Two scenario's for a solar world economy

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Abstract: Solar energy using Concentrating Solar Power (CSP) technology will become the most abundant source of renewable energy. The technology and the economics of CSP are explained. An overview is given for the deployed CSP capacity, the CSP capacity which is currently being built, and the planned capacity. We make the following assumptions: (1) The learning curve for CSP technology will finally lead to a price for the solar collector field which is half of the most competitive CSP technology that is available today; (2) It becomes technically and economically feasible to produce some sort of solar fuel out of the concentrated solar heat. The investment that is needed for a CSP capacity which is able to meet the global demand of electricity as it was in the year 2003 amounts to 18% of the Gross Domestic Product (GDP) of one year of the whole world. At a 30% growth rate per year until the 1% GDP level is reached, followed by a constant growth, the 2003 consumption level would be met by solar electricity in the year 2047. This power production rate would be reached already in 2027, when CSP-investments would be made at the 1% GDP level immediately.

Keywords: Concentrating Solar Power; CSP; energy scenario; energy strategy; solar energy.

Reference to this paper should be made as follows: Evert du Marchie van Voorthuysen (xxxx) 'Two scenario's for a solar world economy', *Int. J. Global Environmental Issues*, Vol. x, No. x, pp.xx–xx.

Biographical note: Evert Henrick du Marchie van Voorthuysen (The Hague, The Netherlands, 1942) performed his PhD in 1975 at the University of Groningen, The Netherlands in experimental nuclear physics. He was a teacher at the Nautical College in Delfzijl, The Netherlands and the University of Groningen. He performed research in nuclear physics, solid-state physics and fundamental quantum mechanics in Groningen and Baltimore (USA) until 2003. Starting in 2003, he specialises in the technique and the economics of Concentrating Solar Power and in energy policy. He is founder and Director of GEZEN Foundation for Massive Scale Solar Energy.

1 Introduction

Energy is the basic food for human society. If the supply of energy would suddenly stagnate, human society would collapse, in the same way as an individual human being would starve when the food supply would stop. Our planet is sick, because human society uses the wrong kind of energy: easily mineable oil, coal and gas, in the same way as an individual human being would become sick when he would only eat sugar and fat. The Earth has a temperature, and we know very well that the origin of the intensifying fever our planet is suffering from. The fever of the Earth is called ‘climate change’. It is caused by the increasing amount of greenhouse gases in the atmosphere, carbon dioxide being the most important of them. The massive consumption of coal, oil and gas has already brought about a 35% increase of the CO_2-content in the atmosphere, and this content is rising fast.

Mankind has the task to stabilise the fever of the Earth before it becomes lethal. Four different solution strategies are widely proposed to perform this task:

- increase of energy efficiency and energy saving
- massive introduction of renewable energy technologies
- coal gasification together with CO_2-sequestration
- massive (re)introduction of nuclear energy.

There is a widely felt common understanding that the solution strategies at the top of the list are preferable to those lower down.

- Practically, all usage of energy involves environmental pollution, a car running on solar electricity still makes noise. Society should be reorganised in a clever way, with maximum prosperity per person using the least amount of energy. This is in contrast with the example given by the lifestyle in American movies.

The energy efficiency in houses and buildings can be increased tremendously. The energy efficiency of motor vehicles and household appliances can be substantially improved, but that should not lead to a more wasteful usage of them. In the Organisation for Economic Co-operation and Development (OECD) countries and in the countries of the former Soviet Union the absolute consumption of energy can be decreased together with a further increase of prosperity.

- In the so-called Third World the highly necessary decrease of poverty cannot be achieved without a large increase of the energy consumption. The booming economies of China and India bring about a rapid increase of the global energy consumption, whether the Western world succeeds in improving energy efficiency and energy saving or not. An ethical preference for energy saving can therefore not be put forward as an argument against a massive global investment programme in renewable energy.

All renewable energy technologies that have a large worldwide potential utilise the energy from the sun. Direct solar energy (Concentrating Solar Power, CSP; Photo-Voltaics, PV) has a huge potential. If an area in the deserts equal to the size of France is covered with solar panels or solar thermal power plants, both having an efficiency of 15%, the whole current global consumption of oil, coal, gas and uranium can be replaced. A solar thermal power plant in a suitable region with abundant sunshine can reach a continuous production of 30 MegaWatt per km^2, see note[1] and Section 2.4. Solar power plants can be established on any otherwise worthless, level field.

