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Economic evaluation of the industrial solar production of lime

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Abstract

The use of concentrated solar energy in place of fossil fuels for driving the endothermic calcination reaction $CaCO_3 \rightarrow CaO + CO_2$ at above 1300 K has the potential of reducing CO_2 emissions by 20% in a state-of-the-art lime plant and up to 40% in a conventional cement plant. An economic assessment for an industrial solar calcination plant with 25 MW_{th} solar input indicates that the cost of solar produced lime ranges between 128 and 157 \$/t, about twice the current selling price of conventional lime. The solar production of high purity lime for special sectors in the chemical and pharmaceutical industry might be competitive with conventional fossil fuel based calcination processes at current fuel prices.

Keywords: Solar energy; Solar lime; Solar calcination; CO_2 mitigation; Economic assessment

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1. Introduction

Lime and cement manufacturing are high temperature energy intensive processes. The minimum amount of energy in the form of process heat that is required to drive the calcination reaction,

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Nomenclature

A	area, m^2
C	(current) costs, \$
$\tilde{C}$	solar concentration ratio
d	diameter, m
DNI	direct normal irradiance, kWh/m^2 annual
f	(multiplication) factor
h	height, m
i	real interest rate (discount rate), %
I	investment, \$
IRR	internal rate of return, %
I_{solar}	solar insolation, W/m^2
l	length, m
n	number
N	net income, \$
NPV	net present value, \$
p	price of product, \$/t
PBT	payback time, a
q	quantity of product, t
$\dot{Q}_{\text{solar}}$	solar power input to kiln, MW_{th}
S	savings, \$
t	time (s, min, h, d, a)
V	value of product, \$

Greek letters

α	availability
ΔH	heat of dissociation, MWh/kg
η	efficiency
φ	angle, °

Subscripts

ACS	autonomous control system (for heliostat field)
CO_2-tax	CO_2 tax
CPC	compound parabolic concentrator
EPCM	engineering, procurement, commissioning, management
HF	heliostat field
opt	optical
rim	rim angle
t	time
TR	tower reflector

Superscripts

acc	accumulated
add	additional
att	attenuation
conv	conventional
24 h	24 h a day
max	maximum
min	minimum
O&M	operation & maintenance

$$CaCO_3 \rightarrow CaO + CO_2 \tag{1}$$

at the decomposition temperature near 1173 K is about 3029 kJ/kg of CaO, while the heat of dissociation of calcite relative to 298 K is 3184 kJ/kg of CaO [1]. Total heat consumption of modern lime kilns ranges from 3600 kJ/kg of CaO for vertical double shaft kilns to 7500 kJ/kg of CaO for non-preheated long rotary kilns [1,2]. Because the process heat is traditionally supplied by the combustion of fossil fuels (e.g. oil, coal or natural gas), a lime or cement plant releases CO_2 derived both from the calcination reaction (Eq. (1)) and from the combustion process that supplies the energy for the reaction. According to the World Business Council for Sustainable Development [3], the cement industry is responsible for 5% of global anthropogenic CO_2 emissions, of which 50% is derived from the chemical process and 40% from burning fuel. The remainder is split between electricity and transport use. Estimates of the global anthropogenic CO_2 emissions from the lime industry are near 1% [1]. Here, the combustion of fossil fuels contributes 20–40% of the plant's CO_2 emissions depending on the type of kiln used. A number of strategies have been proposed for mitigating these emissions. Examples include the capturing and sequestering of CO_2, fuel switching such as the use of waste products as a fuel source [4] and the use of concentrated solar energy as the source of process heat [5–8]. The cleanliness of the solar process leads to very pure lime. It seems conceivable that a pure product may be advantageous for special niche markets in the chemical and pharmaceutical industries. The technical feasibility of the solar calcination process has already been demonstrated for 10 kW solar reactor prototypes [9,10] tested in a high flux solar furnace [11].

This paper presents an economic assessment of the industrial solar production of lime. The economic analysis requires a definition of the material and energy flows and an estimation of the costs of the solar lime plant components and their operation and maintenance.

2. Methodology

A detailed description of the conventional lime and cement process steps and their inventory and materials is found in Refs. [1,2]. Data have been extracted from various sources, mainly from Ref. [12] on conventional lime production and from Ref. [13] on solar plant design and from literature cited therein. Comparing solar and conventional lime plants is complicated by the fact that the latter are characterized by their wide variation of kiln designs, capacities and fuel used. In contrast, solar applications require a solar concentrating system to provide high temperature process heat for the calcination process. Consequently, our approach follows a methodology that only considers capital and operational cost differences, i.e. system components that are common to both applications are omitted from the cost calculations.

2.1. System boundaries

The conventional lime production process is depicted in Fig. 1 [12]. Only the calcination process (inside the box) is affected by the solar thermal application; the remaining steps are common to

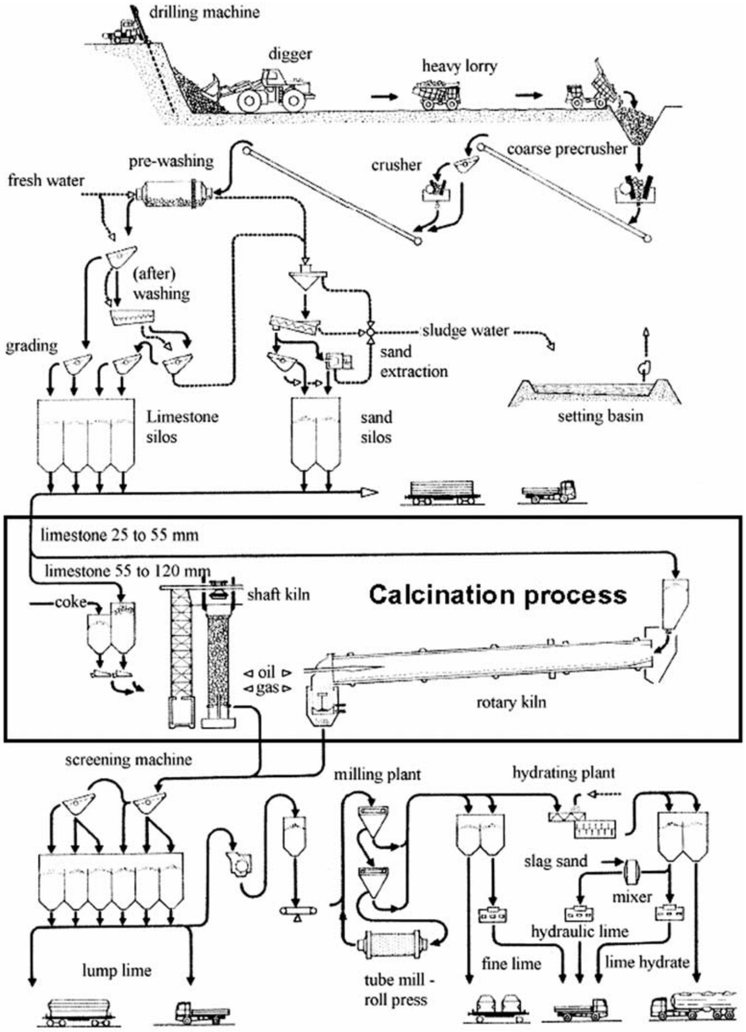

Fig. 1. Schematic representation of the conventional lime production process. Only the calcination process (inside the box) is affected by the solar thermal application [12].

both solar and conventional plants. Thus, capital and operational cost differences between solar and conventional lime plants are predominantly derived from the different types of lime kiln and the process heat source.

