the results and conclusions

For reasons of comparison, the current (2002) energy input in the three markets is presented at a regional scale and distributed among the different energy applications (see source: Price et al., 2006).

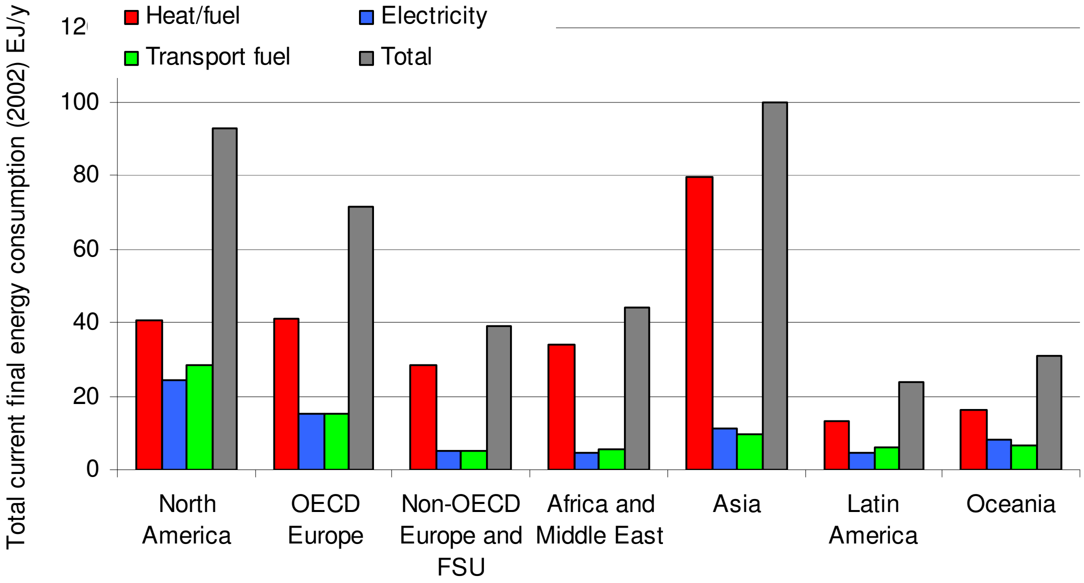

Figure 13: Regional distribution of current energy consumption per fuel type, based on data for 2002 (source: Price et al., 2006)

4.1 Technical potential

Below, in Figure 14 - Figure 20, the technical potential of renewable energy technologies for the long term are presented for each of the regions. Please note the difference in y-axis for the figures. Where possible a more detailed regional disaggregation was used. The total regional figures for all sources are presented in Table 13

