The Role of Concentrating Solar Power and Photovoltaics for Climate Protection

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Abstract

In this paper we discuss the role 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. Sensitivity analyses of the investment costs of CSP and the learning rate of PV demonstrate that while both investment costs and learning rate 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%. To put this number into perspective, we then compare the options values for solar technologies with option values for other technologies like nuclear, carbon capture & storage (CCS) or biomass, finding that excluding solar technologies leads to higher GDP-losses than excluding either wind or nuclear, but to lower GDP-losses than excluding either CCS, all renewable technologies or biomass.

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

1 Motivation

After the rapid expansion 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 to the future energy mix. A recent example of this increased interest is the German “Desertec” project which brings together leading technology and utility companies in order to develop CSP plants as part of an African-European partnership. The decreasing availability of fossil fuels and the aspired realization of the 2°C climate protection target requiring substantial CO_2 abatement are leading to high R&D investments into new energy 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-

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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 led 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, the two solar technologies will compete with each other for two reasons:

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”[2]. 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 employ 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. The other 6% include new technologies like thin films made of amorphous silicon or cadmium telluride and organic photovoltaics. [7] 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%.

PV power generation is easily scalable to adapt to local requirements: for instance, the decentral powering of a water pump is possible using single modules with 200W capacity, while the modules can also be combined into huge arrays (power plants with capacities up to 60MW have been constructed) for grid-connected power supply.

CSP technologies use focusing optics like mirrors to concentrate 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 to allow transformation into electricity at a later time. The two main viable types of CSP systems are 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 on a line absorber that is heated to about 400°C. 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 intensities 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.

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[2] The concept of technological learning describes cost reductions due to capacity development, design improvements or cost reductions associated with economies of scale.

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 a 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. It is also suited for the analysis of optimal investments into energy systems under constraints and time-varying parameters such as emission restrictions due to climate protection, changing technological costs due to learning effects and changing resource costs due to scarcities.

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. Together with the endogenously calculated GDP growth rate of about 2%, this yields a interest rate of 3%.

The energy system model of ReMIND represents the energy sector at a high level of techno-economic disaggregation. Each technology is an energy conversion process that requires capital and primary energy carriers. The model distinguishes between exhaustible and renewable primary energy carriers. The extraction costs of the exhaustible resources (uranium, coal, gas, oil) are given by Rogner Curves [13], [18] to incorporate increasing extraction costs. The renewable energy sources wind (on- and offshore), hydro, solar, geothermal and biomass are restricted by annual technical production potentials[3], which are divided into grades with different full load hours (FLh) 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.

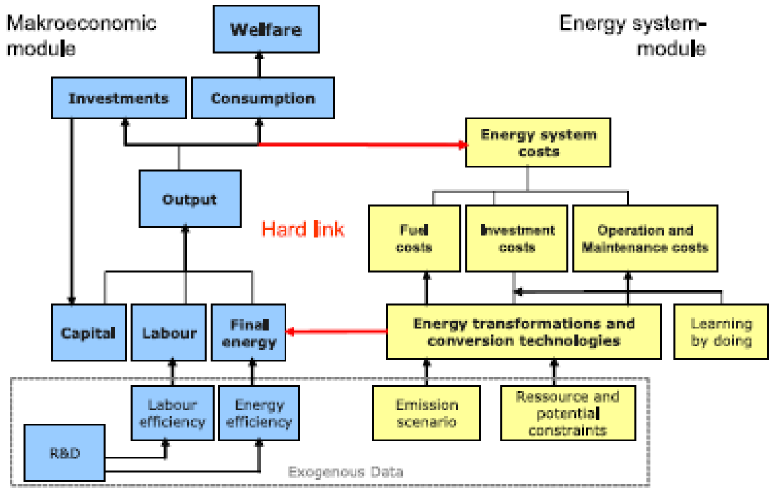

Figure 1: Overview of the model structure

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[3] The technical potential is the maximum amount of energy that can be produced when geographical and social constraints are taken into account, but economic constraints are not considered. It is thus smaller than the theoretical potential but larger than the economic potential.

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

Geographic 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. While the technical potential is measured in annual energy production, the geographical potential is the land area that remains from the theoretical potential once geographical and social 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 equal to or less than the total solar geographical potential.

Technological Learning: 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.

Fluctuations and Storage: 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, PV and CSP 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.

