

Material constraints for concentrating solar thermal power

Erik Pihl^a, Duncan Kushnir^{b,*}, Björn Sandén^b, Filip Johnsson^a

^a Division of Energy Technology, Chalmers University of Technology, Göteborg, Sweden

^b Division of Environmental Systems Analysis, Chalmers University of Technology, Göteborg, Sweden

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ABSTRACT

Scaling up alternative energy systems to replace fossil fuels is a critical imperative. Concentrating Solar Power (CSP) is a promising solar energy technology that is growing steadily in a so far small, but commercial scale. Previous life cycle assessments (LCA) have resulted in confirmation of low environmental impact and high lifetime energy return. This work contributes an assessment of potential material restrictions for a large-scale application of CSP technology using data from an existing parabolic trough plant and one prospective state-of-the-art central tower plant. The material needs for these two CSP designs are calculated, along with the resulting demand for a high adoption (up to about 8000 TWh/yr by 2050) scenario. In general, most of the materials needed for CSP are commonplace. Some CSP material needs could however become significant compared to global production. The need for nitrate salts (NaNO₃ and KNO₃), silver and steel alloys (Nb, Ni and Mo) in particular would be significant if CSP grows to be a major global electricity supply. The possibilities for increased extraction of these materials or substituting them in CSP design, although at a marginal cost, mean that fears of material restriction are likely unfounded.

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1. Introduction

The available solar flux on land is several thousand times higher than today's anthropogenic primary energy conversion and is thereby the dominant potential source for renewable energy. The global solar market has been rapidly growing for the past decade, but is still dwarfed when compared to conventional fossil fuel power. So far, the main barrier to large-scale deployment of solar power has been higher costs of electricity, because of relatively small volumes and less historical investments in technology development than presently dominant power generation technologies. Through development and continued strong growth, as solar technologies progress down the learning-curve, the cost per kWh of solar electricity is projected to reach parity with peaking power in main markets by about 2020–2030 [1–4].

So far, photovoltaic (PV) technologies have the largest share of the solar power market, but there is at present a relatively steady share of concentrating solar thermal power (CSP, also sometimes referred to as Solar Thermal Power, STP). CSP has undergone expansion from about 400 MW installed capacity in the early 2000s, to about 1.3 GW in 2011, with another 2.3 GW under construction and 32 GW in planning. The technology is today in

commercial scale deployment in Spain, USA, Australia, Egypt and India [5–7].

CSP plants use reflective surfaces to concentrate sunlight, providing heat for a thermodynamic cycle, such as a steam turbine. The physical principle is thus very different from photovoltaic panels, which use the photons in sunlight to excite electrons and create currents in solid state matter. These differences mean that CSP will differ significantly from PV regarding properties such as environmental impact and material constraints.

With projected strong growth in view, it is of interest to identify and quantify barriers to large-scale solar power deployment, other than cost as mentioned above. One such barrier is restrictions in either the reserves (extractable resources at a given cost) or annual supply of materials needed for solar power conversion devices. Such restrictions can imply increased raw material costs as the technologies grow, or even set absolute limits to how much that can be built. The recent study on CSP by the EASAC [2] has pinpointed a need to investigate the limits and potential bottlenecks and manufacturing constraints for CSP production.

Material demand and constraints for low-carbon technologies has been evaluated in several studies over the last fifteen years. Some recent studies provide overviews of constraints for many low-carbon technologies [8–11] while others analyse metal resource constraints for specific technologies such as electric vehicle batteries [12–14] and solar photovoltaics [12,15–21]. A general conclusion is that no technology group (such as solar PV or

* Corresponding author. Tel.: +46 317721197.

E-mail address: kushnir@chalmers.se (D. Kushnir).

wind power) is hindered from reaching the TW-scale due to limited supply of materials, but scarcity of some specific metals such as tellurium, indium, ruthenium and silver may constitute a severe problem for specific designs at significantly lower levels of market penetration. The analysis provided by Kleijn et al. (2011) indicates that the build-up of all energy infrastructures, regardless if it is nuclear power, carbon capture and storage (CCS) or renewable energy, will also have some impact on the societal flows of major materials such as stainless steel.