Plant configuration: The plant size is defined by the thermal power input to the kiln, independent of the source of process heat. This approach decouples the solar concentrating system from the conventional lime production process, so that the cost of the solar system can be adopted from previous solar thermal power plant design studies [13]. The concentrating solar system is based on the "Solar Tower" that uses a field of heliostats (two axis tracking parabolic mirrors) that focus the sunrays onto the top of a centrally located tower. Principally, two different optical configurations are conceivable (Fig. 2): (1) tower top (TT) solar system where the solar lime kiln is mounted on top of a tower [14,15]; and (2) tower reflector or "beam down" (BD) solar system where a hyperbolic reflector re-directs the sunrays into the solar lime kiln placed on the ground level [16,17]. BD systems are further equipped with a non-imaging compound parabolic concentrator (CPC) to augment the solar radiation entering the kiln [18]. TT systems may require a CPC as well when the peak concentrated solar flux, typically 1200 suns (1 sun = 1 kW/m^2), is not sufficient to reach calcination temperatures near 1200–1600 K.

Plant size: The reference case is based on a 50 tpd conventional lime plant, corresponding to 3 MW$_{th}$ thermal power entering an 80% efficient single shaft kiln. This plant size represents the lower limit for commercial lime production. Typically, large industrial lime plants produce up

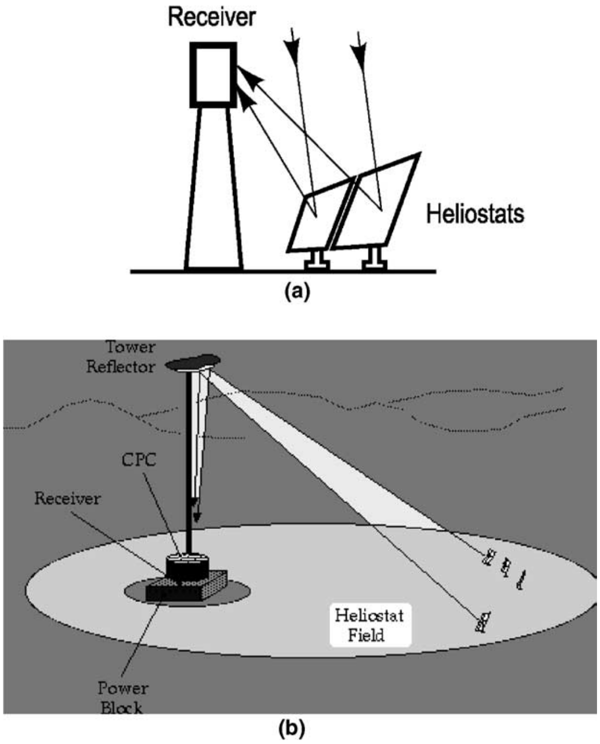

Fig. 2. (a) Scheme of a tower top (TT) system; (b) scheme of a tower reflector or "beam down" (BD) system [19].

Table 1
Specification of a conventional 50 tpd single shaft lime kiln used as a reference case

Parameter	Value	Reference
Efficiency	0.8	[20]
Operating days per year	358 days (24 h a day), 7 days break for refractory lining check	[20]
Output per year	17,900 t/a (50 tpd)	Calculated
Fuel oil consumption	215 kg/h	[20]
Electric energy use	30 kWh/t	[20]
Specific heat consumption	1.163 kWh/kg of lime (CaO)	[20]
Total energy consumption per year	21 GWh	Calculated
CO_2 emission per GWh fuel consumption	440 t/GWh	[21]

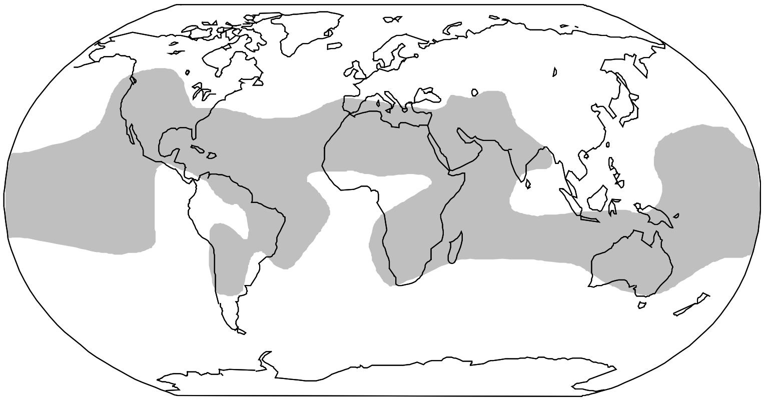

Fig. 3. Regions with an annual solar irradiation exceeding 2000 kWh/m^2.

to 1500 tpd of lime in long rotary kilns with about 45% efficiency [1]. The kiln specification for the reference case is presented in Table 1 according to Ref. [20].

Plant location: Minimum annual solar insolation requirement for the plant location is 2000 kWh/m^2. Possible sites are highlighted in Fig. 3. Typically, solar irradiation of 500–600 W/m^2 is required to start up and for preheating. Initial capital cost is affected by the solar insolation, site topology, land price and the available infrastructure (e.g. roads, electricity, and water). O&M costs depend on local wages and taxes.

2.2. Investment costs calculation

Table 2 lists the economic indicators involved. The three capital investment decision indicators used in our economic analysis are: (1) the payback time (PBT), defined as time required for an investment project to recover its initial cost; (2) the net present value (NPV), defined as the present value of the flow of net incomes minus the present value of the flow of investments (if NPV > 0, the investment becomes profitable); and (3) the internal rate of return (IRR), defined as the discount rate at which NPV equals zero.

Table 2
Economic indicators [22]

Indicator	Parameter definition
Time	t
Quantity of product	q
Price of product	p
Value of product	$V_t = q_t \cdot p_t$
Current costs	C_t
Net income	$N_t = V_t - C_t$
Investments	I_t
Real interest rate (discount rate)	i
Discount factor	$\frac{1}{(1+i)^t}$
Discounted value of net income	$N = \sum_t \frac{N_t}{(1+i)^t}$
Discounted value of investments	$I = \sum_t \frac{I_t}{(1+i)^t}$
Net present value (NPV)	$\mathrm{NPV} = N - I = \sum_t \frac{N_t - I_t}{(1+i)^t}$
Internal rate of return (IRR)	IRR = i for NPV = 0
Payback time (PBT)	$\mathrm{PBT} = \frac{I_t}{N_t}$

Capital costs: The major differences in capital cost between solar and conventional lime plants arise from the solar concentrating system. The heliostat field represents the largest single cost item in the solar plant. Fig. 4 depicts the heliostat cost (which includes material, civil engineering work and installation) as a function of the heliostat field size. The assumed cost of 125 $/m^2 for a heliostat field of about 100,000 m^2 [23] is compatible with previous estimates for large scale production of silvered glass heliostats [24,25]. For smaller purchase orders, the estimated cost is about 400 $/m^2 for a heliostat field of 2000 m^2 [26] and 250 $/m^2 for an intermediate heliostat field of about 10,000 m^2. Land costs are considered as additional capital cost. The cost curves for the solar tower are shown in Fig. 5 and were derived from data of existing solar test facilities or developed in previous engineering studies (see Table 3). The tower costs include material, civil work and installation. The BD system requires additionally a hyperbolic reflector, whose area is 2.3% of the

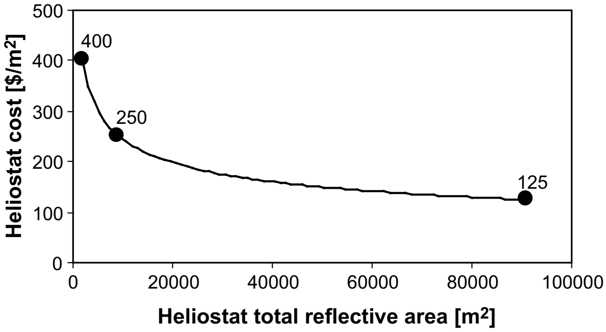

Fig. 4. Heliostat installed cost dependence on plant size.

