# Option values of concentrating solar power and photovoltaic for reaching a 2°C climate target

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## Abstract

In this paper we discuss the role of solar electricity as well as the relative importance of concentrating solar power (CSP) and photovoltaics (PV) for reaching cost-optimal energy related greenhouse gas abatement under the constraint of a 2°C climate protection target.

We use the hybrid energy-economy-climate model ReMIND to analyze the use of solar electricity to understand which parameters determine the deployment of one or both solar technologies. We first carry out a literature review of recent studies on costs and potentials of CSP and PV. After consolidating the data into one set of parameters, we implement the two technologies in ReMIND. The results show that solar power technologies supply a significant share of electricity in the optimal abatement scenario. A sensitivity analysis of the investment costs of CSP demonstrates that while investment costs have a major influence on technology deployment, CSP is used over a wide range of values. Furthermore we calculate option values for the solar technologies by running different climate stabilization scenarios in which either PV, CSP, or both, are excluded. These option values serve as an indicator for the strategic relevance of individual technologies to achieve the climate protection target. Our results suggest that excluding solar electricity from the generation mix increases the total mitigation costs as measured by GDP differences by about 80%.

Keywords: Photovolatic, Concentrating solar power, Learning rates, Modelling

## 1 Motivation

After the rapid installation of wind power capacity since the mid 1990s, power generation directly from the sun using PV or CSP is increasingly being recognized as a major contributor in the future energy mix. A recent example of this increased interest is the German “Desertec” project which brings together leading companies and utilities in order to develop CSP systems as part of an African-European partnership. The decreased availability of fossil fuels and the aspired realization of the 2 degree climate protection target requiring substantial $CO_2$ abatement are leading the R&D to environmentally sound technologies (like PV or CSP). Solar energy has a huge potential – approximately 3 900 000 EJ reach the earth surface every year, which is one order of magnitude larger than the assessed potential of non-renewable energy sources [9]. However, as both PV and CSP were only recently developed and have high initial costs, only minor deployment has taken place: in 2007, solar energy contributed less than 0.2% to the global primary energy consumption. Nevertheless, both technologies have experienced and will continue to see major cost decreases due to technological learning as cumulated capacity increases. This expectation has lead to an impressive market growth for PV in the last ten years, and renewed interest in CSP projects in Spain, California and North Africa over the last five years. In the future, both technologies will compete with each other in two different ways:

1. Due to their dependency on solar radiation, both technologies require similar site conditions. However this rivalry is partly reduced as (a) the overall solar potential is very large, (b) PV – contrary to CSP – only requires diffuse sunlight and can be used at low irradiances and (c) PV is well-suited to distributed applications.

2. Both technologies are deemed “learning technologies”. The concept of technological learning describes cost reductions due to capacity development, design improvements or cost reductions associated with economies of scale. Thus, the two technologies compete for private investments and governmental support during the learning phase until they break even with incumbent technologies in terms of electricity production costs.

# 2 Technology Background

Solar energy can be converted directly into electricity using photovoltaics, or indirectly with thermal CSP plants. PV cells generally exploit semiconductor materials to use the photoelectric effect. The production of PV is currently dominated by poly and mono-crystalline silicon modules, which present 94% of the market. Better understanding of materials and device properties has resulted in continually increasing cell efficiencies, but single-junction cells are thermodynamically limited to a maximum theoretical power conversion efficiency of about 31%. The other 6% include new technologies like thin films made of amorphous silicon or cadmium telluride and organic photovoltaics. [7]

PV power generation is easily scalable to adapt to local requirements: for the decentral powering of a water pump it is possible to use single modules with 200W capacity, for grid-connected power supply they can be combined into arrays of up to 60MW capacity.

CSP technologies use focusing optics like mirrors for concentrating sunlight on an absorber. The absorber contains a heat transfer medium like water or oil which is heated to high temperatures of 400 or 1000°C, depending on the technology. The thermal energy can either be directly used in a secondary circuit to generate electricity via steam turbines or be stored for a transformation into electricity at a later time. The two main viable types of CSP systems are linear trough systems and power tower systems. A trough system uses either long, parabolic mirrors or Fresnel mirrors constructed from many flat mirrors positioned at different angles to focus solar radiation to a line absorber. A power tower system consists of a large field of mirrors (heliostats), concentrating sunlight onto a point-like receiver at the top of a tower, thus producing higher radiation densities and heating the working fluid to about 1000°C.

The present paper focuses on PV and a generalized CSP technology. The issue of differentiation between the main types of CSP systems is not elaborated here.

