GLOBAL ENERGY SUPPLY POTENTIAL OF CONCENTRATING SOLAR POWER

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Abstract

This paper presents the global energy supply potential of concentrating solar thermal power (CSP). Based on the DLR-ISIS data for global direct normal irradiance, an estimate is derived for global potential CSP areas and their electricity supply potential. Assumptions are included for land use restrictions and land use efficiency. Including data of global distribution of population distances of centers of CSP electricity supply to human electricity demand are estimated. Performance characteristics of high voltage direct current (HVDC) power transmission is used for analysing global energy supply potential of CSP. Results are shown for different regions in the world, different distances to potential CSP areas and for electric and non-electric energy needs. The outcome clearly shows that CSP has the potential to become a major source of global energy supply. This supports an important assumption in the DESERTEC concept, which assigns large fraction of power supply to CSP.

Keywords: concentrating solar power, solar thermal electricity generation, solar energy resource assessment, solar energy supply potential, desertec

Introduction

Anthropogenic climate change concerns [1, 2] and ongoing depletion of fossil energy resources [3] created a strong momentum for market diffusion of renewable energy sources and their respective conversion technologies. In order to convert solar energy in energy forms usable for human needs there are several thermodynamic pathways.[4] In general, heat, kinetic energy, electric energy and chemical energy can be provided via solar energy conversion. Concentrating solar thermal power (CSP) plants convert direct solar irradiance into electricity.[5] Suitable sites for CSP plants are located all around the world. Nevertheless, CSP is still a niche application for today's global energy supply but installations of new CSP plants show high growth rates.[6] On basis of satellite data, potential CSP sites are classified and a worldwide distribution of high quality potential CSP sites is derived. Taking into account population distribution on earth and high voltage direct current (HVDC) power transmission, the global energy supply potential of CSP technology is estimated in the following. In addition to CSP, recent research indicates that large scale photovoltaic (PV) power plants in MENA region may lead to comparable electric and economic characteristics referring to conventional CSP plants.[7]

Geographic distribution of direct normal irradiance

Radiation data used in this work are based on the DLR-ISIS (Irradiance at the Surface derived form International Satellite Cloud Climatology Project (ISccp) data) of the German Aerospace Center (DLR).[8, 9] The DLR-ISIS data is subdivided into a 280 km x 280 km equal area grid on grid boxes of 72 latitude steps of 2.5°. The used dataset for the direct normal irradiance comprises monthly values for 1984 to 2004. The annual 21 year mean value for every grid box is refined on a 1° grid by applying distance weighted mean values of the DLR-ISIS data in order to enable a correlation to the population density.[10]

Solar resource maps for CSP assessment are visualised by direct normal irradiance (DNI) per area and year, normally in units of kWh/m²/y which are suitable to CSP requirements. The unit kWh/m²/y describes the sum of solar energy irradiated on the area of one square meter in a year. The global distribution of DNI shown in Figure 1 predominantly overlaps with the deserts of the world (data for Greenland have to be ignored due to satellite constraints for regions in the far North).

The largest areas in the world for CSP use are located in North Africa, South Africa, Middle East, India, Australia, North America and South America. Different from most natural resources, solar energy in form of direct normal irradiance is allocated around the world and nearly all populated areas may be connected to the areas of excellent solar conditions.