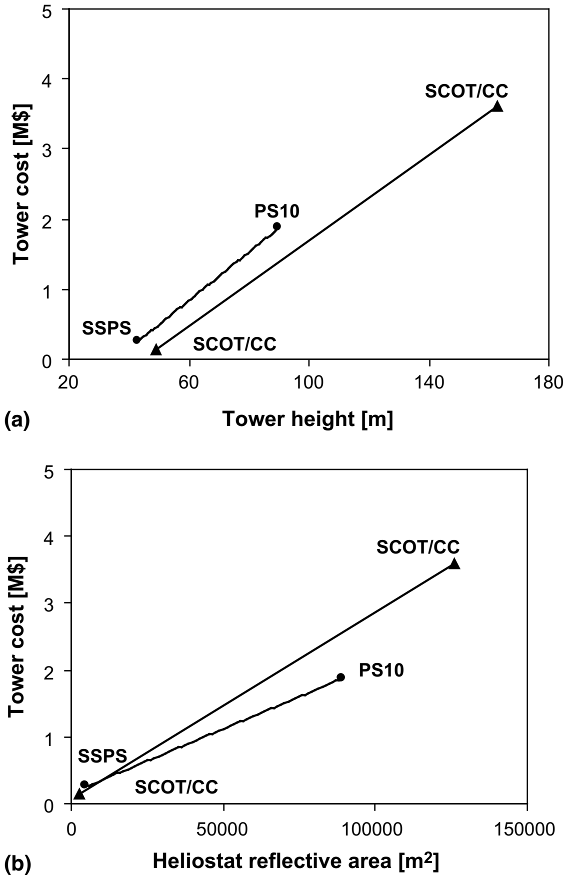

Fig. 5. Tower installed cost dependence (a) on tower height and (b) on heliostat reflective area (data from Table 3).

Table 3
Capital cost of different solar towers

System	Test facility	Tower height, m	Heliostat area, m^2	Thermal power into kiln, MW	Cost, M$	Reference
TT	SSPS-CRS	43	4955	2.7	0.195	[28,29]
TT	PS10	90	89,271	55	1.876	[30]
BD	SCOT/CC	49	2736	0.28	0.134	[28,31]
BD	SCOT/CC	163	126,000	16.2	3.6	[31]

heliostat reflective area. Its cost is estimated to be between 500 $/m^2 for a 30 MW$_{th}$ plant [27] and 1000 $/m^2 for a 0.5 MW$_{th}$ plant (see Fig. 6). While BD systems are always equipped with a CPC, TT solar systems only need it if the concentration ratio is not sufficient to reach the required kiln temperatures. Capital cost estimates for the CPC range from 0.2 M$ for a 0.5 MW$_{th}$ plant to 1 M$ for a 30 MW$_{th}$ plant (Fig. 6). The peripheral components that show significant cost differences are

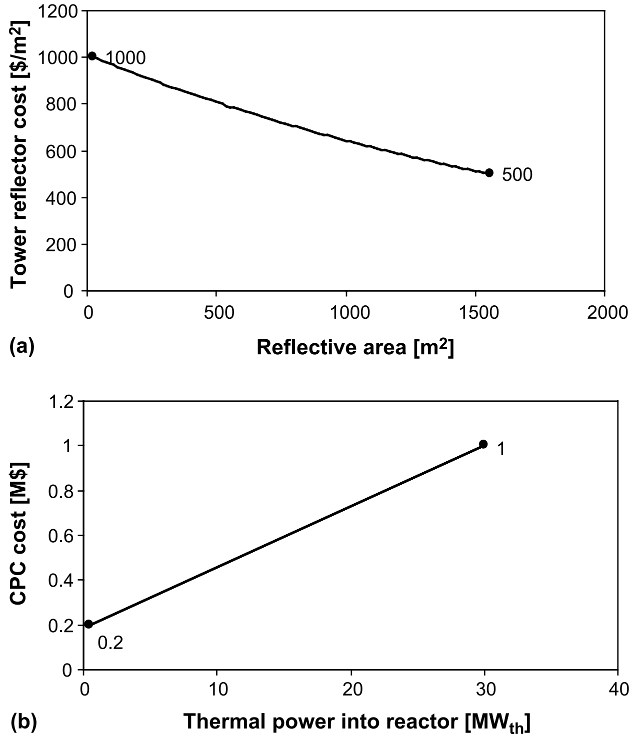

Fig. 6. (a) Tower reflector cost vs. reflective area; (b) CPC cost vs. solar thermal power input into the reactor.

listed in Appendix A, Table 10. Those components that reveal only marginal cost differences have been neglected from the calculations. [2]

Annual costs: The largest single annual cost difference between conventional and solar lime production concerns the fuel costs, which do not occur for the solar plant. An average fuel oil price of 176.5 $/t is assumed [32]. Except for some additional electric energy use for rotational and conveying systems at assumed costs of 100 $/MWh [33], no further O&M cost differences are taken into account. O&M cost estimates for the heliostat field are 7 $/m^2/a [33], for the tower reflector about twice as much and for the CPC 1% of the initial capital cost. These costs include wages, materials and cleaning equipment. The annual accounting of the solar lime plant is charged with a linear depreciation over the lifetime of the plant, as well as with an additional sum for risk insurance, assumed at 1% of the additional capital cost for the solar concentrating system [34].

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[2] Including: kiln steel structure, stairs, platform, and rails, compressed air station, limestone feeding, lime discharging, cooling air blowers, relief valves, piping, measuring and control instrumentation, refractory lining, oil hydraulic plant, machine and control rooms.

3. Plant design and cost estimates

The baseline input parameters are listed in Table 4. Further inputs are the efficiencies of the solar lime kiln and the solar concentrating system (see Appendix A, Table 11). The overall optical efficiency η_{opt} (including CPC) is taken as 61% for the TT solar system and 52% for the BD solar system. The efficiency of the solar lime kiln, defined as the ratio of the process heat used for the chemical reaction to the solar power input, is estimated between 40% and 50% [39]. The non-optimized solar rotary kiln prototype tested at PSI's solar furnace has reached values near 35% [10]. The plant size is specified at the design point by the amount of solar power $\dot{Q}_{solar}$ entering the lime kiln through the aperture at peak insolation I_{solar}^{peak}, conveniently set to 1000 W/m^2 (see Table 4). The minimum insolation level I_{solar}^{min} is about 500 W/m^2, allowing for plant operation at lower temperatures and/or lower lime production rates. The solar concentration ratio $\widetilde{C}$, defined as the ratio of $\dot{Q}_{solar}/A_{aperture}$ to I_{solar}, must exceed 2000 in order to achieve cavity temperatures of 1600 K. The annual direct irradiance DNI depends on the plant location. In the Mediterranean region, it is typically in the range between 1800 and 2500 kWh/m^2/a. The reflective area of a single heliostat has to be adapted to the aperture size of the lime kiln. For large kilns, hence large solar plants, heliostats with reflective areas $A_{heliostat}$ of 91 m^2 [30] or 120 m^2 [35] are ready for the market. The heliostat availability $\alpha_{heliostat}$, i.e. percentage of heliostats working simultaneously, is assumed