# 3 The ReMIND-G Model

We use the hybrid model ReMIND – G that couples a macroeconomic growth model with a highly disaggregated energy system model [1] and the climate model ACC2 [21] to determine the role of solar electricity under the constraint of an upper limit on global mean temperature change (cf. *Figure 1*). [2],[12]

The macroeconomic growth model belongs to the class of Ramsey-type growth models and is formulated as a centralized maximization problem of an intertemporal welfare function. The Ramsey model is generally used for the analysis of intertemporal consumption, saving, and investment decisions. But it is also used within the context of energy, climate change and technological learning due to improved technologies and future scarcities, increased resource costs and emissions restrictions. Subject to a number of constraints ReMIND calculates a general equilibrium solution over the time horizon 2005 to 2100 in time steps of five years. For all experiments, a pure rate of time preference of 1% was used.

The energy system model represents the economic sector of ReMIND at a high level of techno-economic disaggregation of the energy system. Each technology is an energy conversion process that requires capital and fuels. The model distinguishes between exhaustible and renewable primary energy carriers. The extraction costs of the

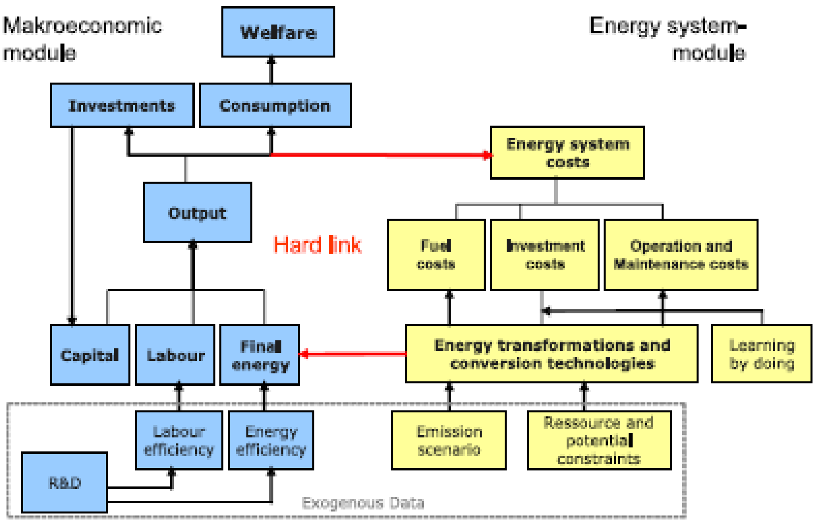


*Figure 1: overview of the model structure*

exhaustible resources (uranium, coal, gas, oil) are given by Rogner Curves [13], [18] to incorporate the intertemporal scarcity due to increasing extraction costs. The renewable energy sources wind (on- and offshore), hydro, solar, geothermal and biomass are restricted by annual production potentials, which are divided into grades with different full load hours to represent the diverse site conditions. The most important technologies representing the different conversion routes originating from primary energy carriers are presented in *Table 1*. Regarding solar technologies the model distinguishes between photovoltaics (PV) and concentrating solar power (CSP) through differences in their parameterization such as investment, operation, and maintenance costs, load factors, learning rates, floor costs and technical potential.

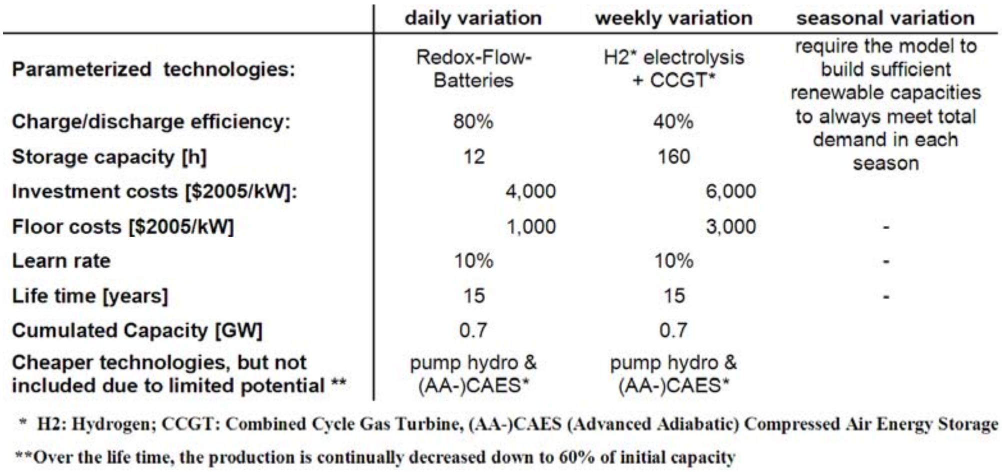
As both technologies are powered by solar radiation they compete for production sites. To model the rivalry in land use endogenously we implemented the geographical potential in addition to the technical potential. The geographical potential is the ”land area” that remains from the theoretical potential once geographical and anthropological restrictions are considered. The geographical potential creates the competition between CSP and PV in ReMIND-G: the area used by PV plus the area used by CSP must be