From the variability parameters of the individual renewable technologies it is possible to calculate the storage capacities which would be necessary to guarantee a stable supply in a world in which all electricity is produced by this one fluctuating renewable energy type. As losses occur when electricity is stored (see charge/discharge efficiencies in *Table 2*), it will also be necessary to install excess production capacities.

	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 in 2005 [GW]	0.7	0.7	
Cheaper technologies, but not included due to limited potential	pump hydro & (AA-)CAES*	pump hydro & (AA-)CAES*	

*Table 2: Storage technologies subdivided by variation. * 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*

Quite intuitively, the amount of storage required depends on the penetration rate of the fluctuating technology for which the storage is used. The full storage requirements described earlier are only necessary when all electricity comes from one source. In a world without any renewable energy, the existing production capacities and the distribution network already need and show a certain flexibility, as both production and demand fluctuate. Adding a minor new 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. The implementation of this observation can be explained on the example of the storage requirements for keeping the energy system stable while adding another kW of PV: the storage need relative to the electricity produced by 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 the square of the penetration rate of PV, as depicted in *Figure 2*.

The differences in storage requirements are one of the main differences between PV and CSP: while PV sees a very strong day-night cycle and thus requires large 12h-storage flow battery systems, CSP includes thermal storage in the basic plant setup and can thus be run 20-24 hours per day.

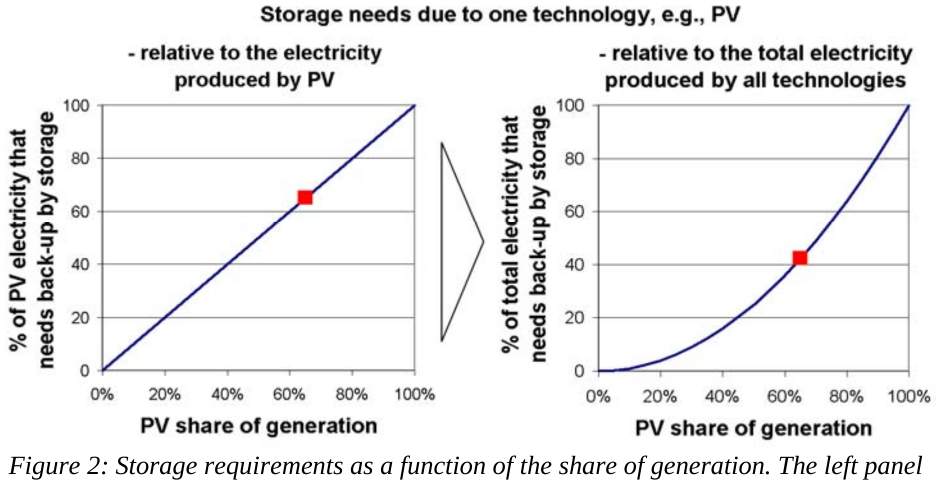

Figure 2: Storage requirements as a function of the share of generation. The left panel depicts the storage need relative to the electricity produced by PV. The right panel depicts the storage need relative to the total electricity production.

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 of PV [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 little 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[4] of 2400 kWh/m^2/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

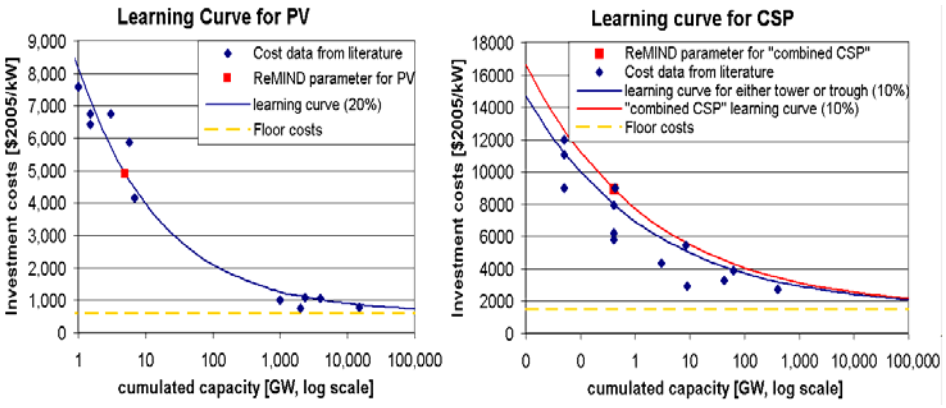

Figure 3: Learning curve a) PV b) CSP. Values above 5GW (PV) and 0.4GW (CSP) are projections into the future performed by the individual studies.