Table 4
Baseline input parameters

Parameter	Unit	Variable	Typical value	Remark
Plant specification				
Solar power input to kiln	MW$_{th}$	$\dot{Q}_{solar}$	5	Design point
Peak insolation level	W/m^2	I_{solar}^{peak}	1000	Max. 1000 (fix)
Minimum insolation level	W/m^2	I_{solar}^{min}	500	Min. 500 (var.)
Solar concentration ratio	–	$\widetilde{C}$	2000	Min. 2000
Direct normal irradiance	kWh/m^2/a	DNI	2300	Site dependent
Single heliostat area	m^2	$A_{heliostat}$	120.0	[35]
Heliostat availability	–	$\alpha_{heliostat}$	0.98	Assumption
Land use factor	–	f^{land}	0.35	[27,36]
Cost specification				
Heliostat cost	\$/m^2	$C_{heliostat}$		Fig. 4
Tower cost	\$1000	C_{tower}		Fig. 5
CPC cost	\$1000	C_{CPC}		Fig. 6
Kiln additional cost	\$1000	C_{kiln}^{add}		Table 10
Land price	\$/m^2	p^{land}	2	Site dependent
O&M cost of the heliostat field	\$/m^2/a	$C_{HF}^{O\&M}$	7.0	[33]
Economic data				
Lime selling price	\$/t	p_{lime}^{conv}	60.0	[37]
Lime quality factor	–	$f^{quality}$	2.0	Lime quality!
CO$_2$ tax	\$/t	$p_{CO_2\text{-tax}}$	38	[38]
Plant lifetime	a	t	25	[27,34]
Discount rate	%	i	15	Assumption

>98%. The land use factor f^{land} depends on the size of the plant and on the latitude of the site; reported values for north/south fields vary between 0.31 and 0.42 [27] with an optimum at 0.35 [36]. Cost for system components like heliostats, tower, tower reflector and solar lime kiln can either be calculated according to data given in figures or tables (see Section 2) or defined as a lump sum. The selling price for conventional lime $p_{\text{lime}}^{\text{conv}}$ is about 60 \$/t of lime [37]. It is conceivable that high quality solar produced lime can be sold at a higher price. Thus, the selling price $p_{\text{lime}}^{\text{conv}}$ for conventional lime may be multiplied with a lime quality factor f^{quality} in order to study its effect on the economics of a solar lime plant. Usually, the lime quality factor is chosen such that the resulting payback time PBT is in the order of 5–7 years. In addition, a CO_2 tax $P_{CO_2\text{-tax}}$ (typically 30–50 \$/t of CO_2 released) may be charged on conventional lime [38].

A solar lime plant lifetime of 20 to 30 years is assumed [27,34]. The discount rate (real interest rate) of 15% per annum is representative of private ownership with a significant fraction of borrowed money. Early plants would probably have a higher discount rate because of the perceived higher risk. Note that the discount rate is charged on the cost difference only and not on the whole lime plant investment. The time period between ordering and commissioning of the solar lime plant is assumed as 3 years. For the investment cost calculation, it is assumed that the necessary capital is invested by three installments, each at the beginning of the year. All R&D costs for the optical system are considered as sunk costs that are due before the start of the investment project. However, engineering costs for the design of the plant are taken into account as part of the indirect cost such as for engineering, procurement, commissioning and management (EPCM). Generally, indirect costs C_{EPCM} amount to 20% of the initial capital cost except those for the heliostats that amount to only 10% of the total capital cost [32]. On top of the total investment cost (including indirect cost), a contingency $C_{\text{contingency}}$ of 15%, typical for high risk projects, is added. No state taxes are included.

A detailed description of the output parameters is given in Appendix A. The list comprises plant specification (Table 12), lime production (Table 13), capital cost (Table 14), annual cost and savings (Table 15), and specific cost (Table 16).

4. Results and discussion

The design specifications of the TT and BD solar lime plants are shown in Table 5, for three different solar thermal power inputs: 1, 5 and 25 MW_{th}. The cost breakdown is presented in Table 6 for the baseline case. From Table 5, one sees that the hours of operation per year and the accumulated solar irradiance are independent of the plant size and configuration. The annual plant efficiency is also independent of the plant size but is higher for the TT than for the BD solar system. For example, a 5 MW_{th} solar lime plant has a peak production rate of 2.5 t/h. Its average daily production rate amounts to 48.7 tpd during 24 h of hybrid operation. However, for purely solar operation, it is reduced to 14.9 tpd.

From Table 6, it follows that the BD solar system is generally more expensive than the TT one due to the higher number of heliostats, the higher tower and the tower reflector required for the BD optical configuration. The specific costs per kW of installed power decrease with plant size. Assuming $f^{\text{quality}} = 2$, i.e. doubling the selling price for solar produced lime, neither the TT nor the BD solar systems achieve positive net present values NPV after the end of the investment

Table 5
Design specifications of the TT and BD solar lime plants

Plant design	Plant size	1 MW_{th}		5 MW_{th}		25 MW_{th}	
	Unit	TT	BD	TT	BD	TT	BD
Plant specification							
Solar power input on HF	MW_{th}	1.65	1.92	8.24	9.58	41.20	47.92
Annual solar energy input on HF	MW h/a	3586	4171	17,932	20,857	89,662	104,284
Hours of operation per year	h/a	2677	2677	2677	2677	2677	2677
Accumulated solar irradiance	kW h/m^2/a	2133	2133	2133	2133	2133	2133
Optical efficiency (incl. CPC)	–	0.61	0.52	0.61	0.52	0.61	0.52
Kiln efficiency	–	0.45	0.45	0.45	0.45	0.45	0.45
Annual solar lime plant efficiency	–	0.27	0.23	0.27	0.23	0.27	0.23
Optical system specification							
Heliostat field (HF) reflective area	m^2	1682	1956	8408	9779	42,040	48,896
Number of heliostats	–	14	16	70	81	350	407
Heliostat field (HF) land area	m^2	4805	5588	24,023	27,940	120,115	139,702
HF diameter (fictitious)	m	78	84	175	189	391	422
Tower height	m	58	48	61	55	74	90
Tower reflector (TR) surface	m^2	–	45	–	225	–	1 125
TR diameter (fictitious)	m	–	4	–	8	–	19
CPC entrance diameter	m	1.41	3.11	3.14	6.96	7.03	15.57
CPC exit diameter	m	0.81	0.81	1.80	1.80	4.03	4.03
CPC length	m	1.58	7.31	3.53	16.36	7.89	36.57
Lime production							
Annual	t/a	**1086**	**1086**	**5429**	**5429**	**27,146**	**27,146**
Daily (average)	t/d	3.0	3.0	**14.9**	14.9	74.4	74.4
24 h a day (hybrid mode)	t/d	9.7	9.7	**48.7**	48.7	243.4	243.4
Hourly (peak)	t/h	0.5	0.5	**2.5**	2.5	12.7	12.7

period, except for the 25 MW_{th} TT solar system. Here, the effective internal rate of return IRR from the investment exceeds the 15% discount rate that is economically required by an investor ($IRR = i$ for $NPV = 0$). However, the PBT of more than 8 years makes it less attractive. Small solar lime plants below 5 MW_{th} will not become profitable unless costs can be reduced or a higher selling price for the high purity solar lime can be achieved. The annual additional costs are mainly determined by the depreciation of the capital cost, the O&M costs for the heliostats and the additional insurance tax. The annual savings for fuel oil cannot compensate for these costs. The effect of a CO_2 tax amounting to 38 $/t of CO_2 is only marginal. Fig. 7 graphically represents the capital cost breakdown for a 5 MW_{th} solar lime plant configured as a TT solar system (see Table 6). Since the heliostat field costs typically constitute about 60% of the additional costs for the solar lime plant, reducing its costs will have the largest impact on the profitability of a solar lime plant.