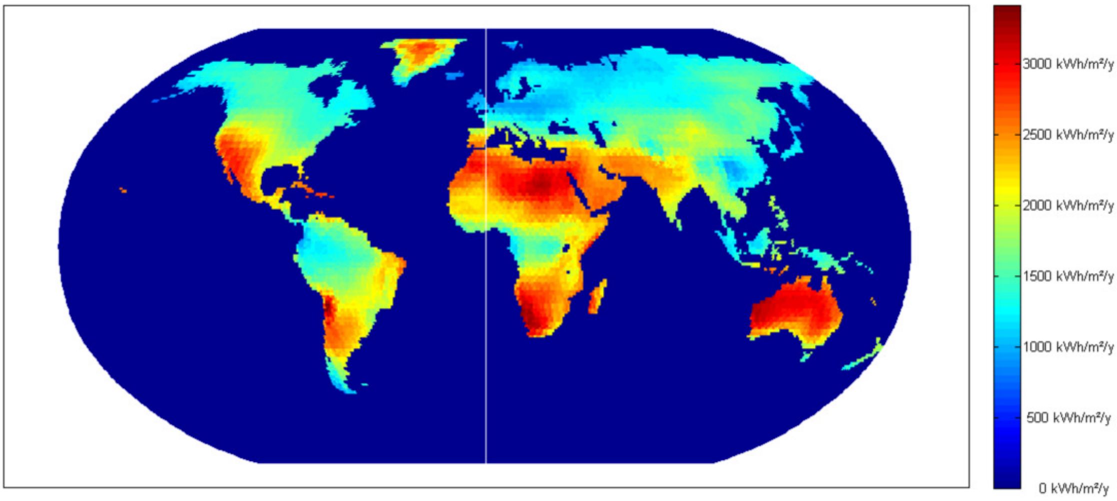

Figure 1: Global direct normal irradiance. Data are based on DLR-ISIS [9] of German Aerospace Center (DLR) and are derived from International Satellite Cloud Climatology Project. Areas of at least 2000 kWh/m²/y are needed for CSP plants due to economic constraints.[12]

Geographic distribution of world population

The energy supply potential of CSP can be assessed if the geographic distribution of the world population is taken into account. The Center for International Earth Science Information Network (CIESIN) of the Columbia University, New York, makes data available about the global population density. The data chosen for the investigation of this work are in the resolution of a 1° grid, suitable to the recalculated radiation data. The dataset is now available in the third version, “Gridded Population of the World Version 3” (GPWv3), updated to the year 2000 with a world population of 6.05 billion people.[11] The population density data are depicted in Figure 2.

High and very high population densities shown in Figure 2 are given for India, China, parts of South East Asia, Japan, most parts of Europe, a few parts of North America, the Caribbean and generally for islands. A comparison of the Figures 1 and 2 illustrates, that most of the areas with excellent solar resources exhibit a low population density, for instance in deserts like Sahara desert, Namib desert or Western Australia.

Global energy supply potential

The global distribution of DNI (Figure 1) is used to identify potential CSP sites. The solar radiation quality limit of potential sites is set to a direct normal irradiance of at least 2000 kWh/m²/y due to economic constraints.[12] Today’s projects are commercially developed for at least 2000 kWh/m²/y. Nevertheless, future plants may be built in areas of at least 1800 kWh/m²/y, as lower costs for the solar field, would improve profitability. CSP plants at sites with restricted access to water can be operated by using dry air cooling towers which slightly lowers the overall conversion efficiency. The identified coherent potential CSP areas range from a minimum of about 9,000 km² (which was set to the lower limit) to more than 31 million km² (before exclusion of not suitable sites for CSP plants). The regional aggregation of the single sites is summarised in Table 1.