| | | Primary enery types | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Exhaustible | | | | Renewable | | |
| | | Coal | Crude oil | Natural gas | Uranium | Solar Wind, Hydro | Geothermal | Biomass |
| Secondary energy types | Electricity | PC*<br>IGCC*<br>CoalCHP | DOT | GT<br>NGCC*<br>GasCHP | LWR | SPV<br>CSP<br>WT<br>Hydro | HDR | BioCHP |
| | Hydrogen | C2H2* | | SMR* | | | | B2H2* |
| | Gases | C2G | | GasTr | | | | B2G |
| | Heat | CoalHP<br>CoalCHP | | GasHP<br>GasCHP | | | GeoHP | BioHP<br>BioCHP |
| | Transport fuels | C2L* | Refinery | | | | | B2L*<br>BioEthanol |
| | Other liquids | | Refinery | | | | | |
| | Solids | CoalTR | | | | | | BioTR |

Abbreviations: PC – conventional coal power plant, IGCC – integrated coal gasification combined cycle power plant, CoalCHP – coal combined heat and power plant,C2H2 - coal to hydrogen, C2G - coal to gas, CoalHP - coal heating plant, C2L coal to liquids, CoalTR - coal transformation, DOT - diesel oil turbine, GT - gas turbine, SMR - steam methane reforming, GasTR - gas transformation, GasHP - gas heating plant, LWR - light water reactor, SPV - solar photovoltaic, CSP - concentrating solar power, WT - wind turbine, Hydro - hydroelectric power plant, HDR - hot dry rock, GeoHP - heat pump, BioCHP - biomass combined heat and power, B2H2 - biomass to hydrogen, B2G - biogas plant, BioHP - biomass heating plant, B2L - biomass to liquid, BioEthanol - biomass to ethanol, BioTR - biomass transformation.

* this technology is also available with carbon capture and sequestration (CCS)

*Table 1: Conversion routes from primary to secondary energy carriers*



| | daily variation | weekly variation | seasonal variation |
|---|---|---|---|
| **Parameterized technologies:** | Redox-Flow-Batteries | H2* electrolysis + CCGT* | require the model to build sufficient renewable capacities to always meet total demand in each season |
| **Charge/discharge efficiency:** | 80% | 40% | |
| **Storage capacity [h]** | 12 | 160 | |
| **Investment costs [$2005/kW]:** | 4,000 | 6,000 | |
| **Floor costs [$2005/kW]** | 1,000 | 3,000 | - |
| **Learn rate** | 10% | 10% | - |
| **Life time [years]** | 15 | 15 | - |
| **Cumulated Capacity [GW]** | 0.7 | 0.7 | |
| **Cheaper technologies, but not included due to limited potential **** | pump hydro &<br>(AA-)CAES* | pump hydro &<br>(AA-)CAES* | |

*** H2: Hydrogen; CCGT: Combined Cycle Gas Turbine, (AA-)CAES (Advanced Adiabatic) Compressed Air Energy Storage**

****Over the life time, the production is continually decreased down to 60% of initial capacity**

*Table 2: Storage technologies subdivided to variation.*

equal to or less than the total solar geographical potential.

To model technology development of comparatively young technologies like wind, PV and CSP through learning-by-doing, we use the ”learning curve concept” [10]: costs decrease as a power law as cumulated installed capacity increases. To reflect that learning slows down as a technology matures, we modified this commonly used relationship by splitting investment costs into learning costs and floor costs. The former can be reduced through the normal learning curve, while the latter specify the minimum costs that are reached asymptotically at very high cumulated capacities. Thus, total learning slows down as the floor costs are approached.

Renewable energies are intermittent and thus require storage to achieve a stable electricty supply once they make up a large share of generation. We implemented storage requirements for wind, offshore wind and PV along the following lines:

Variations in output are divided into day-long (e.g., day-night for PV), week-long (e.g., one week without wind) and seasonal variations. The storage technology required by each class of variations is stated in *Table 2*. Costs and efficiencies of the storage technologies are based on the values stated in [4] and expert interviews. Quite intuitively, the amount of storage required depends on the penetration rate of the fluctuating technology for which the storage is used. Even without any renewable energy, the existing production capacities and the distribution network already need a certain flexibility, as both production and demand fluctuate. Adding a minor new