The global production potential of all other renewable energy technologies is much less than Solar-CSP and Solar-PV. The maximum yield that can be obtained from biomass is 2 $MW_{electrical}/km^2$, see note[2]. Wood plantations need more or less fertile soil with sufficient rainfall. The maximum yield from wind parks is 1.5 MW km^{-2}, see note[3]. Only coastal regions, shallow seas and hilltops are suitable. The potential for more hydropower is limited. The environmental problems caused by dams and reservoirs are serious.

- Electricity production from coal combined with CCS is considered as a powerful method for producing energy without CO_2-emission. The best method is CCS coupled to a coal gasification plant. The investments for a CCS infrastructure are considerable and there is not much commercial experience yet. The costs in energy of the whole CO_2-capture and underground storage are tremendous, ranging from 10 to 30% of the electricity production of the plant. Nevertheless, CCS is receiving much political support nowadays.

Coal + CO_2-sequestration is not a sustainable method for producing energy because the availability of suitable geological formations for storing CO_2 is limited and the supply of coal will finally run out. The most serious drawback of CCS is its vulnerability for political alteration. The costs of capturing the carbon dioxide and compressing this gas to the high pressures that are necessary are rewarded by the value of the CO_2-certificates that will be earned. As soon as the CO_2-market collapses, for economical reasons, or political reasons (breakdown of the international support for the carbon cap and -trade system), there is no commercial incentive anymore for the operator of the coal-CCS plants to continue the expensive CCS-process. Carbon dioxide will be ejected again, as in the past, and all CCS-investments will turn out to be fruitless.

- Nuclear technology entails dealing with radioactive materials and commodities for making atomic weapons. In a well-organised society, the related safety problems can be adequately dealt with. The share of nuclear energy is 17% of the global electricity production and 6% of the total global energy consumption. The application of nuclear energy as a solution strategy for solving the climate problem implies a tenfold increase of the global nuclear capacity, at least. Most countries in the world will start to build and to exploit nuclear power stations, and many of them will insist on developing the full fuel cycle, like Iran nowadays. Many countries are not well-organised enough to be able to guarantee a safe exploitation of nuclear power. The world will become a more dangerous place when nuclear energy is applied for solving the climate problem.

In this paper, we will describe two scenarios for a fully solar society, both based on CSP technology. We will show two strategies for achieving one of these solar options, the 'Continuous Growth Strategy', and the 'War Strategy'. We will make elaborate calculations of the necessary investments for both solar scenarios. These investments turn out to be comparable to those for a nuclear scenario.

2 Concentrating Solar Power (CSP) technology and CSP-economics

In this paper, all prices are given in dollars of 2005, without taking inflation into account. Most of the contents of this section and all relevant references are dealt with more extensively in (Marchie, 2005).

2.1 Harvesting solar heat

A solar thermal power station is a conventional power station in which the burning fossil-fuel in the boiler is replaced by the heat from concentrated solar rays. For a good overview of the status of the technology see Brakmann et al. (2005). Six different optical methods can be applied to concentrate sunlight, see Table 1. As all relevant information originates from private companies, we give their names in the footnote to Table 1 enabling the reader to continue his/her investigation.

Table 1 Concentrating technologies and commercial applications

					World capacity September 2006 (MW_e) and operators			
Optical method		*focus*	*Temperature (^{0}C)*	*Heat transport to boiler*	*In operation*	*Under construction*	*Planned*	*Suppliers*
1	Parabolic trough mirror	Line	300–550	Oil, liquid salt, water + steam[a]	355[b,c]	214[d,e]	550[d,f]	–[g,h]
2	Linear Fresnel mirror[i]	Line	250–500	Water + steam	1[j]	13[j]	15[j,k,l]	–[j,m]
3	Linear Fresnel lens[n]	Line	250–400	–	–	–	–	–
4	Solar tower with field of heliostats	Point	250–1,000	Air, liquid salt and water + steam gas turbine	12[o]	–	20[o]	–
5	Solar dish	Point	400–1,500	Stirling engine	1	–	800 [p]	–[p]
6	Fresnel lens[q]	Point	400–1,200	Micro turbine	–	–	–	–[q]

[a] Zarza, Hennecke and Goebel (1999).

[b] FPL Energy, Juno beach, FL, USA; the plants were built in 1984–1990 by Luz International, USA.

[c] Arizona.

[d] Solarmillennium AG, Erlangen, Germany and ACS Cobra, Madrid, Spain.

[e] Nevada Boulder City.

[f] Iberdrola, Bilbao, Spain.

[g] Schott AG, solar, Mainz, Germany.

[h] Solargenix Energy, Raleigh, NC, USA.

[i] Bockamp et al. (2003) and Häberle et al. (2002).

[j] Solar Heat and Power, Sydney, Australia.