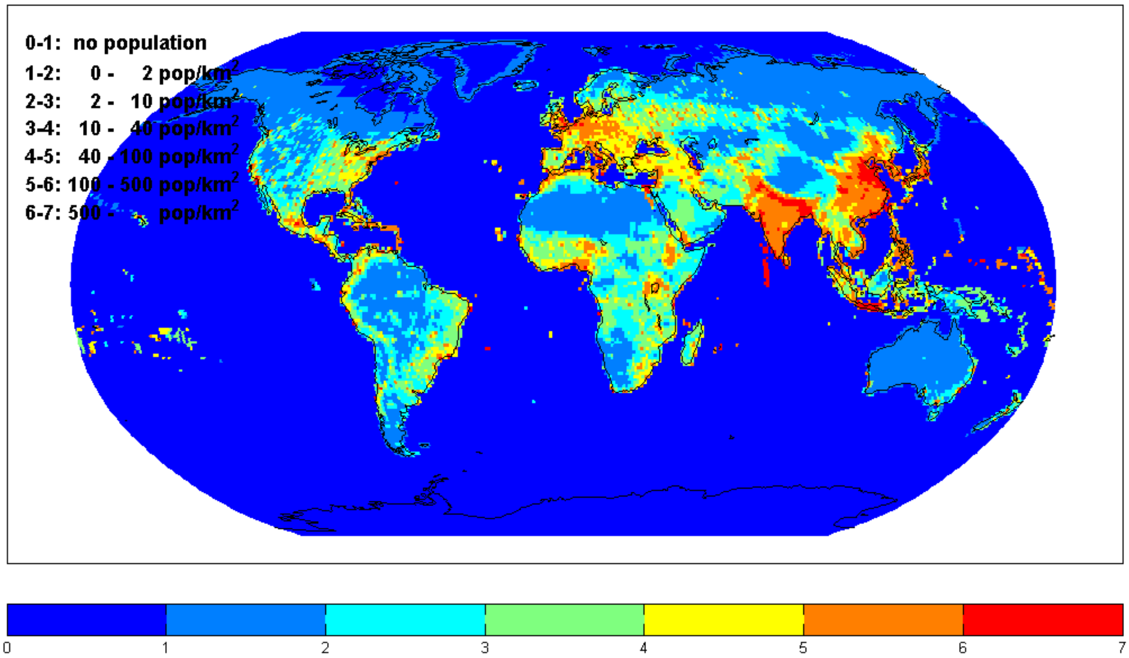

Figure 2: Global population density for the year 2000. Areas coloured yellow show a high and orange and red a very high population density. The unit for population density is persons/km². Data are provided by Center for International Earth Science Information Network (CIESIN).[11]

Electricity generated in CSP areas can be transported via high voltage direct current (HVDC) power lines over several thousands of kilometers.[13] HVDC transmission losses can be kept in the range of 3%/1000 km plus HVDC terminal loss of 0.6% per inlet and outlet station. Power transmission over distances up to 3,000 km counts for transmission losses of not more than 10%, whereas high voltage alternating current (HVAC) would cause power losses higher than 20% and investment cost per km significantly higher than HVDC power lines.[13] It should be noted that if generation costs of electricity are low, the increase in transmission cost will not be significant.

Identified potential CSP areas are shown in Figure 3. Regions which might be in reach of respective CSP areas by applying HVDC power lines for electricity transmission are indicated by surrounding areas of multiples of 900 km. Power lines might not be built in the shortest possible distance between centers of demand and supply due to land restrictions, therefore multiples of 900 km are taken instead of 1000 km. The energy supply potential of CSP can be assessed if the geographic distribution of the world population is taken into account. Population living close to CSP areas and within multiples of 900 km is shown in Figure 4 and Table 2. A regional breakdown of CSP supply potential shows that North and South America could be completely supplied within 2,000 km of potential CSP areas and the world region Africa/ Europe/ Asia could power 3.5 billion people via CSP within 2,000 km. As shown by Figure 4 and Table 2 energy supply potential of CSP technology for the world population living within 3,000 km distance to potential CSP areas exceed 90% of world population.

Power potential for electricity supply is calculated assuming an exclusion of 30% of the area which fulfill the solar quality conditions but not land availability constraints, e.g. natural resorts, slopes, water, shifting sands, human dwellings, roads, agricultural use, etc. In these potential CSP areas it is assumed that the solar radiation potential accounts for a respective power potential by applying a land use efficiency of 10%, i.e. for generating one MWh_{el}/y at a DNI of 2000 kWh/m²/y 5 m² suitable ground is needed.[12] Higher exclusion of area or lower land use efficiency, respectively, would lead to lower power potential of CSP areas. A similar assessment of global potential of CSP presented in this conference shows land use efficiencies ranging between 2.5% and 20% but calculates with an average land use efficiency of 4.5% for recently built CSP plants and higher land exclusions.[14] Total global power potential of CSP estimated in this paper and by Trieb et al [14] differs by a factor of four due to a stricter land exclusion and lower assumed land use efficiency. For the general estimate of energy supply potential of CSP technology in this paper a transfer of today's CSP research results to the market is expected in the years and decades to come.