Fig. 8 shows the variation of the costs of solar produced lime as a function of the plant size for a TT solar system. The parameter is the PBT in comparison to the current selling price of conventional lime (60 $/t [37]). Indicated also is the heliostat cost used for the calculation. As expected, the solar lime costs decrease monotonically with plant size as a result of the reduced costs for

Table 6
Estimated cost for solar lime plants (1 MW_{th}, 5 MW_{th}, and 25 MW_{th}) specified in Table 5

Cost	Plant size	1 MW_{th}		5 MW_{th}		25 MW_{th}	
	Unit	TT	BD	TT	BD	TT	BD
Capital cost (add. for solar appl.)							
Heliostat	$/m^2	430	411	267	256	168	161
Heliostat field (installed)	$1000	723	804	2249	2502	7052	7855
Tower (installed)	$1000	193	116	328	350	1001	1524
Tower reflector (installed)	$1000	–	45	–	203	–	648
CPC (installed)	$1000	80	214	207	322	841	864
Kiln (additional)	$1000	−76	−132	37	−21	417	352
Land	$1000	10	11	48	56	240	279
Total direct cost	$1000	921	1046	2820	3357	9310	11,243
EPCM (indirect)	$1000	112	129	339	421	1157	1463
Contingency	$1000	138	157	423	504	1396	1686
Total capital cost	$1000	1171	1332	3583	4282	11,863	14,393
Specific inst. cost (kiln)	$/kW	1171	1332	717	856	475	576
Specific inst. cost (process)	$/kW	2601	2960	1592	1903	1054	1279
Annual cost (add. for solar appl.)							
Annual capital cost (depreciation)	$1000	47	53	143	171	475	576
Additional energy use	$1000	0	0	1	1	24	24
O&M for heliostat field	$1000	12	14	59	68	294	342
O&M for tower reflector	$1000	–	1	–	3	–	16
O&M for CPC	$1000	1	2	2	3	8	9
Insurance	$1000	12	13	36	43	119	144
Total annual costs	$1000	71	83	241	290	920	1111
Annual savings (add. conv. appl.)							
Savings of fuel oil	$1000	19	19	97	97	485	485
Savings of CO_2 tax	$1000	21	21	104	104	518	518
Additional earnings (lime quality)	$1000	65	65	326	326	1629	1629
Total annual savings	$1000	105	105	526	526	2631	2631
Annual surplus (savings – costs)	$1000	34	22	285	236	1711	1521
Specific cost							
Additional cost for solar lime	$/t	65.5	76.5	44.4	53.4	33.9	40.9
Savings of fuel oil	$/t	17.9	17.9	17.9	17.9	17.9	17.9
Extra cost for solar lime	$/t	47.7	58.7	26.5	35.5	16.0	23.0
Selling price of conventional lime	$/t	60.0	60.0	60.0	60.0	60.0	60.0
Minimum price for solar lime	$/t	107.7	118.7	86.5	95.5	76.0	83.0
Deduction for CO_2 tax	$/t	19.1	19.1	19.1	19.1	19.1	19.1
Extra charge (lime quality)	$/t	31.4	20.4	52.5	43.5	63.0	56.0
Maximum price for solar lime	$/t	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Economics							
NPV after 25 years; $i = 15\%$	$1000	−832	−1054	−1377	−2321	**399**	−3107
IRR (for NPV = 0)	%	4.32	2.64	9.81	7.35	**15.41**	12.20
PBT	a	17.5	20.7	11.4	13.5	8.4	9.9

heliostat mass production. However, it is still at least 2–4 times higher than the current selling price for conventional lime, depending on PBT.

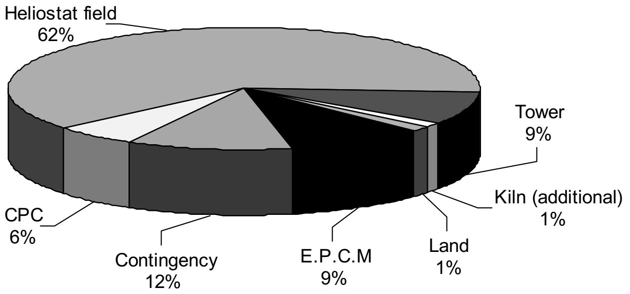

Fig. 7. Capital cost breakdown for a 5 MW_{th} TT solar lime plant including CPC.

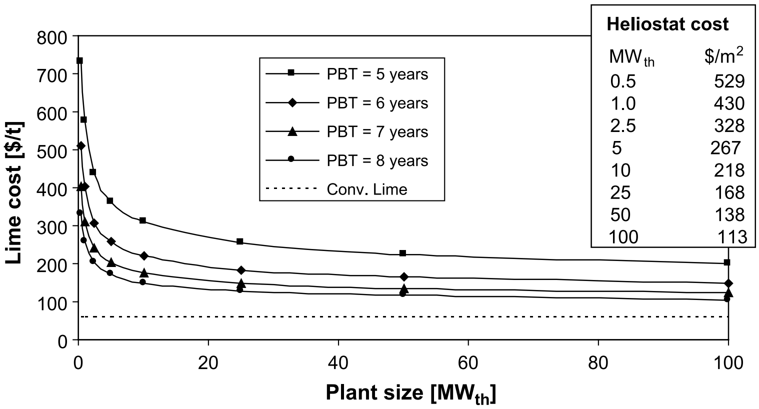

Fig. 8. Estimated cost of solar produced lime vs. TT plant size. The parameter is the PBT in comparison to the current selling price of conventional lime (60 $/t [37]). Inset: heliostat cost used for the calculation.

Sensitivity analysis: A sensitivity analysis has been performed using PBT as the sensitivity criterion. This choice allows elucidating the relative influence of all parameters independent of the discount rate. The baseline case given in Table 4 is assumed. For the three different plant sizes (1, 5 and 25 MW_{th}), the sensitivity of PBT relative to variations of different baseline parameters is plotted in Fig. 9. Each baseline value is varied by 10% in such a way that PBT is always decreasing. The most sensitive parameters are, in this order: the annual direct irradiance, the kiln efficiency, the heliostat cost, the optical efficiency and the lime selling price. There is no significant qualitative difference between the TT and the BD application. Changing all sensitive parameters listed in Fig. 9 simultaneously by 10% yields the results shown in Table 7. Only for large plants (25 MW_{th}), is PBT close to the economically required 5–6 years. For smaller plants, reduced heliostat costs of about 100 $/m^2 would yield acceptable PBT and positive NPV (see Table 8). Furthermore, improving the kiln efficiency from 45% to about 50% compared to the baseline case would yield favourable results as well (see Table 9). These measures, together with a moderately higher selling price for solar produced lime, help ensure the economic viability of the industrial solar production of lime.