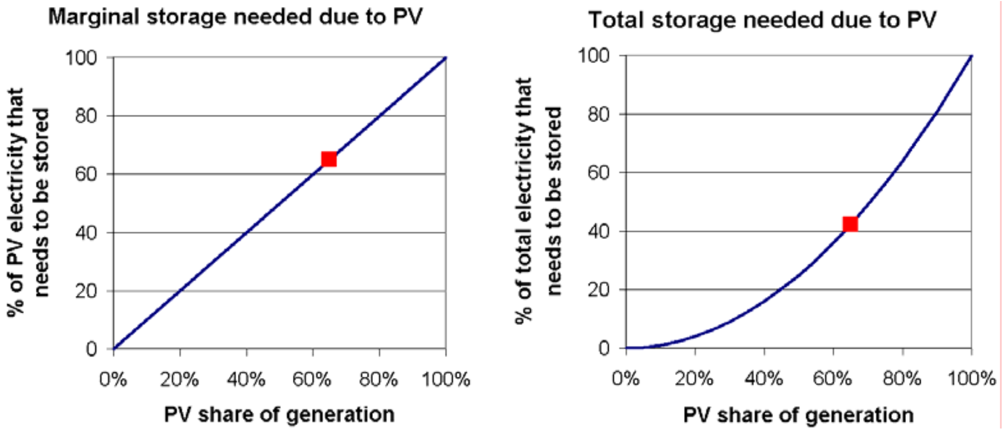


*Figure 2: Storage requirements as a function of the share of generation. The left panel depicts the storage need for each additional unit of PV capacity. The right panel depicts the total storage need.*

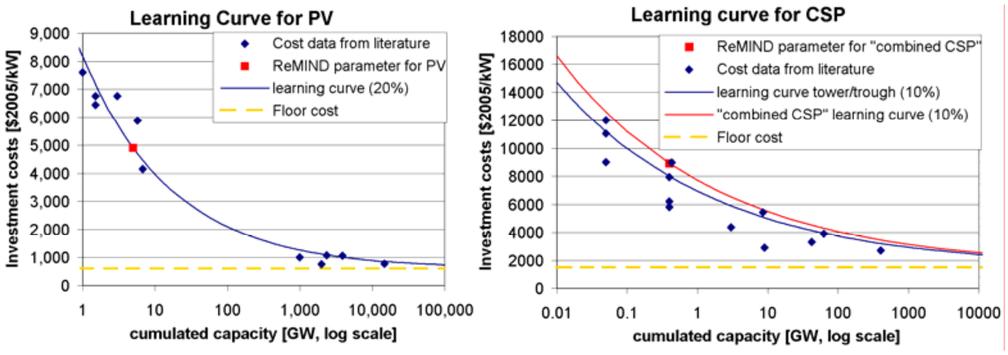


*Figure 3: Learning curve a) PV b) CSP. Values above 5GW (PV) and 0.4GW (CSP) are projections into the future performed by the individual studies.*

fluctuating source does not have a large impact on the system as the individual uncorrelated fluctuations (e.g., wind and PV) cancel each other out. As one technology dominates the energy mix, however, its fluctuations have much more impact on the energy system and thus require more storage. This observation was implemented as follows: Taking electricity from PV as an example, the marginal storage required for keeping the system stable while adding another kW of PV rises linearly with the penetration rate. This leads to the effect that the total amount of storage required to compensate the PV usage increases with square of the penetration rate of PV, as depicted in *Figure 2*.

# 4 Data

To determine the cost and production potential parameters for PV and CSP, we performed an extended literature review.

## 4.1 Costs

Numerous studies have analyzed cost parameters and learning curves [6],[8],[10],[11],[15],[16],[17],[20] since the boom starting at the end of the 90s. Although economic cycles (due to, e.g., scarcity of feedstock silicon or feed-in tariffs) caused price fluctuations lasting for 2-4 years, over longer time scales PV consistently showed a very high learn rate of 20±3%. The resulting learning curve and its position with respect to the values from different studies can be seen in *Figure 3a*.

For CSP, the data base is much more limited. The only commercial plants are the SEGS plants in California. Apart from that, several smaller research and demonstration projects were built, but few cost data exists. Parameterization is further complicated by the fact that heat storage – one of the main advantages of CSP over PV – has only once been implemented in a commercial plant, namely Andasol 1 in Spain. We therefore used studies in which costs from the individual parts – power block, solar field and heat storage – are scaled up to yield a configuration which can be used as base-load plant: a 12-16h storage CSP plant with a solar multiple of 3, able to produce 5500 full load hours at a DNI[1] of 2400 kWh/m²/a [14],[15],[19], [22],[25]. For CSP trough technology, which was already used for 400MW of power plants, values between 4000 and 9000 $/kW are stated, while for the power tower technology – a much less mature technology with only 30 MW of cumulated installed capacity – costs of 6500 to 11000 $/kW are projected. To aggregate the values for trough and tower plants into a “combined CSP”-parameterization, we used the learning curve for trough technology and doubled the capacity additions required to achieve a given cost reduction. Thus, the current cost of a