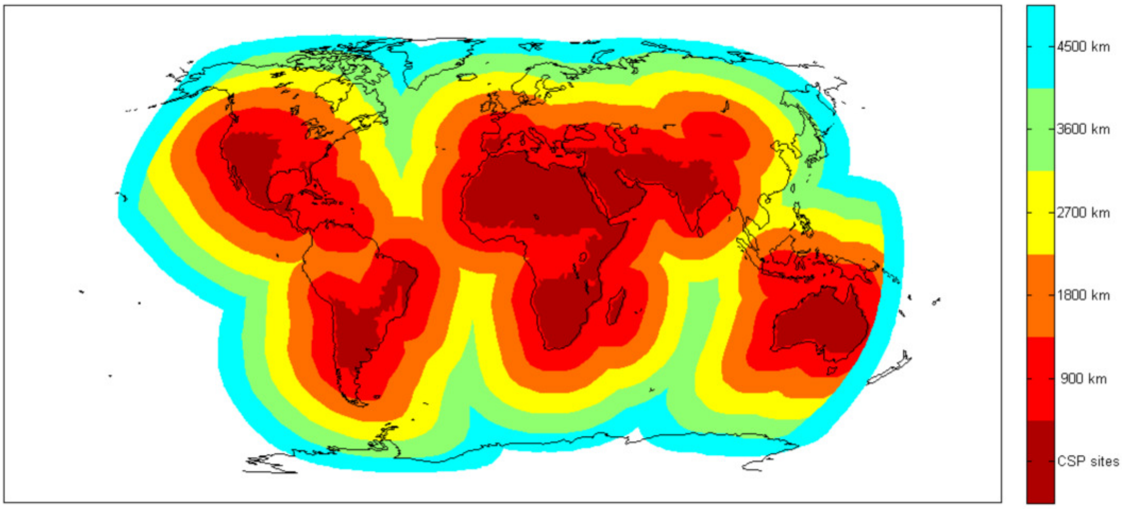

Figure 3: Global potential CSP areas (dark red) with enlarged boundaries within reach of HVDC power lines. Potential CSP areas are shown classified by a direct normal irradiance better than 2,000 kWh/m²/y and larger than 9,000 km².

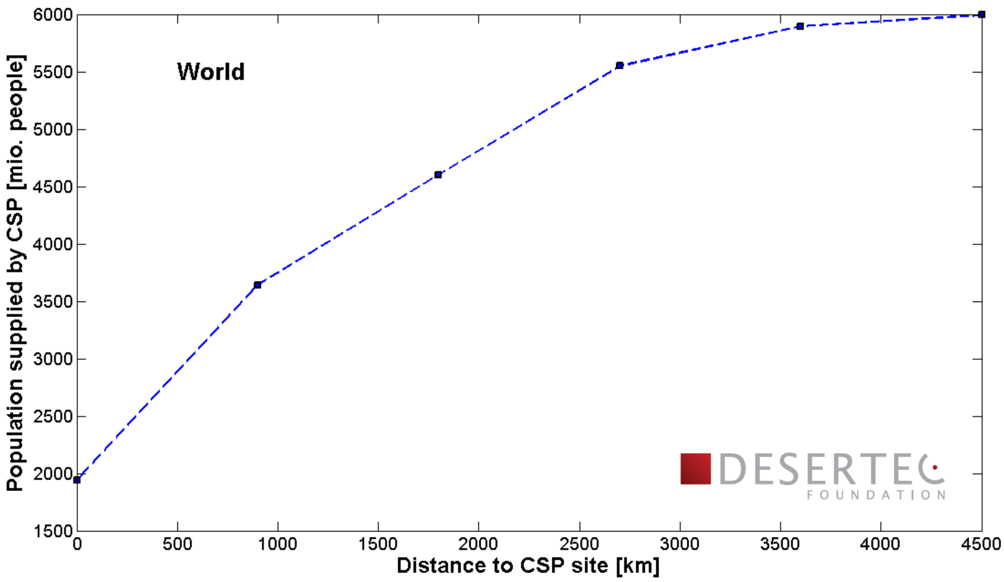

Figure 4: Energy supply potential of CSP in the world versus distance to CSP sites. Data for world population of 6.05 billion people are for the year 2000.[11]