CO_2 mitigation potential: By substituting concentrated solar energy for the fossil fuels used to drive the calcination reaction, CO_2 emissions can be reduced between 20% in a state-of-the-art

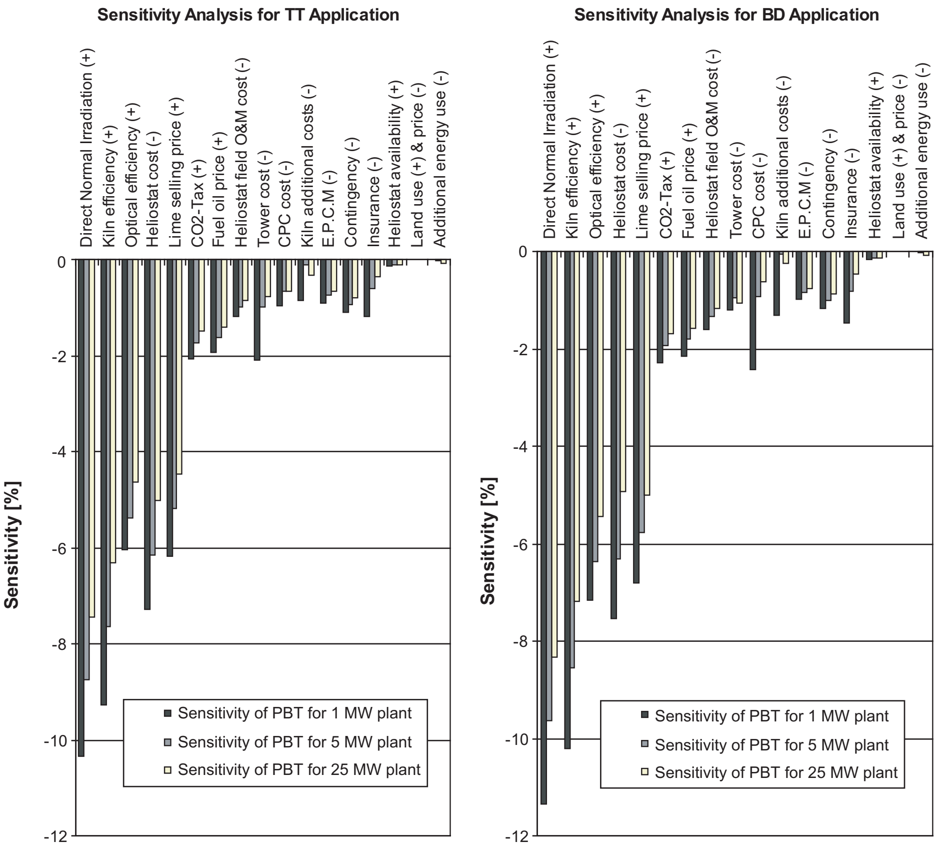

Fig. 9. Sensitivity analysis for TT and BD solar systems. “(+)”/“(−)” denotes a 10% increase/decrease.

Table 7
NPV, IRR, and PBT for 1, 5, and 25 MW_{th} solar plants

Economics	Plant size	1 MW_{th}		5 MW_{th}		25 MW_{th}	
	Unit	TT	BD	TT	BD	TT	BD
NPV after 25 years; $i = 15\%$	$1000	−474	−670	**201**	−633	**7645**	**4523**
IRR (for NPV = 0)	%	9.02	7.29	**15.74**	12.93	**22.86**	**19.02**
PBT	a	12.0	13.6	8.3	9.5	6.5	7.3

Assumption: all sensitive parameters are simultaneously changed by 10%.

lime plant and 40% in a conventional cement plant. A Life Cycle Analysis (LCA) concludes that the solar production of lime is ecologically beneficial [40]. About 95% of the greenhouse gas emissions released by the combustion of fossil fuels from an average single shaft kiln can be saved. The CO_2 mitigation potential is higher if the conventional shaft kiln is fired with coal or fuel oil instead of natural gas. These findings are practically independent of the solar plant configuration (TT and BD solar systems).

Table 8
NPV, IRR, and PBT for 1, 5, and 25 MW_{th} solar plants

Economics	Plant size	1 MW_{th}		5 MW_{th}		25 MW_{th}	
	Unit	TT	BD	TT	BD	TT	BD
NPV after 25 years; $i = 15\%$	$1000	**305**	**185**	**2192**	**1524**	**11,762**	**8828**
IRR (for NPV = 0)	%	**22.75**	**19.15**	**28.88**	**22.94**	**31.10**	**25.02**
PBT	a	6.5	7.3	**5.6**	6.5	**5.4**	6.1

Assumptions: all sensitive parameters are simultaneously changed by 10%, except for the heliostat cost, which is set to 100 $/m^2.

Table 9
NPV, IRR, and PBT for 1, 5, and 25 MW_{th} solar plants

Economics	Plant size	1 MW_{th}		5 MW_{th}		25 MW_{th}	
	Unit	TT	BD	TT	BD	TT	BD
$f^{quality}$	–	2.81	3.30	2.28	2.84	2.14	2.62
Maximum price for solar lime	$/t	**168.6**	**198.0**	136.8	170.4	**128.4**	**157.2**
NPV after 25 years; $i = 15\%$	$1000	466	555	1780	2324	8112	10,402
IRR (for NPV = 0)	%	25.65	25.61	25.61	25.64	25.60	25.60
PBT	a	6.0	6.0	6.0	6.0	6.0	6.0

Assumption: baseline case, except for the heliostat costs of 100 $/m^2 and the kiln efficiency of 50%.

5. Conclusions and outlook

Our economic assessment indicates that the cost for solar produced lime ranges from 128–157 $/t for a 25 MW_{th} plant to 168–198 $/t for a 1 MW_{th} plant. The solar production of lime has the potential of being economically viable provided some prerequisites are fulfilled. Firstly, the heliostat costs should not exceed 100 $/m^2. In this respect, a significant effect from the economy of scale can be expected. Secondly, the kiln efficiency should attain 50%, resulting in a smaller heliostat field and, consequently, reducing the investment costs. Thirdly, it is conceivable that the extremely pure solar produced lime will allow for a much higher selling price than the actual market price for lime (at about 60 $/t). Finally, governmental subsidies and regulations like the levy of a CO_2 tax may help introduce the solar lime technology into the market. As much as 95% of the greenhouse gas emissions released by fossil fuel based production of lime could be avoided by solar based lime production.

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Appendix A

Kiln and peripheral components showing significant capital cost differences between solar and conventional lime plants are presented in Table 10.

The baseline input parameters listed in Table 4 are completed with further inputs: (1) the efficiencies of the solar concentrating system components and (2) the efficiency of the solar lime kiln (Table 11). The list of output parameters comprises plant specification (Table 12), lime production (Table 13), capital cost (Table 14), annual cost and savings (Table 15) and specific cost (Table 16).

Plant specification (Table 12): The solar power input on the heliostat field (HF) at the design point, $\dot{Q}_{\mathrm{HF}}$, is calculated from the solar power input $\dot{Q}_{\mathrm{solar}}$ into the kiln and the optical efficiency η_{opt}. The annual solar energy input on the heliostat field, $Q_{\mathrm{HF}}^{\mathrm{annual}}$, is given by the direct normal irradiance $\mathrm{DNI}^{\mathrm{acc}}$ at the plant site accumulated for insolation levels above $I_{\mathrm{solar}}^{\mathrm{min}}$ and the heliostat field area A_{HF}. The maximum hours of operation per year n_{hours} is derived for the specific site location and the minimum insolation level $I_{\mathrm{solar}}^{\mathrm{min}}$. The annual solar lime plant efficiency, η_{plant}, is calculated from the optical efficiency η_{opt} and the kiln efficiency η_{kiln}. CPC dimensions are derived using formulas from Ref. [18].