[k] Kernenergieen, Stuttgart, Germany.

[l] SOLAQ, Groningen, The Netherlands.

[m] Solar Power Group GmbH München (successor of Solarmundo, Belgium).

[n] Chris van Felius, Rotterdam, The Netherlands, private communication.

[o] Solucar, Sevilla, Spain.

[p] Stirling Energy Systems, Phoenix, Arizona.

[q] International Automated Systems, Utah, USA.

In the first two configurations of Table 1, the mirrors rotate along a single North–South oriented axis in order to keep the rays concentrated onto a line-focus. A receiver tube located in this line-focus contains a flowing liquid that absorbs the solar heat. The liquid is either oil, a mixture of liquid salts or boiling water. The receiver tube of a linear Fresnel mirror field is stationary whereas parabolic troughs and linear Fresnel lenses have moving receiver tubes.

The last three configurations of Table 1 have a point focus and the necessary tilting takes place along two axes. The concentration factor of the solar radiation is higher, leading to higher operating temperatures. The common focal point of heliostat mirrors is located in a receiver on top of a solar tower.

Solar thermal power stations are located in dry climates, often deserts. During sandstorms and heavy hail-storms the mirrors are turned upside down. The protection strategy for lens systems is still unknown.

2.2 Electricity out of solar heat

The most common method for producing mechanical power and hence electricity from concentrated solar heat using the first four technologies of Table 1 is the Rankine cycle. The basic solar thermal power station consists of a mirror field (or the roof of a greenhouse consisting of linear Fresnel lenses), receiver(s), a heat exchanger, a boiler, a turbine, a generator and a condenser. The heat exchanger can be omitted when steam is produced directly in the receiver. The condenser is cooled by seawater, a wet cooling tower or by air.

An extension of the elementary configuration with extra mirrors and receivers and with heat-storage tanks enables around-the-clock solar electricity generation. The heat-storage tanks may contain a mixture of molten salts, in fact any material that is able to survive the temperatures will do. A storage capacity of 16 hours is sufficient to compensate completely for the unproductive part of the 24 hours' day. In order to guarantee complete supply security two measures can be taken to compensate for a sequence of cloudy days

1 a substantial increase in storage capacity, or

2 addition of a facility for burning gas, oil, hydrogen or some solar fuel in the boiler.

It is advantageous to include a gas turbine and apply the fuel in the more efficient combined-cycle mode of operation.

Most solar thermal power stations will be located in the subtropical belts between the latitudes 20 and 40º on the Northern and Southern hemisphere. In these regions, there is a considerable difference in solar radiation intensity between summer and winter. A mirror field in the Northern hemisphere that is designed for the yearly average value of the solar radiation strength produces too much steam in June and July, and to little steam in December and January. A complex of solar thermal power plants in Southern Morocco that is designed to produce 1 GW under average conditions (March 21 and September 21) has a solar production of only 500 MW in December. In principle, the extra solar heat in the summer could be stored in heat-storage tanks, and consumed in winter time. However, the enormous investment in tanks and heat-storage material makes this solution impractical. A much better method would be to produce some sort of solar fuel in summer time, see Section 2.3.

Like many conventional power stations in the subtropics, solar power stations in coastal regions can be combined with desalination of sea water; the temperature of the condenser is increased to about 75 ºC, resulting in a somewhat lower steam turbine efficiency. In the Multiple-Effect Desalination (MED) process, seawater is distilled in a series of 10–15 vessels at decreasing temperatures and pressures. In a novel membrane-distillation process the number of steps is increased to about 30, resulting in a factor 2 to 3 higher water production for the same amount of heat than with MED (MEMSTILL, 2000).

In the future, solar towers may become equipped with novel hybrid gas turbines employing solar pre-heating (Pitz-Paal, Dersch and Milow, 2005). Solar dishes and Fresnel lenses usually have Stirling engines or microturbines in their focal points and are by nature comparatively small (20–100 kWe). They do not enjoy the same economy of scale as do the trough, linear Fresnel and tower systems so it is doubtful whether they will ever form the backbone of multi-GW grid-connected systems.

2.3 Solar fuel

At the current status of technology solar energy is available in the form of low-temperature heat (non-concentrating collectors), high-temperature heat (CSP) and direct electricity (PV). Stored solar energy is also available in the form of biomass, but due to the low efficiency of the photosynthesis process and the required quality of the millions of square kilometres where the wood plantations are growing it is highly doubtful whether biomass will play a dominant role in the 100% sustainable world economy of the future.