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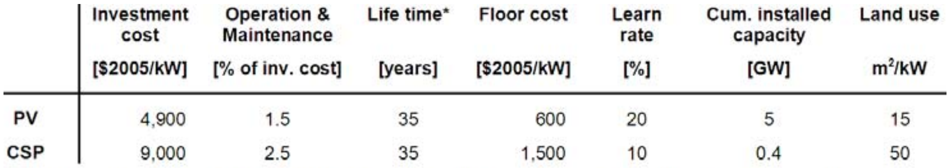
[4] Direct Normal Irradiance (DNI) is the total amount of sunlight that directly hits a plane which is kept perpendicular to the incident rays.



	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**

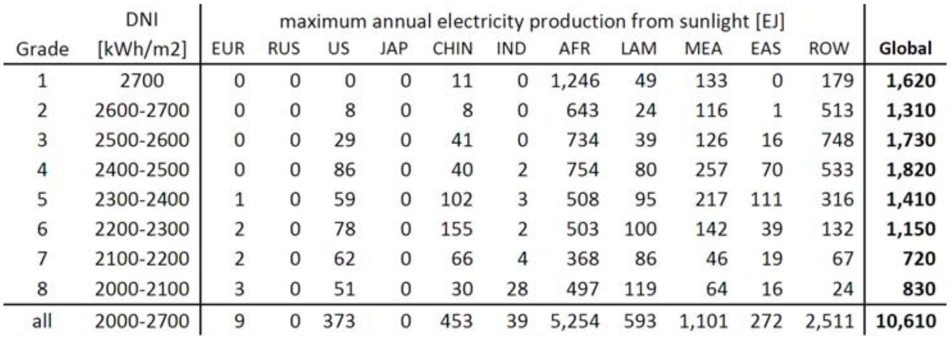
Table 3: Parameterization of PV and CSP

trough power plant at 400 MW cumulated capacity is equal to the cost of "combined CSP" at 800 MW of cumulated capacity. This penalty is a conservative estimation of the costs required to advance the tower technology to the level at which trough technology is today. 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

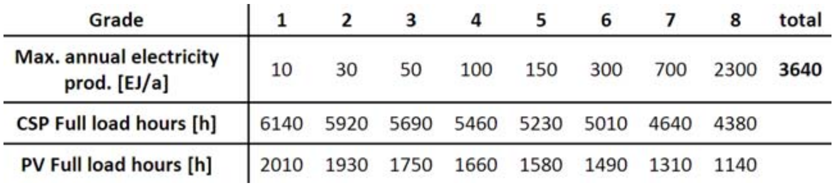
To calculate the technical potential of solar technologies, researchers have used world-wide satellite data for DNI and constructed GIS-based filters to exclude areas that are not available for power plant construction due to geographical (marsh, sand desert, forest, slope>2%) or social (habitation, 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.



	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]

When aggregating the regional potentials into one global potential (see *Table 5*), we strongly decreased the total potential of solar energy with respect to the estimated technical potential given in other studies like [24], giving us a safety margin. Furthermore we reduced 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. As a result we reduced especially the first three grades which are dominated by the high potential in Africa and increased instead the potential in the very low grades.



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

This is equivalent to a reduction of full load hours for the sites represented by these potentials, and we can thus indirectly account for the increasing electricity costs due to the rising grid integration and transmission costs when a large share of power generation comes from solar power.

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 in such a way as to achieve the EU climate policy target of limiting global warming to 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 in the second 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 phased out completely, 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 is almost 90%. In addition, nuclear energy and gas (NGCC) combined with CCS technology are deployed.