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[1] Direct Normal Irradiance (DNI) is the total amount of sunlight that directly hits a plane which is kept perpendicular to the incident rays.

| | Investment cost [$2005/kW] | Operation & Maintenance [% of inv. cost] | Life time* [years] | Floor cost [$2005/kW] | Learn rate [%] | Cum. installed capacity [GW] | Land use m$^2$/kW |
|---|---|---|---|---|---|---|---|
| **PV** | 4,900 | 1.5 | 35 | 600 | 20 | 5 | 15 |
| **CSP** | 9,000 | 2.5 | 35 | 1,500 | 10 | 0.4 | 50 |

***Over the life time, the production is continually decreased down to 60% of initial capacity**

*Table 3: Parameterization of PV and CSP*

trough power plant at 400 MW cumulated capacity is equal to the cost of “combined CSP” at 800 MW of cumulated capacity. The learning curves are shown in *Figure 3b*.

Our final parameterization for both technologies is displayed in *Table 3*.

## 4.2 Potential and capacity factors

To calculate the technical potential of solar technologies, researchers have used world-wide satellite data for DNI and constructed GIS-based filters to exclude areas that are not available for power plant construction due to geographical (marsh, sand desert, forest, slope>2%) or anthropological (habitation, agriculture, cultural site) reasons [23],[24]. Using our own power plant parameterization, we calculated the total electricity that could be produced on the land area given by [23]. We then used regional conversion factors from DNI to the diffuse irradiance on a fixed tilted surface to calculate the PV potential.

When aggregating the regional potentials into one global potential (see *Table 5*), we strongly decreased the total potential for the upper grades to reflect that some regions only have very low-grade potentials. Even though one region like Africa can have a very high grade 1 potential which is theoretically sufficient to supply the whole world with electricity, in reality this would not happen due to transmission costs between continents.

| | DNI | maximum annual electricity production from sunlight [EJ] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grade | [kWh/m2] | EUR | RUS | US | JAP | CHIN | IND | AFR | LAM | MEA | EAS | ROW | **Global** |
| 1 | 2700 | 0 | 0 | 0 | 0 | 11 | 0 | 1,246 | 49 | 133 | 0 | 179 | **1,620** |
| 2 | 2600-2700 | 0 | 0 | 8 | 0 | 8 | 0 | 643 | 24 | 116 | 1 | 513 | **1,310** |
| 3 | 2500-2600 | 0 | 0 | 29 | 0 | 41 | 0 | 734 | 39 | 126 | 16 | 748 | **1,730** |
| 4 | 2400-2500 | 0 | 0 | 86 | 0 | 40 | 2 | 754 | 80 | 257 | 70 | 533 | **1,820** |
| 5 | 2300-2400 | 1 | 0 | 59 | 0 | 102 | 3 | 508 | 95 | 217 | 111 | 316 | **1,410** |
| 6 | 2200-2300 | 2 | 0 | 78 | 0 | 155 | 2 | 503 | 100 | 142 | 39 | 132 | **1,150** |
| 7 | 2100-2200 | 2 | 0 | 62 | 0 | 66 | 4 | 368 | 86 | 46 | 19 | 67 | **720** |
| 8 | 2000-2100 | 3 | 0 | 51 | 0 | 30 | 28 | 497 | 119 | 64 | 16 | 24 | **830** |
| all | 2000-2700 | 9 | 0 | 373 | 0 | 453 | 39 | 5,254 | 593 | 1,101 | 272 | 2,511 | **10,610** |

*Table 4: Regionalized technical potential for annual electricity production from CSP. Calculated from [23]*

| **Grade** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **total** |
|---|---|---|---|---|---|---|---|---|---|
| **Max. annual electricity prod. [EJ/a]** | 10 | 30 | 50 | 100 | 150 | 300 | 700 | 2300 | **3640** |
| **CSP Full load hours [h]** | 6140 | 5920 | 5690 | 5460 | 5230 | 5010 | 4640 | 4380 | |
| **PV Full load hours [h]** | 2010 | 1930 | 1750 | 1660 | 1580 | 1490 | 1310 | 1140 | |

*Table 5: Adjusted global technical potential for electricity production from CSP and PV in ReMIND-G*

# 5 Results

This section shows the major results from the simulations carried out with the model ReMIND-G, considering two basic classes of scenarios: BAU (business-as-usual) and POL (policy). In the BAU case we simulate a development as if no climate policy was imposed. Thus there is no constraint on global $CO_2$ emissions. Within the POL scenario the $CO_2$ emissions are limited to the EU climate policy target to avoid a global warming by more than 2°C compared to the pre-industrial level. Moreover, for both BAU and POL runs two main technology scenarios are distinguished: Basic and Solar.