Solar fuel is defined as a combustible chemical compound in liquid form containing hydrogen and carbon synthesised out of water and CO_2 from the atmosphere using solar energy. The solar energy powers the chemical reactions in the form of photons or in the form of concentrated solar heat. In the latter case, the summer excess heat in a solar thermal power plant could be used to produce the fuel that is needed in wintertime to compensate for the lacking solar radiation. The efficiency of the process photon energy to chemical energy should be at least 30% and the efficiency of the process: heat to chemical energy should be at least 50%.

All scientific research leading to solve the solar fuel problem should be given high priority. The scientist who makes the crucial step towards the solution is very likely to receive a Nobel Prize. Although the production of solar fuel is possible from an energetic point of view, it is not clear whether other fundamental obstacles will spoil the game.

2.4 Solar economics

The kiloWatthour costs of electricity from CSP plants are much lower than from plants consisting of solar panels (PV). According to a study by the International Energy Agency (IEA, 2004). CSP is a factor 3 cheaper than PV, at present, and in the future. Nevertheless, photovoltaics can play an important role in the decentralised part of the solar economy. But without CSP-plants in all sunbelt countries of the world, a real global solar economy will not be realised. Therefore, we restrict ourselves in this paper to CSP.

A complete solar thermal power station consists of the following components:

The solar field, delivering steam to the steam turbine of the *Combined-cycle thermal power station* and to the *Thermal storage*.

In summer time the *Solar fuel factory* is active, producing fuel for operating the gas turbine of the *combined-cycle thermal power station* during cloudy days and part of the time during the winter.

The most expensive component is the solar field, consisting of the mirrors, the receiver tubes, pumps and heat exchangers. The current square meter price varies from 300 \$ m^{-2} for parabolic trough mirrors and solar dishes to 106 \$ m^{-2} for the cheapest kind of linear Fresnel mirrors. CSP is a young technology, the total global capacity is only 370 MW_e. Any developing technology becomes cheaper when there is a market and when there is competition. It is certain that the solar field of CSP-plants will become cheaper until some sort of saturation value is reached. We make the assumption that the saturation value will be 50 \$ m^{-2} and that this value will be reached well before a substantial, say 10% fraction, of the global electricity consumption is generated by solar thermal power plants. So, we do not introduce a large error when we attribute 50 \$ m^{-2} to the costs of the solar field of all solar thermal power plants in the world when the global solar economy is realised.

In this section, we will specify the investment of a complex of solar thermal power stations having a base load capacity of 1 GW = 1 $GW_{installed}$ at a typical location in a sunbelt country at 28° latitude. In Section 3, we will calculate the investment needed for delivering 1 GW of solar electricity on average, 1 $GW_{average}$ to a location which is 3500 km away from the CSP-plant. The detailed investments depend upon the scenario which will be realised in the coming decades.

Applying formulas for the absorption of the solar rays in the atmosphere for a number of calendar data at latitude 28° North, using a solar to thermal efficiency of 50%, and neglecting any clouds, we calculate the year average of collected concentrated heat from a horizontal surface: 100.2 $W_{thermal}$ m^{-2}. There is a substantial seasonal variation in this number. On June 21, the daily average is 134.4 $W_{thermal}$ m^{-2} and on December 21 56.2 $W_{thermal}$ m^{-2}. We assume a thermal to electric eficiency of $\eta_s = 30\%$, so the year average of collected electricity from a horizontal surface is 30.06 W_e m^{-2} or 30.06 MW_e km^{-2}. We need a solar field of 33 km^2 for an average electricity production of 1 GW.

The investment of the solar field is 33 km^2 × 50 M\$ km^{-2} = 1650 M\$.

The investment for a combined-cycle thermal power station running on gas of 1 $GW_{installed}$ is 625 M\$.

The current investment in a thermal storage system using a mixture of KNO_3 and $NaNO_3$ is 10 \$ $kWh_{thermal}^{-1}$. Our CSP-plant at latitude 28° North needs 46 $GWh_{thermal}$ in order to be able to deliver 1 GW_e around the clock, the total investment in thermal storage is 460 M\$.

We need a chemical storage system in order to harvest the overcapacity of the solar field with respect to the steam turbines during the summer. Therefore, a solar fuel factory consumes the excess heat and produces a solar fuel. The capacity of the solar fuel factory should be just sufficient to process the excess heat on June 21. The excess heat production is than $134.4–100.2 = 34.2$ $W_{thermal}$ $m^{-2} \times 33\times10^6$ $m^2 = 1.13$ $GW_{thermal}$, averaged over the 24 hours. If the solar fuel has the same combustion heat as fuel oil, the production capacity of the solar fuel factory must be 24 kg sec or 2055 ton day^{-1}.