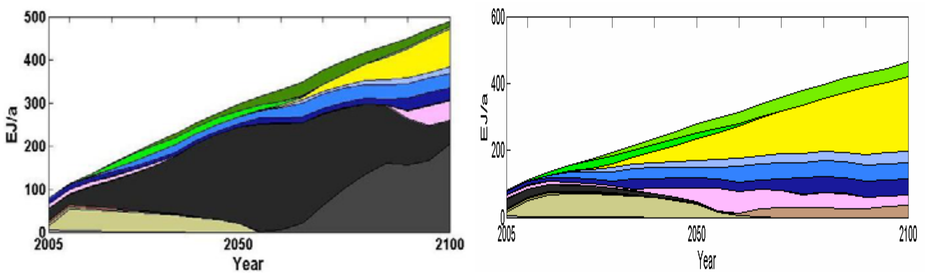


Figure 4: Basic Scenario: technology mix in the power sector a) BAU case b) POL case

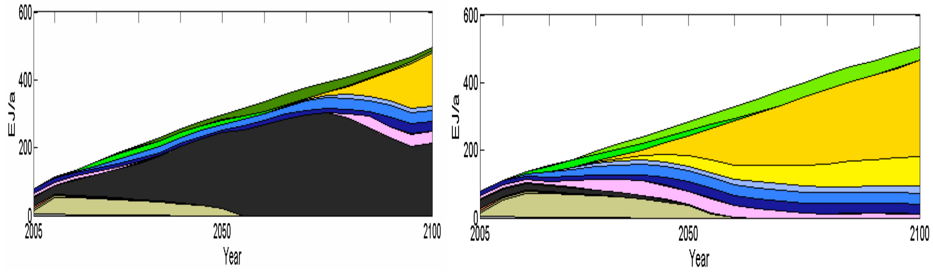


Figure 5: Solar Scenario: technology mix in the power sector a) BAU b) POL[5]

🟫 ngccc	⬜ dot	⬛ pc	🟪 tnrs	🟦 wind	🟨 spv	🟩 biochp
🟨 ngcc	⬛ igcc	⬛ coalchp	🟦 hydro	🟦 winof	🟧 sth	🟩 bioftcot

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 BAU scenario does not change with respect to the Basic BAU scenario: CSP is not deployed at all. However, if we force the model to deploy CSP, it completely replaces PV, and it is being deployed a bit stronger than PV was in Basic BAU. Welfare is only minimally reduced when CSP is used in the BAU case (by 0.002%), so the two technologies are close to a break-even.

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. While this development might at first seem astonishing as PV has both higher learning rate and lower investment costs and floor costs (Table 3), the higher full load hours of CSP and the additional costs of storage for PV result in ultimately lower electricity costs for CSP than for PV. A more detailed explanation is given in *section 5.3*. 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.

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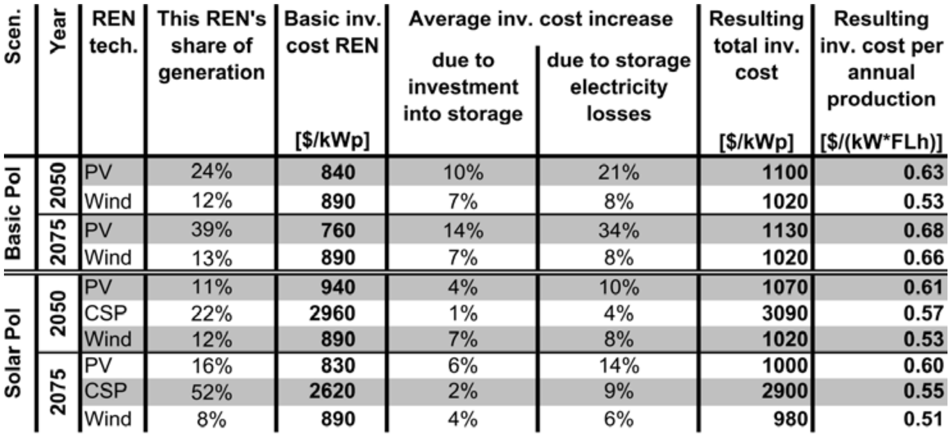
[5] Abbrev.: NGCCC – natural gas combined cycle with CCS, NGCC – natural gas combined cycle, DOT – diesel oil turbine, IGCC – integrated coal gasification combined cycle, PC – conv. coal, CoalCHP – coal combined heat and power, TNRS - light water reactor, HYDRO – hydroelectric power, Winof – wind offshore, SPV – solar photovoltaic, CSP – concentrating solar power, BioCHP – biomass combined heat and power, BioFTCot – biomass Fischer-Tropsch with CCS