	potential CSP area [mio km²]	solar radiation potential [1000 TWh_{rad}/y]	average DNI quality [kWh/m²/y]	power potential [1000 TWh_{el}/y]
North America	4.9	11,500	2410	1,150
South America	5.9	13,500	2330	1,350
Africa/Europe/ Asia	32.3	73,500	2600	7,350
Pacific	6.8	23,000	2950	2,300
Total	**49.9**	121,500		12,150

Table 1: Global aggregated potential CSP area, solar radiation potential, average DNI quality and power potential limited to sites of at least 2000 kWh/m²/y DNI. 70% of all identified areas are classified as potential CSP areas. Land use efficiency of 10% is assumed.

	potential CSP area [mio km²]	power potential [1000 TWh_{el}/y]	site [mio. pop]	900km [mio. pop]	1,800km [mio. pop]	2,700km [mio. pop]	3,600km [mio. pop]	4,500km [mio. pop]
North America	4.9	1,150	160	400	460	470	470	470
South America	5.9	1,350	160	310	360	370	370	370
Africa/ Europe/ Asia	32.3	7,350	1,610	2,730	3,510	4,400	4,840	5,120
Pacific	6.8	2,300	20	190	260	430	740	1,800
Intersection Asia/Pacific			0	0	0	130	520	1,750
Total	**49.9**	**12,150**	**1,950**	**3,630**	**4,590**	**5,540**	**5,900**	**6,010**

Table 2: Segmentation of world population into world regions and their distance to potential CSP sites. According to figures and tables in this section 900 km enlargement steps of the potential CSP areas are taken into account. Due to an intersection of potential supply areas out of Asia and the Pacific rim the population of the intersection area is given.

Contribution potential of CSP to global energy demand

According to Table 1 global aggregated CSP energy supply potential adds up to about 12 million TWh_{el}/y. Annual energy needs for electric and non-electric supply are in the world in total 16,100 TWh_{el} and 76,500 TWh_{th}, which relates to 2.7 MWh_{el}/capita and 12.7 MWh_{th}/capita in the world and 6.7 MWh_{el}/capita and 26.5 MWh_{th}/capita in Europe, respectively, based on data for the year 2000.[15] Annual growth rate of primary energy demand is expected to be 1.6% p.a.

Based on the CSP energy supply potential (Table 1) and the energy demand for human needs supply coverage of CSP can be estimated. Several assumptions have to be incorporated. HVDC power lines could interconnect centers of CSP supply and energy demand. Power loss of HVDC power transmission is included and accounts for 3%/1000 km plus HVDC terminal loss of 0.6% per inlet and outlet station. Taking all assumptions into account electricity demand of world population on European consumption level would be approximately 44,000 TWh/y.[10]

Noteworthy, if all humans lived at European electricity consumption level, 0.4% of the electricity potential of worldwide potential CSP area could supply more than 90% of the world population connectable per grid to deserts. In every world region (Table 1) this number stays well below 0.7%, including only sites of a radiation quality of at least 2000 kWh/m²/y in the calculations. It would be possible to supply 6 billion people with nearly threefold the electricity generation of today and using only CSP. Every other renewable energy source, i.e. wind power, hydro-electric power, photovoltaic power, geothermal power and biomass, at sites not used for CSP generation would even improve access to energy around the world.