There is currently a lack of studies of materials constraints on CSP deployment. Some material needs and energy issues for CSP have been studied through life cycle assessment, see e.g. Burkhardt et al. [22], Lechón et al. [23], Viebahn et al. [24], May [25] and Weinrebe [26]. General conclusions are that CSP plants have energy pay-back times of about one year, which can be compared to typical lifetimes of about 30 years, and a relatively minor ecological footprint, indicating resource effectiveness and low external costs. Yet, they are overall significantly more material intensive at construction (per kWh basis) than fossil fuel plants of equivalent capacity. Water use has also been a contested issue, particularly as many high-insolation areas suited for CSP are water stressed. The use of water can be reduced by more than 90% by switching from wet to dry cooling technologies and these design modifications have been included in some LCAs, e.g. Burkhardt et al. [22].

Estimates on constraints for steel, concrete and nitrate salts, used for dish Stirling and parabolic trough plants, were included in a study by García-Olivares et al. [27]. The study suggests that steel and concrete are not restricting, while the natural reserves of nitrate salts are relatively small and calls for synthetic production of salts. Trieb et al. [28] have calculated the need for steel, glass, aluminium, copper, lead and concrete for a growth scenario where CSP increases linearly in capacity over 30 years to cover 15% of the EU electricity in 2050. This scenario is found to require 1.6% of the annual 2010 global production of glass, the corresponding figures for the other materials are in the range 0.1–0.4%.

The aim of this work is to further assess possible material constraints that will set limits for large-scale concentrating solar thermal power (CSP) deployment. The main purpose of this study is to create inventories for the material commodity needs of a TW-scale capacity of CSP plants, as well as of the annual demands required for the build-up of such a system. Further, these inventories are compared to the total available resources and current production capacity of the materials in question. A special focus is on the materials found most restricted in production, compared to the demand. These include nitrate salts (NaNO_3 and KNO_3), silver, steel alloys (Nb, Ni, Mo, Mg and Mn in particular) and to some degree glass and materials used for glass manufacturing. The demand for water during the operation phase is quantified but not compared to global availability, since water scarcity is a local issue and demands a more detailed, site-specific analysis. We use data representative for commercial designs of parabolic trough and central tower (central receiver) plants, the two most widespread CSP technologies.

2. Method

The basis for evaluating material constraints is constructing an inventory of the materials used for producing a given production capacity of plants and comparing the inventory and a scenario of adoption with the available stocks and flows of resources. Two ratios are of particular importance [15]:

1. S_{MC} , material constrained stock: The total CSP capacity (in TWh/yr) that can be built, given the amount of available resources of a specific material.

2. G_{MC} , material constrained growth: The maximum CSP growth per year (in TWh/yr²), constrained by the production of a specific material.

We use two measures of resources. By *resources* we denote material occurrence “in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.” [29]. This includes undiscovered resources. *Reserves* are defined as “That part of the reserve base which could be economically extracted or produced at the time of determination.” [29]. The term includes only demonstrated reserves. The reserve base is the “in-place demonstrated (measured plus indicated) resource from which reserves are estimated” [29]. The term *production* in most cases refers to mine production. For some commodities (steel, glass, nitrate salts, cement) production refers to the output from a manufacturing process.

2.1. Technology diffusion scenario

In order to give context to the G_{MC} values and analyse the possible consequences of strong policy to promote solar technologies, the results are applied to a scenario where CSP grows according to the “Advanced Outlook” scenario of Greenpeace, IEA SolarPACES and ESTELA [30]. This scenario is cited as the highest growth function in the IEA CSP Technology Roadmap [31]. The function is exponential with a stepwise decreasing growth rate, giving system capacities of about 120 TWh/yr in 2015, 360 TWh/yr in 2020, 1500 TWh/yr in 2030 and close to 8000 TWh/yr in 2050. A constant yearly growth factor is assumed to describe the capacity increase 2030–2050. The 2050 value is in close correlation to Pacala and Socolow [32] who suggested that CSP could supply 8100 TWh/yr by 2050.