Scen.	Year	REN tech.	This REN's share of generation	Basic inv. cost REN [$/kWp]	Average inv. cost increase		Resulting total inv. cost [$/kWp]	Resulting inv. cost per annual production [$/(kW*FLh)]
					due to investment into storage	due to storage electricity losses		
Basic Pol	2050	PV	24%	**840**	10%	21%	**1100**	**0.63**
		Wind	12%	**890**	7%	8%	**1020**	**0.53**
	2075	PV	39%	**760**	14%	34%	**1130**	**0.68**
		Wind	13%	**890**	7%	8%	**1020**	**0.66**
Solar Pol	2050	PV	11%	**940**	4%	10%	**1070**	**0.61**
		CSP	22%	**2960**	1%	4%	**3090**	**0.57**
		Wind	12%	**890**	7%	8%	**1020**	**0.53**
	2075	PV	16%	**830**	6%	14%	**1000**	**0.60**
		CSP	52%	**2620**	2%	9%	**2900**	**0.55**
		Wind	8%	**890**	4%	6%	**980**	**0.51**

Table 6: Basic investment costs as well as total investment costs (when storage requirements are taken into account) for PV, wind and CSP.
Abbrev.: kWp – kWpeak, FLh – Full Load hours

5.3 Cost development

To understand the deployment of either CSP or PV it is illustrative to compare the investment costs the model faces at a given time. Both technologies are learning technologies so their investment costs decrease, and both technologies require some amount of storage in dependence of their share of generation, so it is necessary to specify a time step and a scenario to discuss investment costs.

To compare the Solar and the Basic case, we display the shares of generation in 2050 and 2075 and the resulting investment costs per kW installed capacities in *Table 6*.

As a consequence of technological learning, the basic investment costs for one kW of a given technology decrease continually from 2050 to 2075 as cumulated capacity increases. However, the average total investment costs seen by the model can increase as the market share increases, as happens for PV in the Basic scenario. This is due to the fact that total investment costs include basic costs for the power plant plus investment costs for storage plus additional investment costs for further power plants which become necessary due to the storage losses.

These numbers show the two main reasons why CSP replaces most of the PV, even though it has much higher investment costs and a lower learning rate: The total mark-up for storage is much smaller (~11% for CSP in Solar compared to 48% for PV in Basic in 2075) and the investment cost per annual production capacity is similar due to much higher full load hours (see Table 5).

5.4 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

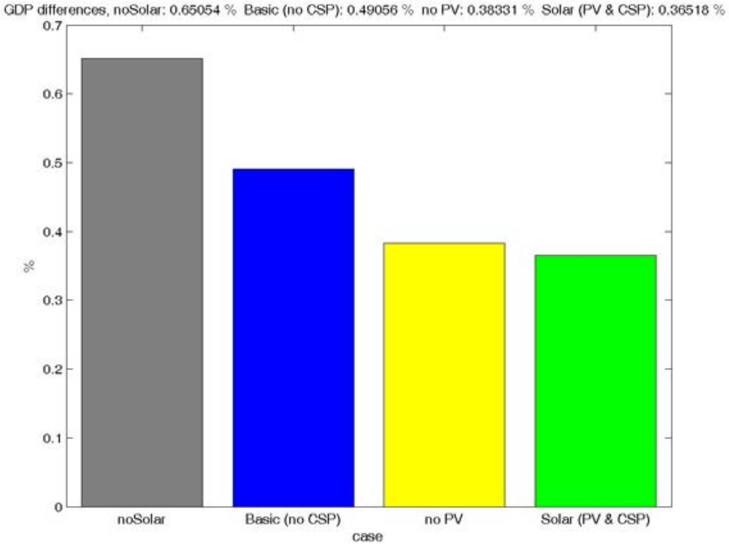


Figure 6: Relative cumulated GDP reductions as percentag of cumulated GDP for different solar technology scenarios, discounted by the model-endogenous interest rate of 3%.

scenario. Furthermore we find that with the current parameterization, CSP can easily compensate for excluding PV (GDP losses increase by 3%), while the reverse does not hold (GDP losses 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.

5.5 Option Values of other Technologies

To estimate the importance of solar technologies in comparison with other energy technologies, we performed further option value experiments in which we excluded one of the following: biomass use (in electricity and all other energy sectors like transport or heating), all renewable technologies (wind, wind offshore, hydro, PV, CSP), all CCS technologies (in electricity and all other energy sectors like transport or heating), nuclear, wind, and all solar technologies. The resulting accumulated GDP losses (discounted with the model-endogenous interest rate of 3%) are depicted in *Figure 7*, with the value for a Solar scenario in which all technologies are allowed added for comparison.