It is very difficult to make a reasonable estimation of the investment in a chemical factory when even the chemical reactions of the production process are still not determined. For the moment, we define the still unknown parameter C_{sff} as the investment in M\$ for a solar fuel factory with a production capacity of 1000 ton day^{-1}. Experience from the oil industry gives as a very crude indication for a value of this parameter: C_{sff} = 150 M\$, leading to an investment for the solar fuel factory of 308 M\$.

The total amount of excess summer heat, to be fed into the plant in winter time is about 13% of the total year production, or 13% × 3.33 $GW_{thermal}$ × 24 × 365 = 3790

$GWh_{thermal}$ or 287,000 ton of solar fuel. We neglect the investment that is needed to store this amount of solar fuel.

During solar operation the heat is available in the form of high-pressure steam and the thermal to electric efficiency η_s = 30%. During fuel operation the fuel is fed into the gas turbine of the combined-cycle power station, resulting in a thermal to electric efficiency η_g = 50%. This improved efficiency is assumed to compensate for the unavoidable losses in the solar fuel production process.

The result of this section is the following. The total investment for a complex of solar thermal power plants able to deliver 1 GW_e in 24-hour operation at a cloudless location at a latitude of 28^o is 1,650 + 625 + 460 + 308 = 3,043 M$.

3 Two scenario's for the solar age

In the solar age, most of the energy that is consumed by mankind originates from CSP plants in the 70 sunbelt countries on the globe. The main problem to be solved is the transport of the energy to the billions of people living outside these countries, or into cloudy provinces within these countries. In this section, we describe two scenario's in which all electricity is from solar origin: The Solar Electric Scenario and The Solar Fuel Scenario. We make a rough calculation of the costs of both scenario's, and compare these costs with that of the Nuclear Scenario, in which all electricity in the world is produced by nuclear power stations.

At present and in the near future three types of power stations are feeding the electric grid:

1. Base-load stations, which have the right to deliver all electricity they can produce in 24 hours' operation because of their high capital cost and relatively low fuel costs (nuclear plants, CSP-plants with thermal storage and fuel back-up capacity, coal plants, hydro plants).
2. Unreliable power stations, which have the right to deliver all electricity they can produce at any time they are able to produce (wind farms, CSP-plants without thermal storage and without fuel back-up capacity, PV-plants, combined heat- and electricity generation with priority given to heat production).
3. Compensating stations with low capital costs and high fuel costs deliver electricity only when the types 1 and 2 are unable to follow the demand of electricity (gas plants, oil plants and some hydro plants).

In this paper, we make the simplification that all electrical energy is originating from either CSP-installations or from nuclear power plants. So there is no further back-up capacity available to ensure the reliable delivery of electricity. We also make the simplification of neglecting the electricity production from decentralised production units (local combined heat and power, small wind turbines, local PV, small biomass, small hydro power, etc.).

The electricity consumption fluctuates over the time of the day and the time of the year. At any time, the power stations of the grid should be able to deliver the required amount of electricity[4]. We deal with this demand by increasing the installed capacity by 45% with respect to the yearly averaged capacity.

Any unit in a grid should have extra capacity available in case of a sudden calamity in other parts of the grid. We deal with this demand by increasing the installed capacity with an extra 10%, except for the Solar Electric Scenario. Both demands together result in a 60% increase of the installed capacity with respect to the yearly averaged capacity.

We calculate the total capital investment that is needed to deliver on average 1 GW of electricity (1 $\text{GW}_{\text{average}}$) to a location 3,500 km away from the solar production location at 28° latitude.

3.1 The investment for the Solar Electric Scenario

In the Solar Electric Scenario, the electricity from the solar thermal power plants is transported to most inhabitants on Earth by means of High-Voltage Direct-Current (HVDC) transmission lines. For long distance transport of electric energy the application of direct current has clear advantages with respect to conventional alternating current. The transport of electricity produced at remote hydro power plants is nowadays already done by means of HVDC. So in the Solar Electric Scenario, the existing high-voltage alternating current grid will be covered by a wide meshed grid of HVDC lines, like the road system of the early 20th century has been covered by a mesh of highways in the second half of last century. North–South running HVDC lines dominate in order to transport the solar electricity from the deserts to the countries in the temperate climate and tropical climate regions. East–West running HVDC lines have a distributing function, and transport electricity from wind farms along remote coasts to the inhabited world. Extensive studies of the Solar Electric Scenario for the EUMENA region (Europe + Middle-East + North-Africa) have been performed at the German Space Research Institute (DLR; see Trieb, 2006).