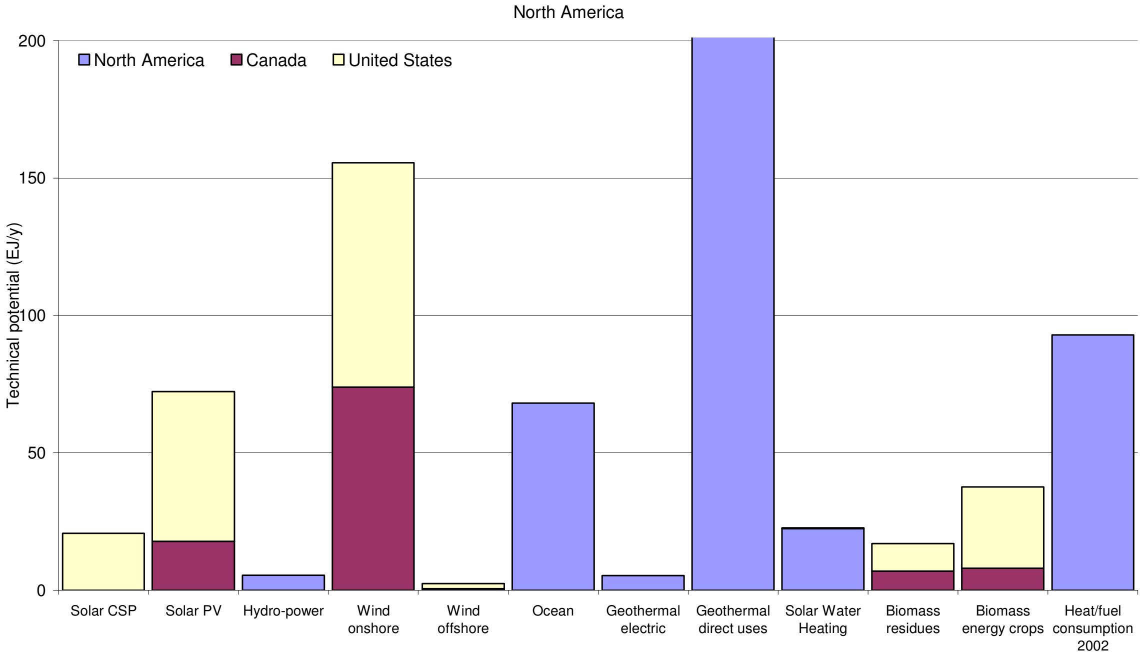

Figure 14: Technical potential of renewable energy sources for North America

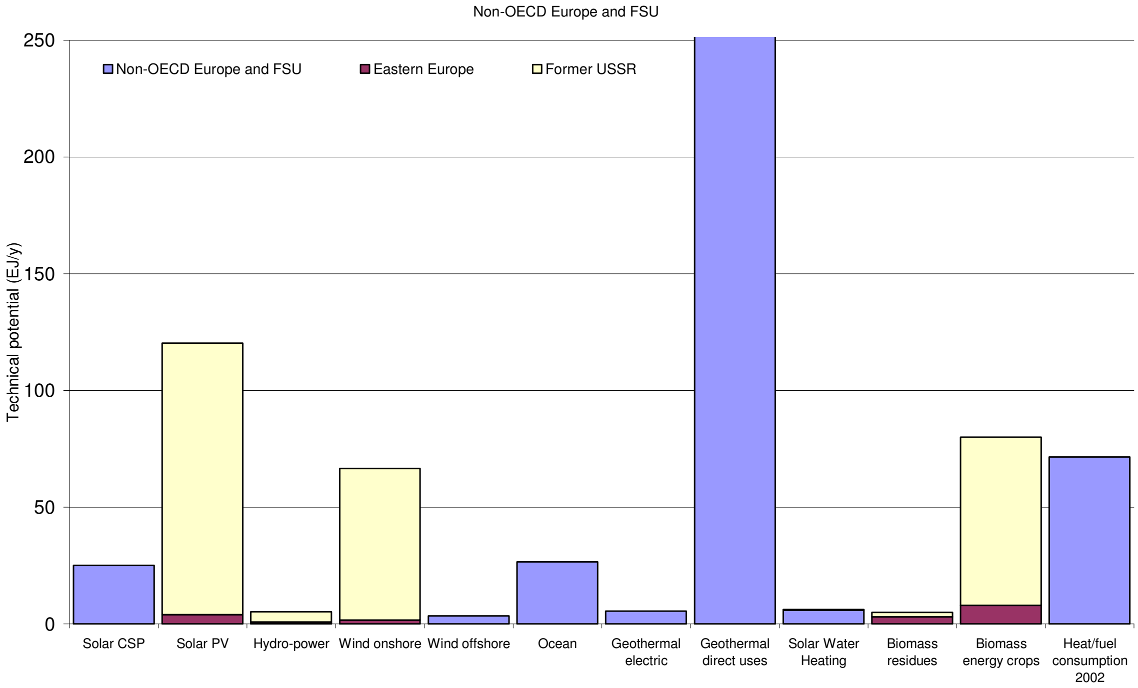

Figure 15: Technical potential of renewable energy sources for Eastern Europe and Former USSR