Immediately apparent are the high GDP losses of almost 1.6% which arise when biomass is excluded. This might at first seem astonishing as biomass does not produce a major share of electricity (see *Figure 5*). It is, however, heavily used in the transport and heat sectors (not displayed here), so replacing biomass is very costly. Excluding all renewables incurs slightly higher losses than disabling CCS, both about 0.8% of GDP. The high costs of not using CCS are again mostly explained by the transport sector: fuels whose carbon is sequestrated in refineries are important for decarbonising the transport sector. If only the electricity sector is not allowed to use CCS, the GDP losses are within few percent from those of the optimal abatement scenario, thus CCS is not important for the electricity sector.

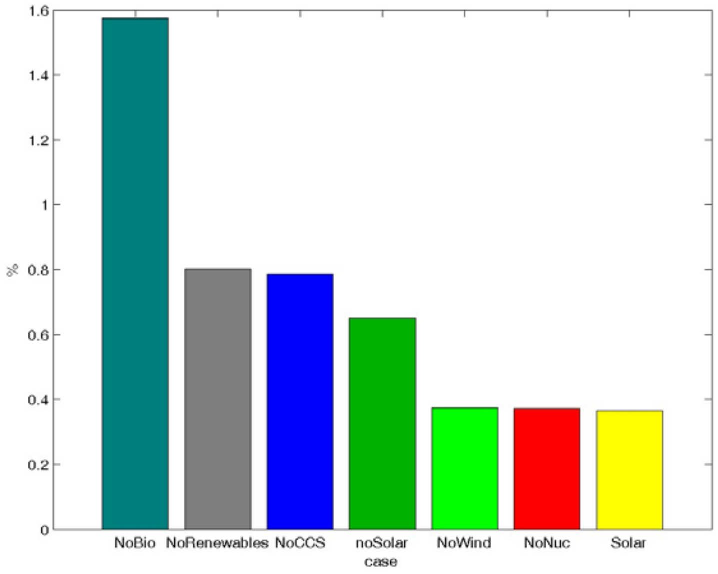


Figure 7: Relative cumulated GDP reductions mitigation costs as percentag of cumulated GDP for different technology scenarios, discounted by the model-endogenous interest rate of 3%

Not using any solar technology is next, with losses of 0.65% of GDP. Excluding either wind use or nuclear technologies has only a very limited negative influence on GDP, increasing the lowest achievable mitigation costs of 0.35% of GDP by only a few percent. This is due to the facts that they contribute only a minor share to the electricity mix (wind 13%, nuclear8%) and that they are not needed in other sectors of the energy model.

5.6 Sensitivity Analysis

As CSP is still a relatively new 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.

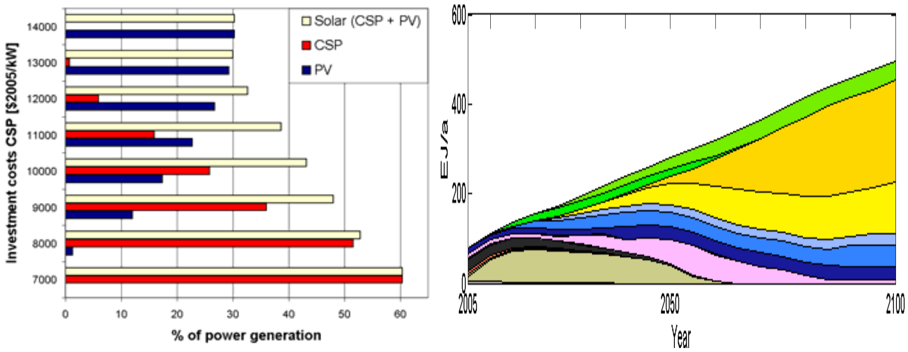


Figure 8: Parameter variation (a) shares of cumulated electricity production by CSP and PV in the policy scenario (b) Elecricity mix with CSP inv. costs of 10000 $/kW