## 5.1 Basic Scenario

In the “Basic” scenario we simulate a development with PV but without CSP power plants, representing the default ReMIND setting. *Figure* 4 represents the development of the energy system for the BAU and the POL case. In both cases, the electricity production increases steadily during the century from 89 EJ in 2005 to 490 respectively 450 EJ in 2100. The energy demand is determined largely by two factors: the assumed population growth scenario (exogenous assumption) and the economic growth calculated endogenously by ReMIND-G. Only the continuous decrease of fossil fuel resources and the increase in energy efficiency dampen the upward development of electricity consumption.

The electricity production in the BAU case is mainly based on fossil fuels like coal, gas and oil. The use of coal increases strongly over time because of low costs and flexible trade and replaces gas and oil during the first half of the century. As for renewable energies, wind and biomass become competitive after 2010 due to increasing extraction costs of coal. The use of solar energy will not start before 2060. Nuclear energy will be used as a substitution for coal at the end of the century. Due to the high share of coal, $CO_2$ emissions are particularly high during the first half of the century.

In the policy scenario, drastic changes in the energy system are induced by climate policy. While the use of fossil fuels is significantly reduced and coal is completely to

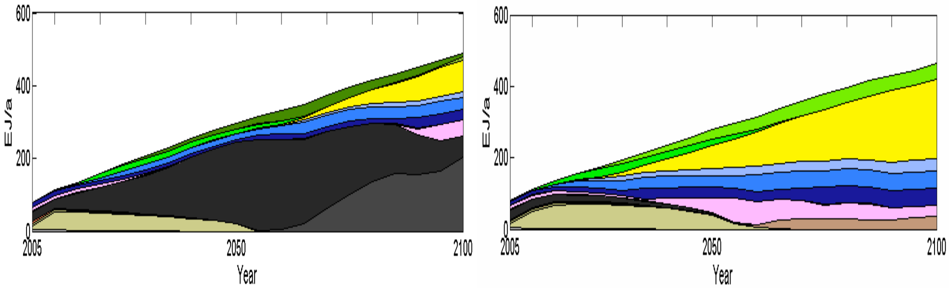


*Figure 4: Basic case: technology mix in the power sector a) BAU case b) POL case*

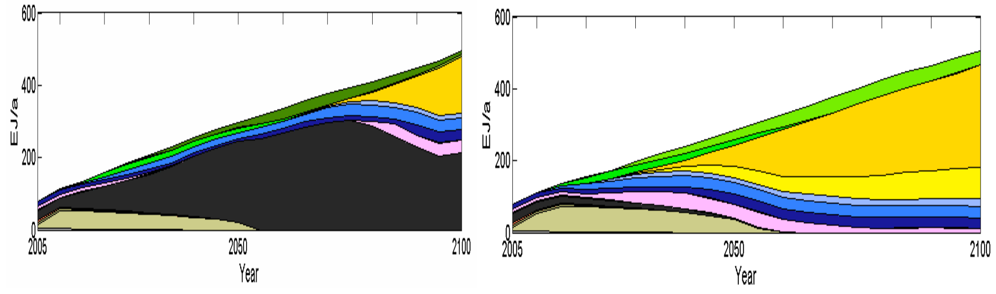
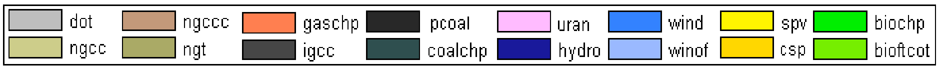


*Figure 5: Solar Scenario: technology mix in the power sector a) BAU b) POL*



phased out, renewable technologies and nuclear energy are developed earlier. In contrast to the BAU scenario wind and solar energy play an increasing role already after 2020. In 2100 the share of renewable technologies in the electricity mix accounts for a total of 90%. In addition, nuclear energy and gas (NGCC) combined with CCS technology are deployed.

## 5.2 Solar Scenario

In the ”Solar” scenario we additionally implemented CSP to investigate how the two solar technologies influence each other. *Figure 5* shows the changes in the electricity mix caused by CSP.

The Solar BAU scenario is similar to the Basic BAU scenario: Coal is still the dominant energy carrier and quickly replaces gas and oil. Renewables contribute only a minor share, with CSP being deployed from 2075 onwards. CSP completely replaces PV, and it is being deployed a bit stronger than PV was in Basic BAU. Nuclear energy is reintroduced about 2080, but it is deployed to a lesser extent than without CSP.