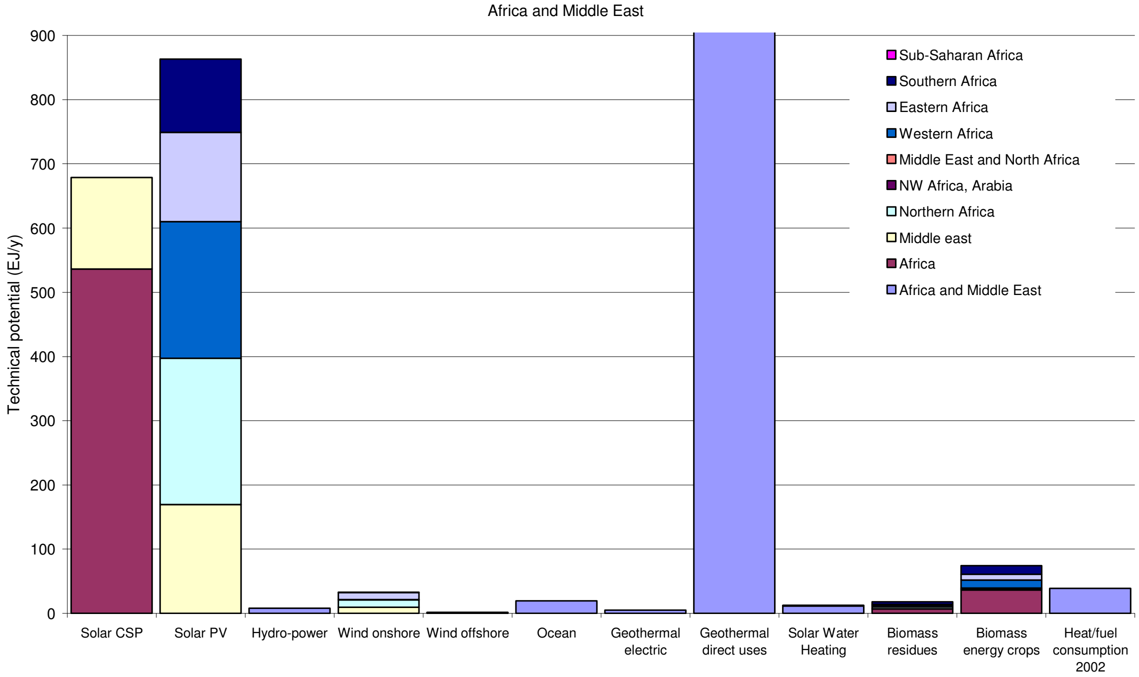

Figure 16: Technical potential of renewable energy sources for Africa and Middle East