A similar consideration can be done for non-electric energy needs. The specific non-electric energy demand is higher than the specific electricity demand. Non-electric energy is normally used in form of thermal energy stored as chemical energy. In principle electricity could be used for such purposes via converting it into hydrogen. Energetically this would not be favourable due to the low efficiency of the total process chain of about 50%.[16, 17] An electricity-to-hydrogen conversion efficiency of 50% including transport is an estimate of losses, reality may be better. Direct use of electricity for heat pumps, electrical heating, electric vehicles, et cetera, is very likely to be a better alternative due to efficiency criteria and the scenario of broad hydrogen use can be considered a worst case assumption. Because of economic reasons electricity would be transmitted to the destination region and converted in hydrogen at the place of demand. The non-electric energy demand of the world population is assumed to be on the today's European energy consumption level of 26.5 MWh_{th}/capita/y. All other assumptions are identical to the calculations of the electricity demand in the paragraphs above. Taking these assumptions into account including those for HVDC power transmission, non-electric energy demand of world population on today's European consumption level would be approximately 340,000 TWh_{el}/y.[10] It should be noted that a large fraction of this energy amount is used for today's vehicles powered by combustion engines and for heating purposes of houses thermally inadequately insulated. In general, improved efficiency standards would significantly decrease energy demand.

Noteworthy, 2.8% of the electricity potential of worldwide potential CSP areas would be sufficient to supply more than 90% of the world population connectable per grid to deserts with non-electric energy. In every world region (Table 1) this number stays well below 5.0%, including only sites of a radiation quality of at least 2000 kWh/m²/y in the calculations. Again, every other renewable energy source improves the access to energy around the world. The contribution of non-concentrating solar heat collectors, geothermal and biomass energy supply could be significant, as they provide thermal or chemically stored energy, in contrary to CSP, which has to be converted in electricity, transmitted and then in worst case scenario converted in chemical energy via hydrogen.

Depending on future growth rates of the world population, the CSP supply coverage of 0.4% for electric needs and 2.8% for non-electric needs has to be adjusted to the stabilized future world population.

The broad implementation of further renewable energy sources, i.e. photovoltaic power, wind power, hydro-electric power, geothermal power, biomass and ocean power, complemented by energy efficiency improvements, renewable energies can supply world population with much more energy ever needed – in an economically, ecologically and socially sustainable way. Today's global energy problems, the scarcity of resources and the damage to the world climate could be solved once and for ever by renewable energy technologies. Fossil energies are not needed, except for niche applications. Nuclear fission and fusion energy are not needed at all.

DESERTEC project for the EUMENA region

In deserts, clean power can be produced by CSP plants in a truly sustainable way and at any volume of conceivable demand. Power can be transmitted with low losses by HVDC power lines to more than 90% of the world‘s population. This gives the deserts a new role: Together with the many other forms of locally accessible renewable energy sources the newly utilised deserts would enable us to replace fossil fuels and thus end the ongoing destruction of our natural living conditions.

To put this into practice, countries with deserts, countries with high energy demand and countries with technology competence should cooperate. Particularly for the Mediterranean riparian regions of Europe, the Middle East and North Africa (EUMENA), this is an opportunity to form a community for energy, water and climate security - with some similarities to the Community of Coal and Steel established in Europe some 60 years ago. With the political will, EUMENA countries could now launch an Apollo-like DESERTEC project (Figure 5), to bring humankind back into balance with its environment, by putting deserts and technology into service for energy, water and climate security. This would be an important step towards creating a truly sustainable civilization.[18]

Leading German companies led by Münchner Rück have recently established the DESERTEC Industrial

Initiative to start the realization of the DESERTEC project. The initiative is advised by the German Aerospace Center (DLR) and the DESERTEC Foundation and is supported by several German Ministries. The outcome of this initiative could be the starting point of one of the largest infrastructure projects in EUMENA ever undertaken. Several regions in the world with similar characteristics could follow the DESERTEC path of energy, water and climate security, in particular Southwest of the US/ Mexico, South America, Southern Africa, Central Asia and the Pacific rim.