The AC to DC transformation, the transport of the direct current over 3500 km, and the DC to AC transformation together cause a loss of 14.5% (Trieb and Knies, 2004). We compensate for this loss by increasing the investments for the solar thermal power plant by 17%.

The capacities of the solar field, the thermal storage and the solar fuel factory do not need to be increased in order to compensate for the load fluctuation. The only part of the solar thermal power station that should be dimensioned 45% larger with respect to 1 GW of peak power is the combined-cycle thermal power plant. It is assumed that there is always sufficient heat available in the thermal storage, if not there is enough solar fuel available. The enormous size of the grid, connecting hundreds of giga watt plants, obviates the need for calamity compensation.

The investment for the complete transmission line having a peak capacity of 1 GW is 430 M$. It has to be increased in order to compensate for the load fluctuation. The number of different HVDC lines is limited, so a 10% calamity compensation is probably necessary.

All corrections are applied to the investment amounts as given in Section 2 (see Table 2).

Table 2 Investment needed for the infrastructure for an average capacity of 1 GW_e continuous solar electricity, delivered at 3,500 km distance from the solar plant

	Solar electric scenario				*Solar fuel scenario*		
	HVDC compensation (%)	*Load fluctuation compensation (%)*	*Calamity compensation (%)*	*Corrected investment (M$)*	*Load fluctuation compensation (%)*	*Calamity compensation (%)*	*Corrected investment (M$)*
Solar field	17	0	0	1,931	0	0	1,650
Combined-cycle thermal power plant	17	45	0	1,060	45	10	1,000
Thermal storage	17	0	0	538	0	0	460
Solar fuel factory	17	0	0	360	0	0	1,210
Energy transport	–	45	10	686	–	–	0
Total	–	–	–	4,575	–	–	4,320

3.2 The investment for the Solar Fuel Scenario

In the Solar Fuel Scenario, the transport of energy from the deserts where the CSP-installations are located to the regions where most electricity consumers are living is done in the form of solar fuel. There is no HVDC grid. All solar thermal power plants in the 70 sun-belt countries are connected to the local AC-grid and serve the local population. Most CSP-installations consist of solar fields connected to solar fuel factories without a thermal power plant.

We model the Solar Fuel Scenario in its pure form: all electric power stations are combined-cycle thermal power stations located all over the world, near to the consumers, and connected to the consumers by means of the existing AC-grid. We have to compensate for the load fluctuation and have to apply the calamity compensation in the usual way. They consume solar fuel which is produced by CSP-solar fuel factories in the deserts.

We neglect the energy costs of transporting the solar fuel. The investment for the solar field can therefore remain equal to the calculated value in Section 2. The investment for the solar fuel factory is much higher. If thermal storage is included, the capacity of the solar fuel factory must be able to process the full yield of June 21: 134.4 W_{thermal} m^{-2} * 33×10^6 m^2 = 4.44 GW_{thermal}, averaged over the 24 hours, or 93 kg sec^{-1} [5]= 8070 ton day^{-1}. The investment of the factory is $C_{\text{sff}} \times 8.07 = 150 \times 8.07 = 1210$ M$. If no thermal storage is present, the solar fuel factory must be able to process the full instantaneous concentrated heat at noon, June 21, which is 423 W_{thermal} $m^{-2} \times 33 \times 10^6$ m^2 = 13.96 GW_{thermal}, or 294 kg sec^{-1} [5]. We assume that inclusion of thermal storage is the most economic option.

We neglect the investments for transport and storage of the solar fuel. The result of the calculation is given in Table 2, last column.

3.3 A comparison of both solar scenario's

The calculations suffer from two major uncertainties: the final cost of the solar field and the cost of the solar fuel factory, of which the working principle is still not known. In case, the solar fuel factory turns out to be not feasible, the Solar Electric Scenario is the only possible one, albeit in a handicapped version, as an alternative solution has to be found for the seasonal problem. However, if an economical production method for solar fuel is found, with a thermal to chemical efficiency of at least 50%, and an investment less then C_{sff} = 150 M$/kton/day, the Solar Fuel Scenario has a clear advantage. The locations of production and consumption of solar electricity are decoupled and countries like Australia and South-Africa may become serious competitors with the North-African countries on the European energy market. But, the most obvious advantage is the solution of the most difficult problem: to find a sustainable way to power road, sea and air traffic.

Nuclear power is receiving wide attention nowadays. Therefore, it is an interesting exercise to make a realistic calculation of the investments that are needed per giga watt of average nuclear power for the Nuclear Scenario, which is a global economy in which all electricity is produced by fission reactors. The investment for a modern light-water nuclear power with an installed capacity of 1 GW is 2,500 M$. We have to compensate for the load fluctuation and for calamities, so the investment for the average continuous capacity of 1 GW nuclear power is 4,000 M$.