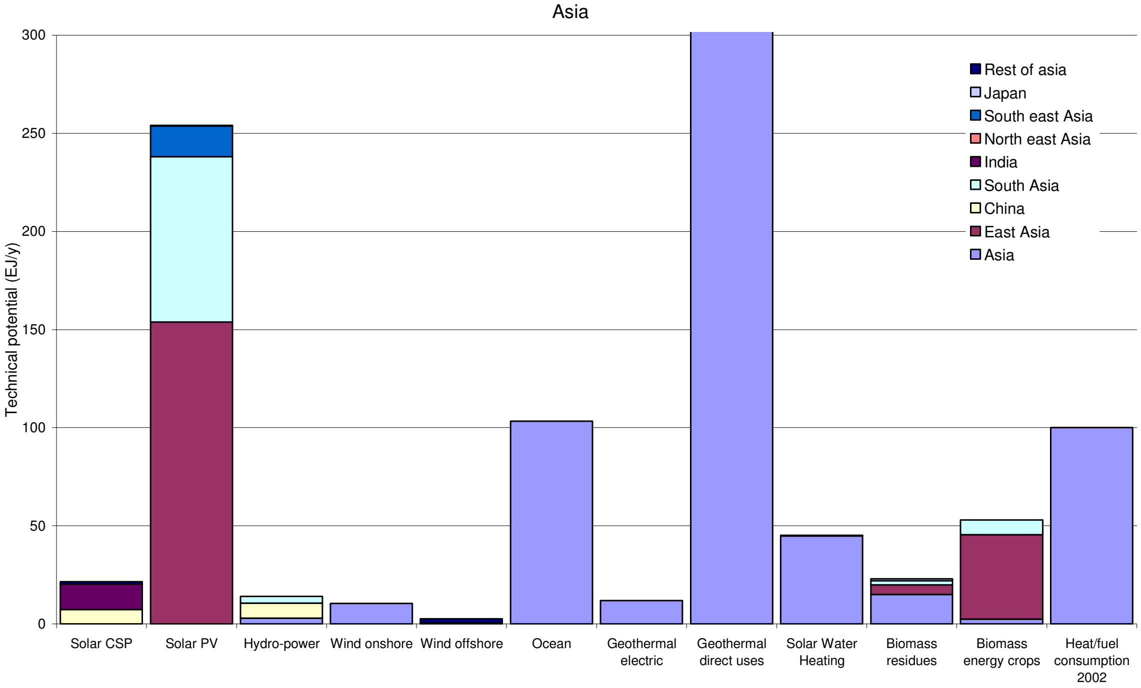

Figure 17: Technical potential of renewable energy sources for Asia

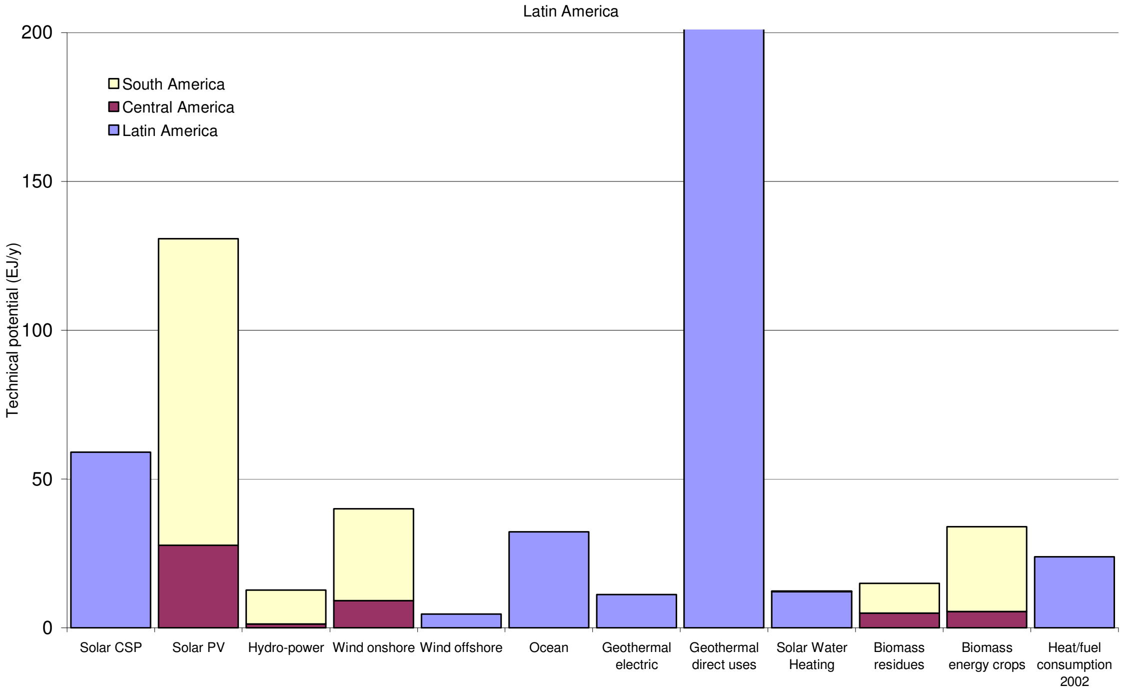

Figure 18: Technical potential of renewable energy sources for Latin America

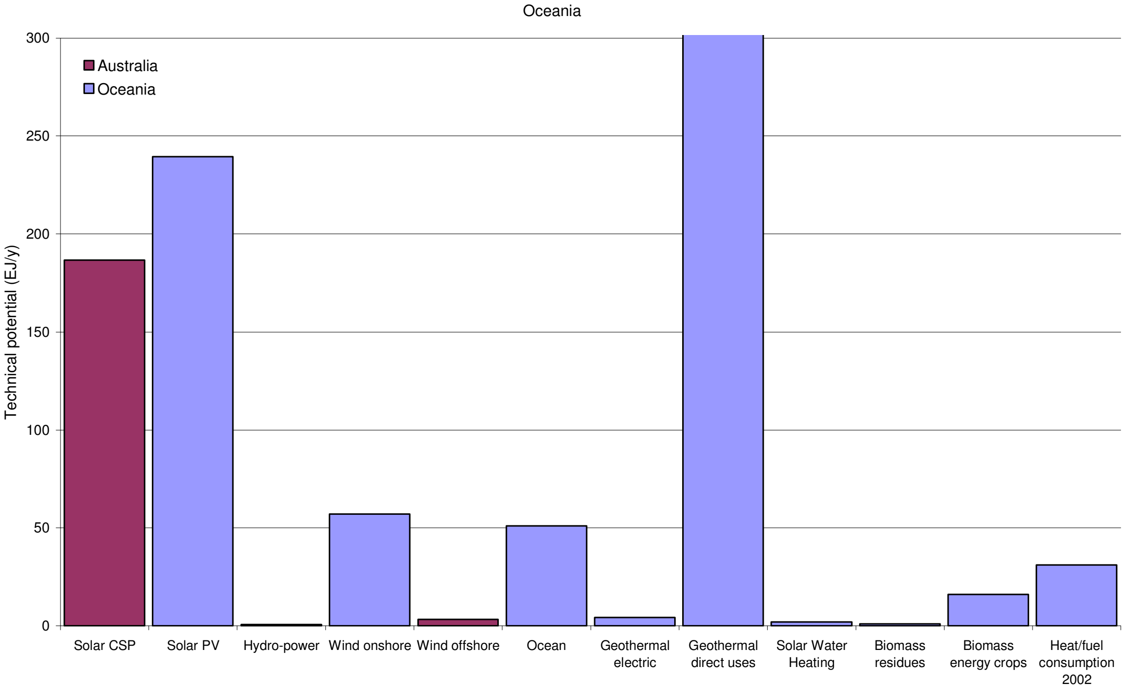