Lime production (Table 13): The average annual quantity of solar produced lime is

$$q_{\mathrm{lime}}^{\mathrm{annual}} = \frac{\eta_{\mathrm{kiln}} \cdot \eta_{\mathrm{opt}} \cdot \alpha_{\mathrm{heliostat}} \cdot A_{\mathrm{HF}} \cdot DNI^{\mathrm{acc}}}{\Delta H_{\mathrm{CaCO_3}}} \tag{A.1}$$

where $\Delta H_{\mathrm{CaCO_3}}$ is the heat of dissociation of $\mathrm{CaCO_3}$, 0.88 MW h/kg of CaO produced [1]. For the design of the solar lime kiln, the peak production per hour, $q_{\mathrm{lime}}^{\mathrm{peak}}$, is of interest.

Capital cost (Table 14): The heliostat costs $C_{\mathrm{heliostat}}$ are dependent on the heliostat total reflective area A_{HF}, as shown in Fig. 4. The total heliostat field installed costs C_{HF} include additionally the costs for an autonomous control system. The tower installed costs C_{tower} depend on the heliostat reflective area A_{HF} according to Fig. 5. The size dependence of the tower reflector installed costs C_{TR} and the CPC installed costs C_{CPC} is shown in Fig. 6. The additional costs for the solar lime kiln $C_{\mathrm{kiln}}^{\mathrm{add}}$ are presented in Table 10. The land costs C^{land} are calculated for the total area $A_{\mathrm{HF}}^{\mathrm{land}}$

Table 10
Kiln and peripheral components showing significant capital cost differences

Conventional components	Capital cost of conventional components	Impact on solar component cost
Skip hoist	\$30,000 for 50 tpd shaft kiln (20 m high)	Higher cost for TT system; lower cost for BD system
Air/air heat exchanger	\$720,000 for 3000 tpd rotary kiln	Not used in single shaft kiln, required in solar application
Blower for air curtain	\$55,000 for 3000 tpd rotary kiln	Additional cost for CPC
Control instrumentation for air curtain	\$100,000 for 3000 tpd rotary kiln	Additional cost for CPC
Combustion air blower	\$20,000 for 50 tpd shaft kiln	Not used for solar kiln
Relief valves	\$15,000 for 50 tpd shaft kiln	Not used for solar kiln
Firing equipment	\$35,000–\$70,000 for 50 tpd shaft kiln	Not used for solar kiln
Waste gas filter system	\$80,000 for 50 tpd shaft kiln	Not used for solar kiln

Data for 50 tpd shaft kiln taken from [20] and for 3000 tpd rotary kiln taken from [33].

Table 11
Input parameters: optical system losses and efficiencies used for baseline case

Parameter	Variable	Efficiency	Loss	Reference
Heliostat field efficiency				
Shading/shadowing	η_{shading}	0.975	0.025	[41,42]
Blocking	η_{blocking}	0.99	0.01	[41,42]
Cosine effect	η_{cosine}	0.855	0.145	[41,42]
Mirror surface absorption	η_{mirror}	0.90	0.1	[31,36,43,44]
Tower top efficiency				
Atmospheric attenuation to tower	$\eta_{\text{tower}}^{\text{att}}$	0.96	0.04	[41,45]
Spillage around CPC/receiver	η_{spillage}	0.92	0.08	[46]
Beam down efficiency				
Atmospheric attenuation to tower	$\eta_{\text{tower}}^{\text{att}}$	0.96	0.04	[41,45]
Tower reflector absorption	$\eta_{\text{reflector}}$	0.94	0.06	[16,27,45]
Atmospheric attenuation to CPC/reactor	$\eta_{\text{reactor}}^{\text{att}}$	0.99	0.01	[36,43]
Spillage around CPC/receiver	η_{spillage}	0.85	0.15	[27,47]
CPC efficiency				
CPC surface absorption	η_{CPC}	0.925	0.075	[36,43]
Kiln efficiency				
Kiln efficiency	η_{kiln}	0.45	0.55	[39]

Table 12
Output parameters: plant specification

Parameter	Unit	Parameter definition	Remark
Plant specification			
Solar power input on HF	MW_{th}	$\dot{Q}_{\text{HF}} = \dot{Q}_{\text{solar}}/\eta_{\text{opt}}$	
Annual solar energy input on HF	MW h/a	$\dot{Q}_{\text{HF}}^{\text{annual}} = \text{DNI}^{\text{acc}} \cdot A_{\text{HF}}$	
Hours of operation per year	h/a	n_{hours}	
Accumulated solar irradiance	$\text{kW h/m}^2\text{/a}$	DNI^{acc}	
Optical efficiency (incl. CPC)	–	η_{opt}	Table 10
Kiln efficiency	–	η_{kiln}	Table 10
Annual solar plant efficiency	–	$\eta_{\text{plant}} = \eta_{\text{opt}} \cdot \eta_{\text{kiln}}$	
Optical system specification			
HF reflective area	m^2	$A_{\text{HF}} = \dot{Q}_{\text{HF}}/(\alpha_{\text{heliostat}} \cdot I_{\text{solar}}^{\text{peak}})$	
Number of heliostats	–	$n_{\text{heliostat}} = A_{\text{HF}}/A_{\text{heliostat}}$	
HF land area	m^2	$A_{\text{HF}}^{\text{land}} = A_{\text{HF}}/f^{\text{land}}$	
HF diameter (fictitious)	m	$d_{\text{HF}}^{\text{land}} = \sqrt{4 \cdot A_{\text{HF}}^{\text{land}}/\pi}$	
Tower height	m	h_{tower}	Fig. 5
Tower reflector (TR) surface	m^2	$A_{\text{TR}} = f_{\text{TR}} \cdot A_{\text{HF}}$	[27]
CPC exit area	m^2	$A_{\text{CPC}}^{\text{exit}} = A_{\text{HF}} \cdot \eta_{\text{opt}}/\widetilde{C}$	
CPC exit diameter	m	$d_{\text{CPC}}^{\text{exit}} = \sqrt{4 \cdot A_{\text{CPC}}^{\text{exit}}/\pi}$	
CPC entrance area	m^2	$A_{\text{CPC}}^{\text{entrance}} = A_{\text{CPC}}^{\text{exit}}/\sin^2(\varphi_{\text{rim}}/2)$	[18]
CPC entrance diameter	m	$d_{\text{CPC}}^{\text{entrance}} = \sqrt{4 \cdot A_{\text{CPC}}^{\text{entrance}}/\pi}$	
CPC length	m	$l_{\text{CPC}} = \frac{d_{\text{CPC}}^{\text{entrance}} + d_{\text{CPC}}^{\text{exit}}}{2 \cdot \tan(\varphi_{\text{rim}}/2)}$	[18]