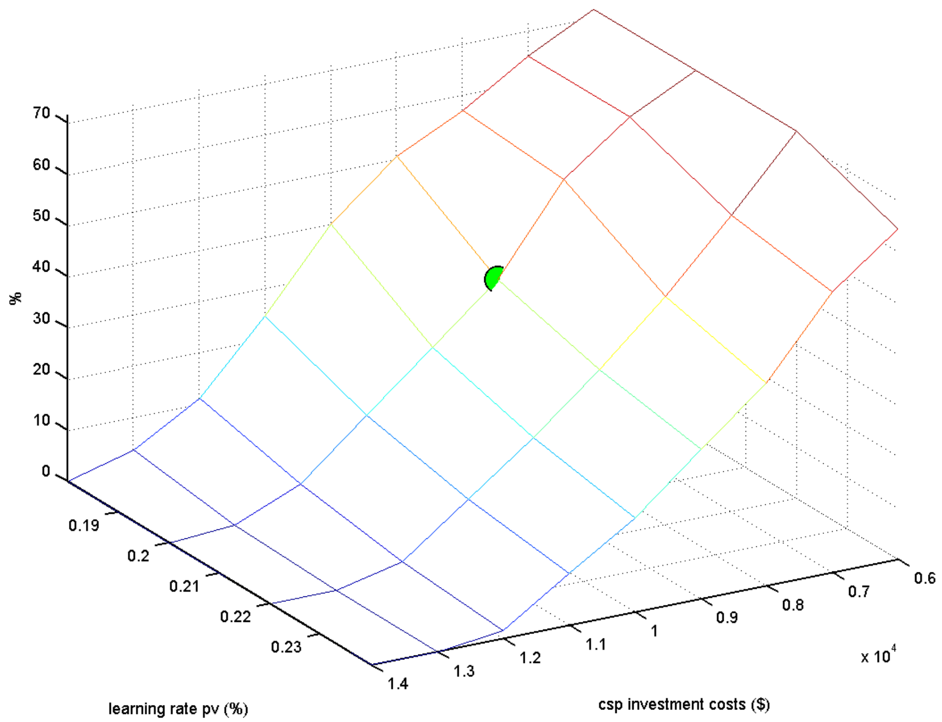


Figure 9: CSP share of cumulated electricity production in the policy scenario when both CSP investment costs and the learning rate of PV are varied. The green dot represents our chosen ReMIND values.

Figure 8a 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 8b 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.

We then analyzed how the generation share of CSP is influenced when both investment cost for CSP as well as the learning rate for PV is varied. The results are displayed in *Figure 9*. Clearly, both investment costs and learning rate have the expected influence on deployment: the higher the investment costs for CSP and the higher the learning rate for PV – and thus the lower the investment cost for PV –, the less CSP is deployed by ReMIND. However, even an increase of PV learning rate up to 24% and an investment cost of 1200$/kWp does not lead to complete replacemtent of CSP.

In summary it can be stated that CSP will play an important role in the electricity mix in the POL scenario. Due to uncertainties of investment costs and neglected grid integration costs we performed sensitivity analyses 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.

6 Conclusion

In this paper we present the results of using the hybrid-energy-economy-model ReMIND to analyze the role of solar electricity in general 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 construction 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 and the learning rate of PV.

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 very similar 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 main role in the energy mix, supplying about 50% in 2100. When CSP is introduced, it becomes the main 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 the model is restricted to only use one solar technology, PV is readily replaced by CSP with only minor GDP losses, while the inverse is not true.

When compared to other technology options, solar technologies seem to be more important than nuclear or wind, but less important than CCS or biomass which both are very important for the decarbonization of the transport and heat sectors.

We can conclude that if policy makers decide to enforce climate protection, CSP could 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 presented 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 be realized. Thus, a prudent policymaker will not solely rely on one learning technology but rather try to promote a portfolio of promising low carbon technologies.
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. Thus, grid integration costs will be high for CSP from the

outset, while they will start very low for PV at low generation shares when most of the capacities can be built close to settlements. Only when substantial amounts of PV are deployed, similar remote areas like those chosen for CSP will be used, requiring major investments into long-distance electricity lines.

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.
5. When one renewable technology supplies a very large share of electricity, the question arises how the production is distributed over different countries. It is not plausible that each individual country has sufficient potential of this renewable energy type. It then becomes necessary to use the high potential in other countries to satisfy one’s own energy demand, leading to possible complications on a political level.

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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