Figure 19: Technical potential of renewable energy sources for Oceania

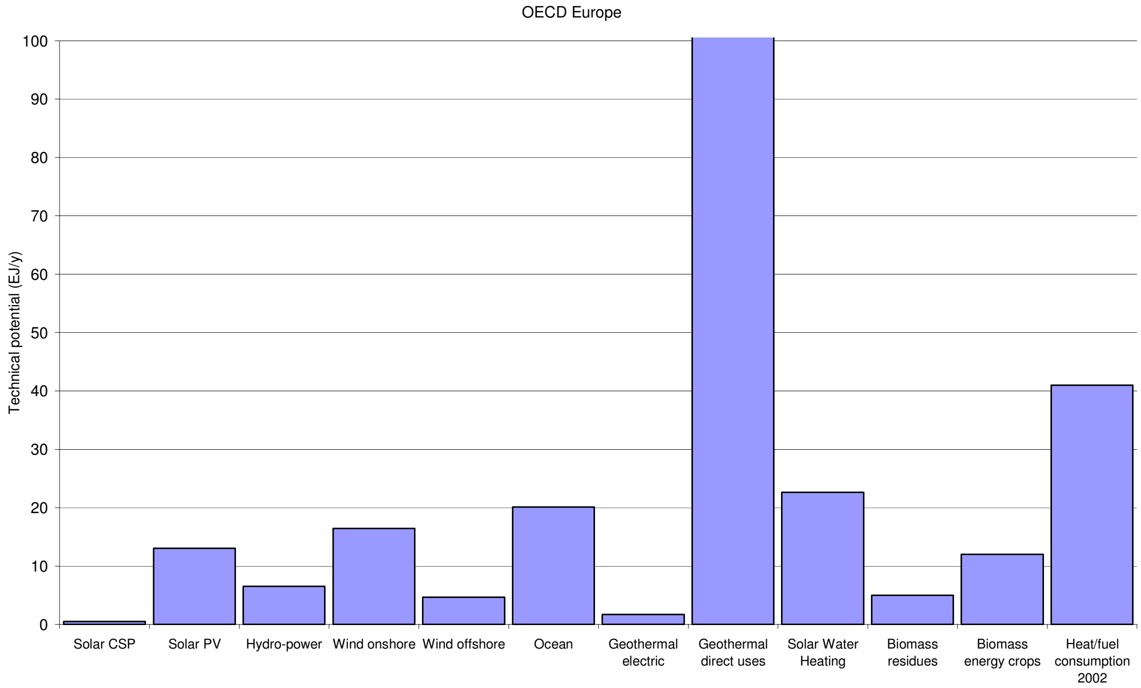

Figure 20: Technical potential of renewable energy sources for OECD Europe

Table 13: The total regional technical potential for renewable energy technologies on the long term as assessed in this study.