Table 13
Output parameters: lime production

Parameter	Unit	Parameter definition	Remark
Lime production			
Annual	t/a	$q_{\text{lime}}^{\text{annual}}$	Eq. (A.1)
Daily (average)	t/d	$q_{\text{lime}}^{\text{daily}} = q_{\text{lime}}^{\text{annual}}/365$	
24 h a day (hybrid mode)	t/d	$q_{\text{lime}}^{24\text{ h}} = q_{\text{lime}}^{\text{annual}}/n_{\text{hours}} \cdot 24$	
Hourly (peak)	t/h	$q_{\text{lime}}^{\text{peak}} = \eta_{\text{kiln}} \cdot \dot{Q}_{\text{solar}}/\Delta H_{\text{CaCO}_3}$	

Table 14
Output parameters: capital cost

Parameter	Unit	Variable	Remark
Capital cost (add. for solar appl.)			
Heliostat	$/m^2	$C_{\text{heliostat}}$	Fig. 4
Heliostat field (installed)	$1000	$C_{\text{HF}} = (C_{\text{heliostat}} + C_{\text{ACS}}) \cdot A_{\text{HF}}$	Table 4
Tower (installed)	$1000	C_{tower}	Fig. 5
Tower reflector (installed)	$1000	C_{TR}	Fig. 6
CPC (installed)	$1000	C_{CPC}	Fig. 6
Kiln (additional)	$1000	$C_{\text{kiln}}^{\text{add}}$	Table 10
Land	$1000	$C^{\text{land}} = p^{\text{land}} \cdot A_{\text{HF}}^{\text{land}}$	Table 4
Total direct cost	$1000	$C_{\text{direct}}^{\text{total}}$	
EPCM (indirect)	$1000	C_{EPCM}	Section 3
Contingency	$1000	$C_{\text{contingency}}$	Section 3
Total capital cost	$1000	$C_{\text{capital}}^{\text{total}}$	
Specific installed cost (kiln)	$/kW	$C_{\text{kiln}}^{\text{specific}} = C_{\text{capital}}^{\text{total}}/\dot{Q}_{\text{solar}}$	
Specific installed cost (process)	$/kW	$C_{\text{process}}^{\text{specific}} = C_{\text{capital}}^{\text{total}}/(\dot{Q}_{\text{solar}} \cdot \eta_{\text{kiln}})$	

covered by the heliostat field. Specific installation costs are given for the kiln, $C_{\text{kiln}}^{\text{specific}}$, and relative to the chemical process $C_{\text{process}}^{\text{specific}}$.

Annual cost and savings (Table 15): The annual costs include the (assumed) linear depreciation of the capital cost over the lifetime of the plant, $C_{\text{depreciation}}$, additional electricity costs for rotational and conveying systems, C_{energy}, and O&M cost for the heliostat field $C_{\text{HF}}^{\text{O\&M}}$, the tower reflector $C_{\text{TR}}^{\text{O\&M}}$ and the CPC $C_{\text{CPC}}^{\text{O\&M}}$. Insurance costs $C_{\text{insurance}}$ are taken into account as well. The major annual savings in a solar lime plant concern fuel oil consumption S_{fuel} and the levy of a CO_2 tax $S_{\text{CO}_2\text{-tax}}$. The annual surplus is then given by the difference between $S_{\text{annual}}^{\text{total}}$ and $C_{\text{annual}}^{\text{total}}$.

Specific cost (Table 16): The additional cost per ton of solar produced lime is given by the specific cost $C_{\text{lime}}^{\text{specific}}$. Similarly, the fuel oil savings per ton of lime are given by the specific savings $S_{\text{fuel}}^{\text{specific}}$. Thus, the extra cost per ton of solar lime is the difference between $C_{\text{lime}}^{\text{specific}}$ and $S_{\text{fuel}}^{\text{specific}}$. Adding the selling price of conventional lime $p_{\text{lime}}^{\text{conv}}$ yields the minimum price (ex works) for solar

Table 15
Output parameters: annual cost

Parameter	Unit	Variable	Remark
Annual cost (add. for solar appl.)			
Annual capital cost (depreciation)	\$1000	$C_{\text{depreciation}} = C_{\text{capital}}^{\text{total}}/t$	
Additional energy use	\$1000	C_{energy}	Section 2.2
O&M for heliostat field	\$1000	$C_{\text{HF}}^{\text{O\&M}}$	Section 2.2
O&M for tower reflector	\$1000	$C_{\text{TR}}^{\text{O\&M}}$	Section 2.2
O&M for CPC	\$1000	$C_{\text{CPC}}^{\text{O\&M}}$	Section 2.2
Insurance	\$1000	$C_{\text{insurance}}$	Section 2.2
Total annual costs	\$1000	$C_{\text{annual}}^{\text{total}}$	
Annual savings (add. for conv. appl.)			
Savings of fuel oil	\$1000	S_{fuel}	Section 2.2
Savings of CO_2 tax	\$1000	$S_{CO_2\text{-tax}}$	Section 3
Additional earnings (lime quality)	\$1000	$S_{\text{lime}}^{\text{quality}} = (f^{\text{quality}} - 1) \cdot p_{\text{lime}}^{\text{conv}} \cdot q_{\text{lime}}^{\text{annual}}$	
Total annual savings	\$1000	$S_{\text{annual}}^{\text{total}}$	
Annual surplus (savings minus costs)	\$1000	$S_{\text{annual}}^{\text{total}} - C_{\text{annual}}^{\text{total}}$	

Table 16
Output parameters: specific cost and economic indicators

Parameter	Unit	Variable	Remark
Specific cost			
Additional cost for solar lime	\$/t	$C_{\text{lime}}^{\text{specific}} = C_{\text{annual}}^{\text{total}}/q_{\text{lime}}^{\text{annual}}$	
Savings of fuel oil	\$/t	$S_{\text{fuel}}^{\text{specific}} = S_{\text{annual}}^{\text{total}}/q_{\text{lime}}^{\text{annual}}$	
Extra cost for solar lime	\$/t	$p_{\text{lime}}^{\text{extra}} = C_{\text{lime}}^{\text{specific}} - S_{\text{lime}}^{\text{specific}}$	
Selling price of conventional lime	\$/t	$p_{\text{lime}}^{\text{conv}}$	
Minimum price for solar lime	\$/t	$P_{\text{lime}}^{\text{solar,min}} = p_{\text{lime}}^{\text{conv}} + p_{\text{lime}}^{\text{extra}}$	
Deduction for CO_2 tax	\$/t	$p_{CO_2\text{-tax}}^{\text{specific}}$	
Extra charge (lime quality)	\$/t	$p_{\text{lime}}^{\text{quality}} = p_{\text{lime}}^{\text{solar,max}} - p_{\text{lime}}^{\text{solar,min}} + p_{CO_2\text{-tax}}^{\text{specific}}$	
Maximum price for solar lime	\$/t	$p_{\text{lime}}^{\text{solar,max}} = f^{\text{quality}} \cdot p_{\text{lime}}^{\text{conv}}$	
Net present value (NPV)	\$1000	NPV	Table 2
Internal rate of return (IRR)	%	IRR = i for NPV = 0	Table 2
Payback time (PBT)	a	$\text{PBT} = \frac{C_{\text{capital}}^{\text{total}}}{S_{\text{annual}}^{\text{total}} - (C_{\text{annual}}^{\text{total}} - C_{\text{depreciation}})}$	Table 2

produced lime $p_{\text{lime}}^{\text{solar, min}}$. Deducting the CO_2 tax charged on conventional lime $p_{CO_2\text{-tax}}^{\text{specific}}$ and adding an extra charge for high quality solar lime $p_{\text{lime}}^{\text{quality}}$ yields the maximum price (ex works) for high quality solar lime. The net present value NPV is determined at the end of the plant's lifetime.

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