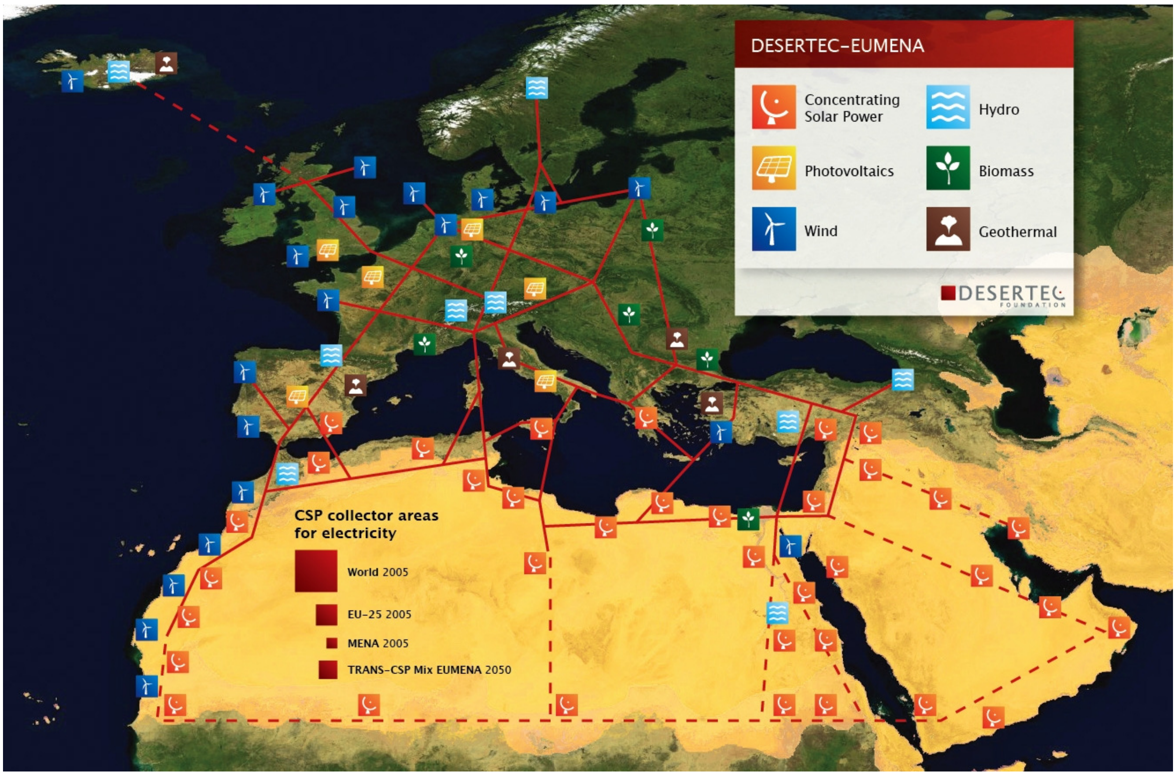

Figure 5: Concept of the DESERTEC project based on all major renewable energy sources and the interconnection of centers of energy supply and centers of energy demand by HVDC power lines. The symbols for power sources and lines are only sketching typical locations.[18]

Conclusions

Based on global datasets for direct normal irradiance and population density the energy supply potential of concentrating solar power was estimated. There are clear indications that 90% of world population connectable per grid to deserts could be supplied only by CSP via HVDC power lines not longer than 3,000 km. Less than 0.4% and 2.8% of the electricity potential of worldwide potential CSP areas would be required for electric and non-electric energy needs, respectively, on the today's European energy consumption level. Therefore, only a small fraction of 0.4% to 2.8% of global CSP energy supply potential would be needed to cover global energy demand. In reality an even smaller fraction will be needed due to the energy supply contribution of all locally installed renewable energy technologies and energy efficiency improvements. The DESERTEC concept for the EUMENA region is close to become a real interregional project for energy, water and climate security and might act as a blueprint for other regions in the world.

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