The availability of CSP leads to fundamental changes in the Solar policy scenario as can be seen in *Figure 5b*. Most notably, CSP becomes the major electricity source, supplying more than 50% from 2075 onwards. The contribution of other renewable technologies is reduced. Nevertheless, the share of renewables reaches about 90% of total electricity from 2060 onwards. The uranium that was required in the middle of the century in the Basic Policy scenario is now used earlier. This allows ReMIND to slightly reduce the gas use in the electricity sector and employ it instead for heat or transport (not displayed here). At the end of the century, the share of renewables in the electricity sector reaches 98%. Accordingly, the emissions of the electricity mix adjust to zero by the end of this century.

## 5.3 Option Values of Solar Technologies

To analyze the importance of solar electricity for achieving the EU climate target, we calculated the changes in mitigation costs which have to be paid to limit global warming to 2°C. As proxy for the mitigation costs we use global discounted GDP, cumulated from 2005 to 2100, and calculate the relative reductions in GDP in POL compared to BAU.

To calculate the option value of a technology, we run a scenario in which this technology is excluded from both BAU and POL. Accordingly, ReMIND must invest into other, more expensive technology options, and thus a lower GDP will be calculated, leading to higher mitigation costs.

We compared the relative mitigation costs for 4 scenarios: “No Solar” (neither CSP nor PV), “Basic” (no CSP), “No PV” and “Solar” (CSP and PV). As can be seen in *Figure 6*, not using solar power at all increases mitigation costs greatly by more than 80%, from 0.44% GDP in the Solar case with both CSP and PV, to 0.78% GDP in the No Solar scenario. Furthermore we find that with the current parameterization, CSP can

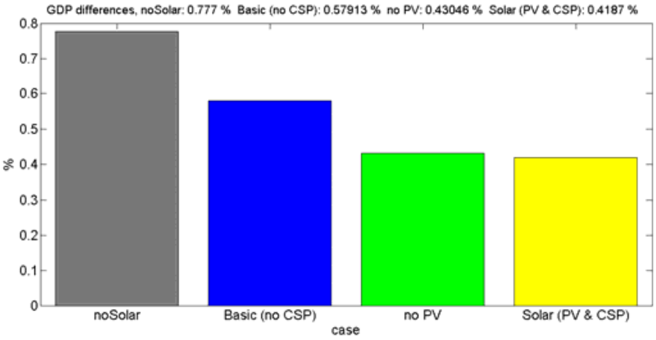


*Figure 6: Relative GDP reductions mitigation costs as percentag of GDP for different technology scenarios.*

easily compensate for excluding PV (mitigation costs increase by 3%), while the reverse does not hold (mitigation costs increase by 39%). This is probably due to the larger dependence of PV on electricity storage which becomes more and more expensive as share of generation increases (cf. Ch. 3). In contrast, CSP uses mostly cheaper thermal storage which is already included in the plant layout and thus does not become more expensive with increased share of generation.

## 5.4 Sensitivity Analysis

As CSP is still a newly developed technology with little commercial experience, the cost parameters are subject to major uncertainties (cf. Ch. 4). In order to test the robustness of our results, we performed a sensitivity analysis on investment costs.

*Figure 7a* shows the shares of CSP and PV in the cumulated electricity production from 2005 to 2100 for the POL scenarios. As investment costs for CSP increase, less and less electric power is produced by CSP plants, while the share of PV is increased. While CSP is completely replaced in the BAU scenario if the investment costs exceed 9000 $/kW, it is still used in the policy scenario due to emission constraints.

*Figure 7b* shows the temporal evolution of the electricity mix for the POL scenario with CSP investment costs of 10000 $/kW. In comparison to *Figure 5*, the decreasing share of CSP in the power production becomes apparent. Apparently, PV compensates the electric power generation by CSP when this technology is used less.

In summary it can be stated that CSP will play an important role in the electricity mix in both the POL and the BAU scenario. Due to uncertainties of investment costs and neglected grid integration costs we have made sensitivity analysis with increasing investment costs to estimate the range where CSP is still employed. The results indicate that CSP is even employed in the policy mix if costs are increased by 45% . This implies that we have a high margin of safety to cover the risks of uncertainty and grid integration. Nevertheless, increasing investment costs leads to a slow replacement of CSP and higher mitigation costs.