The Nuclear Scenario implies an increase in the global nuclear capacity by a factor 10 at least. It is to be expected that nuclear power stations will become cheaper because of the learning curve effect. On the other hand, a tenfold increase in the global uranium demand and radioactive waste production will lead to increase exploitation costs. The uranium problem can be solved by making a transition to breeder reactors. This is a more complicated technology, and the necessary safety measures are costly, so we expect the investment in breeder power plants to be much more than 4,000 M$ $\text{GW}_{\text{average}}^{-1}$.

We conclude this section with the observation that the solar scenario's and the nuclear scenario are approximately just as expensive. However, other arguments favour the solar scenario's, see Section 1. Political decisions that are taken in favour of nuclear energy without serious consideration of the solar alternatives are not justified.

4 Two strategies for achieving the solar age

The global electricity consumption in 2003 was 1,686 $\text{GW}_{\text{average}}$ (NEIC, 2005). The total investment that is needed when the Solar Electric Scenario is performed is 7,713 G$.[6] This enormous sum of money, being 18% of the Gross Domestic Product (GDP) of one year of the whole world, gives an indication of the gigantic task to be accomplished. If mankind decides to make the transition towards the Solar Age, a widely supported concerted action should be undertaken for a successful and continued investment in the CSP infrastructure. Hundreds of thousands of square kilometres of solar fields must be built in at least 50 different countries, complete with power stations, thermal storage tanks and solar fuel factories. Tens of thousands of kilometres of multi-giga watt High-Voltage Direct Current transmission lines must be erected (in case of the Solar Electric Scenario).

We present two strategies for achieving one of the solar options, the 'Continuous Growth Strategy', and the 'War Strategy'.

4.1 Continuous Growth Strategy

By the end of 2006, the world capacity of CSP-plants amounts to 368 and 227 MW is under construction, see Table 1. More than 1,000 MW is planned to be built in the next few years. This growth is the result of favourable economic circumstances (the high oil and gas prices) and favourable political circumstances: the feed-in law in Spain and the renewable portfolio obligations in some states in the USA. We expect that more knowledge of the benefits of CSP will lead to favourable political conditions in many other sun-belt countries. This will lead to a continuous growth of the global CSP-infrastructure. Other renewable energy technologies such as wind energy and photovoltaic solar energy have already shown growth rates of about 30% year^{-1} for many years. So we define the Continuous Growth Strategy as follows:

1 the global CSP-capacity is 368 MW in the year 2006

2 the yearly growth is 30% of the already existing global capacity

3 as soon as the growth has reached the level of 400 billion dollars per year,[7] it remains at that level.

It amounts about 1% of the GDP of the whole world.

The results of the Continuous Growth Strategy are given in Figure 1. We observe:

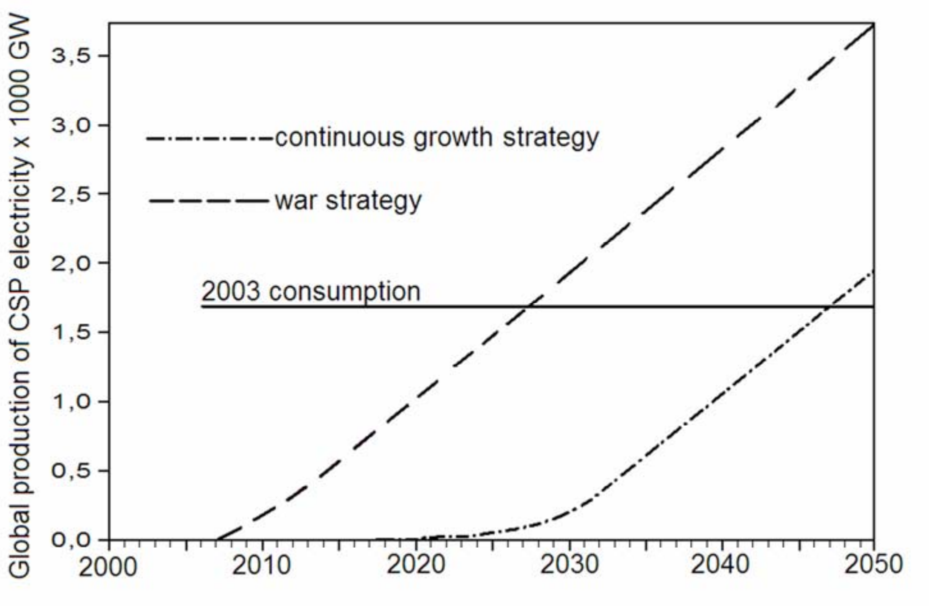
1 In 2033, the growth level of 400 G$ year^{-1} is reached at a global CSP-capacity of 440 GW$_{\text{average}}$.