	Technical potential EJ/y electric power							EJ/y heat		EJ/y primary		
	Solar CSP	Solar PV	Hydro-power	Wind onshore	Wind off-shore	Ocean	Geothermal electric	Geothermal direct uses	Solar Water Heating	Biomass residues	Biomass energy crops	Current (2002) primary energy supply
North America	21	72	5	156	2	68	5	626	23	17	38	93
OECD Europe	0.5	13	7	16	5	20	2	203	23	5	12	72
Non-OECD Europe and FSU	25	120	5	67	4	27	6	667	6	5	80	39
Africa and Middle East	679	863	8	33	1	19	5	1,217	12	7	38	44
Asia	22	254	14	10	3	103	12	1,080	45	23	53	100
Latin America	59	131	10	40	5	32	11	836	12	15	34	24
Oceania	187	239	1	57	3	51	4	328	2	1	16	31
WORLD	**992**	**1693**	**50**	**379**	**22**	**329**	**45**	**4955**	**123**	**73**	**271**	**402**

4.2 The cost of renewable electricity

For renewable electricity, the technical potential has further been presented for different cost categories as presented in Figure 21. There are only limited studies that provide cost distribution. According to the studies assessed here at costs below 3 ¢/kWh there is only wind energy available, both onshore and offshore. However, studies have indicated that also hydropower and geothermal electricity may be generated at costs below 3¢/kWh. However, due to the lack of data we have not indicated the share of the technical potential at this cost level.

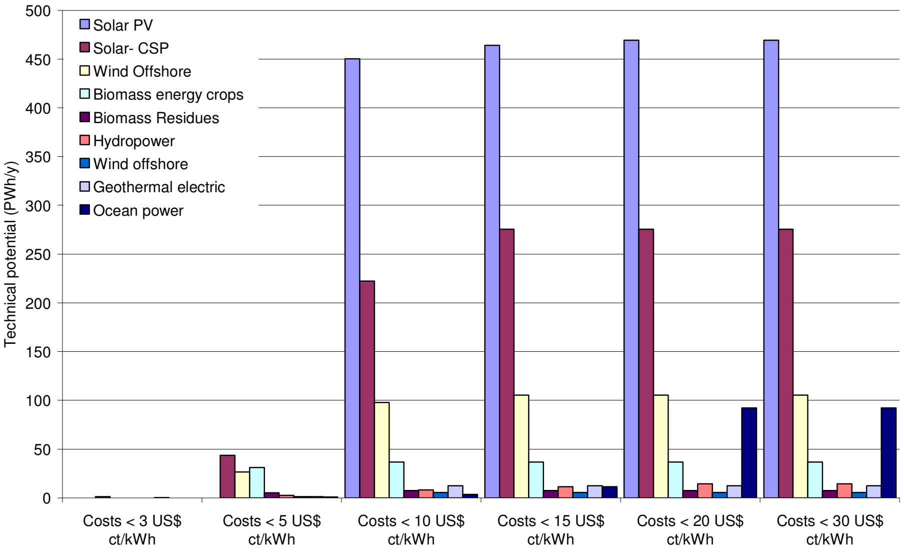

Figure 21: Global potential of renewable electricity sources at different cost categories on the long term

4.3 Discussion and Uncertainties

The data in this study provide insight in the total potential of renewable energy sources. It does not consider additional barriers like additional social obstacles, e.g. or environmental restrictions, e.g. water stress or biodiversity imitations for biomass energy. It is strived to include all technical restrictions that are in place. However, as this study is based on a review of various studies it was not always possible to be consistent in the type of geographical limitations that are included. Some studies might be more restricted on the available areas for certain technologies, e.g. for hydropower whereas other studies only focus on the main measurable parameters, e.g. for geothermal. At this moment there is no study available that consistently analyses the potential for all renewable energy sources using the same potential definitions.

For cost analyses it is even more complicated to make a consistent overview. In this study we have often relied on own expert judgements to estimate the cost distribution due to lack of quantitative data. The cost data should therefore be considered as a first rough indication. In particular the estimates for the lowest costs are uncertain.

4.4 Conclusions

This study presents a literature and expert assessment on the future global and regional technical potential of renewable energy. It turned out that for various sources only limited sources are available and for most global cost distribution is not available. Several additional assumptions were required.

When comparing the renewable electricity sources on a global scale, it can be seen that renewable energy sources can provide several times the current energy supply. Solar power (CSP and PV) is by far the largest renewable energy sources, followed by wind and ocean energy. For solar power North Africa is by far the most interesting region. In North America wind has the largest potential. In Europe there is not one source by far the most interesting. However it has low cost potential by means of hydropower, wind onshore and offshore. Most other regions have a dominated potential from solar power.

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