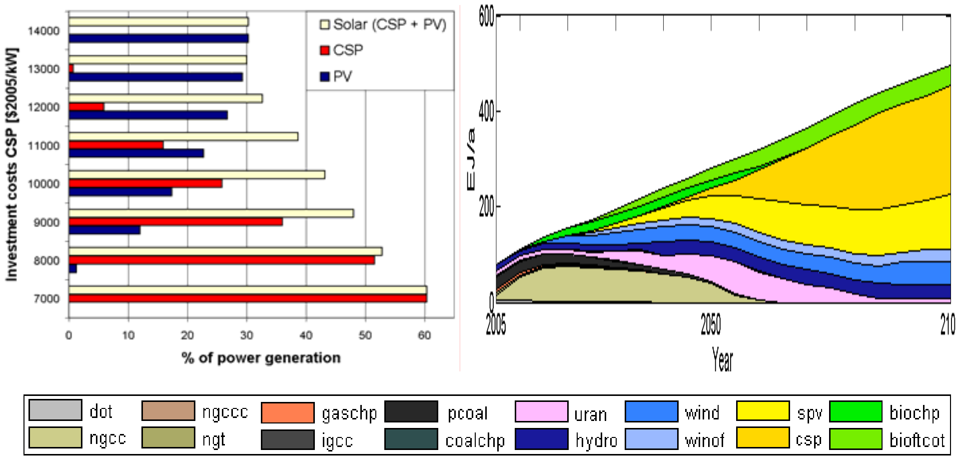


*Figure 7: Parameter variation ( a) Share in cumulated electricity production by CSP and PV in the policy scenario (b) Elecricity mix with CSP inv. costs of 10000 $/kW*

# 6 Conclusion

In this paper we present the results of using the hybrid-energy-economy-model ReMIND to analyze the role of solar electricity as well as the relative importance of CSP and PV in the future energy mix under the constraint of the 2°C EU climate protection goal. The model takes into account the competition between PV and CSP, both for constructions sites with strong irradiance and for investment capital to achieve cost reductions from technological learning. The dynamics of technological progress are modelled endogenously through a learning curve approach. To determine the robustness of the model results, we varied the investment costs of CSP.

The results show that solar power technologies will supply a significant share of electricty in the optimal abatement scenario if a stringent climate target of 2°C is to be met. In the BAU scenario coal dominates the electricty mix due to low costs. Either PV or CSP are deployed from 2070 onwards, with both cases resulting in the same GDP values.

In the Policy scenario the energy system is radically restructured due to the required $CO_2$ abatement, leading to an electricity mix that is dominated by renewable energies, especially CSP and PV. Without CSP implemented, PV plays the major role in the energy mix, supplying about 50% in 2100. When CSP is introduced, it becomes the major electricity source, supplying more than 50% from 2075 onwards. It replaces most of PV, the other renewables are reduced, nuclear energy is used earlier and CCS is not used anymore in the electricity sector.

To analyze the importance of the two solar technogies, we calculated how the GDP difference between BAU and POL cases, which acts as proxy for mitigation costs, changes when an individual technology is removed from the model. We find that exluding solar electricity increases GDP losses by more than 80%. Furthermore, if only one solar technology is used, PV is readily replaced by CSP with only minor GDP losses, while the inverse is not true.

We can conclude that if policy makers decide to enforce climate protection, CSP will play an important role in the power mix due to its base load capability and the resulting low electricity production costs. This result is emphazised by our sensitivity analysis: Up to a cost increase of 45%, CSP remains part of the generation mix in the Policy scenario. This leaves a wide safety margin for possibly underestimated investment costs or grid integration costs, which are neglected in ReMIND. Therefore it seems important to implement CSP in other models to test and consolidate the herein discussed results.

In ReMIND, the PV share of electricity generation is greatly reduced as CSP is introduced into the model. In reality, the rivalry and the resulting crowding-out will probably not be as severe due to several reasons:

1. while CSP plants will only be built by major energy suppliers, PV was in the past mainly financed decentrally by private capital. As increased private capital flowing into PV is expected once grid parity is achieved, small-scale PV growth may even accelerate much faster in the future.
2. It is impossible to know if all expectations about technological learning will come true. Thus, a prudent policymaker will not solely rely on one learning technology but rather try to promote both.
3. Due to its scalability, PV can be used in many less-developped regions to power villages not connected to a central electricity grid. This is not possible with CSP plants which require the economies of scale of 50-400MW-plants to be economically feasible.
4. In certain regions, CSP cannot be used due to low direct sunlight. PV only requires diffuse light, so its geographic deployment zone is larger than that of CSP.

To better analyze the influence of regionally limited potentials and to avoid overestimating CSP deployment, it is necessary to implement CSP systems in a model with a higher regional resolution. This might also allow the estimation of grid integration costs via the proxy of interregional electricty imports and exports and would probably lead to a partial replacement of CSP by PV due to its decentralized utilization.

Furthermore, it needs to be stressed that there is little commercial experience with both tower CSP and thermal storage. Thus, the results of our analysis might change in the near future when cost data from several projects being realized in 2009 or 2010 (more than 5GW of new constructions are projected until 2012) is included in our parameterization.

Owing to these caveats, the presented results should only be seen as a first sketch of the possible importance and deployment of solar technologies as we could not give adequate credit to all possible barriers and constraints.

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