2 In 2047, the global CSP-capacity is equal to the global consumption of electricity in 2003.

4.2 War strategy

A gradual, organic transition like the Continuous Growth Strategy is the best way to make a technology competitive and cheap because the conditions are optimal for the occurrence of a learning curve. However, it takes decades before a significant fraction of the fossil-fuel fired power stations is replaced by solar thermal power plants, see Figure 1. In the mean time, the global electricity consumption will increase significantly, as will the global CO_2-emission. If mankind regards this increased CO_2-emission as unacceptable, it has to take drastic measures, such as those taken in time of war. When the naked survival of a nation is at stake, economics becomes unimportant, and weapon production is given the highest priority. If the survival of our planet demands a much faster decrease of the CO_2-emission than can be achieved with the Continuous Growth Strategy, CO_2-emission reduction by means of CSP-investments must be given the highest priority. We define the War Strategy for the deployment of CSP and the realisation of the Solar Age as follows. Starting in 2007, the world invests 400 billion dollars per year, leading to a global growth of the CSP-capacity of at first 60 GW$_{\text{average}}$ year^{-1}, gradually increasing to 90 GW$_{\text{average}}$ year^{-1}.[8] This forced investment programme is only possible when a majority of the sun-belt countries joins the programme, and when all OECD countries take part in the financing. The result of the War Strategy is that already in 2027, 20 years from now, the total global electricity demand of 2003 can be met by means of CSP (see Figure 1).

Figure 1 Global production of solar electricity for two implementation strategies



5 Conclusions

The solar age is a realistic option. The total investment amounts to about 7,700 billion dollars (dollar value of 2005). If the world would decide to a 'War Strategy' in order to deploy CSP as fast as possible, a global capacity of CSP equal to the electricity consumption in 2003 can be built within 20 years. Such a strained strategy implies a yearly investment of 400 billion dollars, or 1% of the total GDP in the world, starting in 2007.

A more relaxed and natural strategy would be a steady relative growth of the global CSP capacity with 30% per year until the 400 billion \$ year^{-1} level is reached, followed by a continued steady 400 G\$ year^{-1} growth. In this 'Continuous Growth Strategy' the global solar capacity has reached the 2003 consumption level only in 2047, 40 years from now.

We present two rather different conceivable solar scenario's. In the Solar Electric Scenario, all electricity is generated by CSP plants in the deserts and semi-deserts of the world, and transported to most consumers by means of a grid of High-Voltage Direct Current (HVDC) lines over many thousands of kilometres. In the 'Solar Fuel Scenario' most CSP plants in the deserts and semi-deserts are just chemical factories that produce solar fuel out of the concentrated solar heat. Electricity is produced in combined-cycle plants consuming the solar fuel near to the customers. There is no need for establishing continental HVDC grids.

The necessary investments for both solar scenario's are about the same as for a nuclear scenario. The exploitation costs of the solar power stations are lower than for nuclear plants, because solar radiation is for free. The solar scenario's are sustainable, the nuclear scenario is not. There is no justification for a policy which results in larger investments in nuclear power stations than in solar power stations.

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Notes

[1] The production per year is 29 × 365 × 24 = 254,000 MWh km^{-2}. This is only true for CSP plants that have linear Fresnel mirrors. The yield per km^2 of CSP plants using parabolic troughs, heliostats, etc. is lower.

[2] The production of a very efficient wood plantation is 4000 m^3 of wood per km^2 per year. This corresponds to 5 $\text{MW}_{\text{thermal}}\ \text{km}^{-2}$ or 2 $\text{MW}_{\text{electrical}}\ \text{km}^{-2}$. The production from first-generation biomass (ethanol from sugar, rapeseed oil, palm oil, etc.) is lower.

[3] One 5 MW turbine per km^2, with maximum tip height 150 m, and capacity factor 30%. A higher density of turbines is pointless due to increasing sheltering losses.

[4] We neglect the (limited) capacity for storage of electricity in hydro-electric systems.

[5] Assuming the combustion heats of solar fuel and fuel oil to be equal.

[6] Throughout this paper we neglect inflation and apply dollars with their value in 2005.

[7] An investment of 400 G$ means a global increase of CSP-capacity with 90 $GW_{average}$ (see Table 2).

[8] In the first year, we assume a square meter price for the solar field of 100 $ m^{-2}.