2.2. System boundaries and data sources

The material commodity needs for plants are determined by a bottom-up approach, identifying the amount and types of materials required to build a given CSP capacity. This calculation is based on case studies of two plants, one parabolic trough and one central tower design. Data were gathered from a literature review and direct information from CSP plant operators and manufacturers. Data on maintenance material flows (e.g. washing, replacing mirrors) is taken from one of the companies in the solar tower case and from Viebahn et al. [24] in the parabolic trough case. The system boundary includes only the materials used in the construction and operation of the plants. Dismantling and indirect material and energy use, e.g. for the production of capital facilities (mirror factories etc.) and construction (cranes etc.), are not included.

2.3. Component scaling

In cases when data are not available for the materials intensity of a component in one of the two CSP plants, estimates are made based on components with identical functions in other CSP plants (reference plants). The size of the components is scaled to take into account differences in plant capacity. For instance, data from the solar towers PS-10 and Gemasolar are scaled and used for the solar tower in this work. Some of the scaled data is summarized in Table 2.

The mass of solar field components, m_f , are scaled linearly based on capacity:

$$m_f = m_f^* \frac{C}{C^*}, \quad (1)$$

Table 1

Plant Specifications, basis for non-DNI-adjusted data. From eSolar [40] and Cobra Energi [36].

	Parabolic trough	Central tower	Unit
Electric capacity	49.9	100	MW
Operating hours	3640	6250	h/yr
Storage	7.5	12.7	h
Site insolation, DNI	2200	2700	kWh/m ² yr
Solar field size	512,000	1,472,000	m ²
Land occupancy	1,950,000	5,000,000	m ²
Annual production	0.182	0.625	TWh/yr

where C is the thermal capacity of the studied plant and C^* and m_f^* are the thermal capacity and the mass of solar field components of the reference plant, respectively. This is valid for trough fields. No scaling is done for tower field components, as this data has been fully supplied in the right scale from a company source.

Thermal cycle components do not scale linearly with throughput. The material commodity mass for a steam cycle component, m_c , is assumed to follow the same basic function as investment cost, which from Pihl et al. [33] is calculated as:

$$m_c = m_c^* \left(\frac{C}{C^*} \right)^{0.89}, \quad (2)$$

where m_c^* is the known mass data from a reference plant. For thermal power cycle components, C is in thermal capacity (MW_{th}). Masses for storage tanks, m_t , are assumed to follow an exact area to volume scaling:

$$m_t = m_t^* \left(\frac{C}{C^*} \right)^{\frac{2}{3}}, \quad (3)$$

Buildings are also assumed to scale this way.

2.4. Normalisation of values

After producing the per-plant inventory, the material inventories are normalized to an energy production capacity of 1 TWh/yr. This figure is adjusted to compensate for the varying solar resources. The two case study plants that are the source of the material data are in different locations, varying in local “solar resource”, as measured by yearly direct normal irradiation (DNI). In order for the plants to be comparable, the figures are adjusted to a given DNI of 2300 kWh/m² yr. There is significant potential on all inhabited continents to harness solar energy at this rate of irradiation, or higher [34].

Scaling functions for total material use as function of varying DNI have not been found, but there are available relations on cost and DNI that could be applied with high precision. Kearney [35] finds a cost decrease of 4.5% per 100 kWh/m² yr. Using the input of material use, m^* , at reference irradiation, I^* (kWh/m² yr), Eq. (4) gives the material use, m , at given irradiation, I (kWh/m² yr):

$$m = m^* (1 - 0.045)^{(I-I^*)/100} \quad (4)$$

Table 2

Weights of steam cycle components for CSP plants.

Component	Mass (tons)	Reference
Piping	176	55 MW _{th} (PS-10)
Pumps	12.5	[45]
Steam drum	74.5	
Steam turbine	160	50 MW _e (Andasol 3)
Generator	85	[46]

The DNI adjustment is assumed only to affect the figures on material use per TWh/yr, not the material use per GW. This is because higher yearly DNI typically means more hours of sunlight but not that the maximum solar influx (i.e. nominal capacity for a given design) is significantly higher. The maximum influx is a sum of the solar constant and atmospheric losses, showing differences first when two sites differ greatly in latitude or altitude.

2.5. Replacement and recycling of materials

Over a longer timescale, material needs for CSP plants will include replacing plants in addition to net capacity addition. The technical lifetime is here assumed to be 30 years. Some of the materials for new plants can be recycled from old plants. For CSP plants reaching end of life, recycling of materials is assumed to be 95% for aluminium and molten salts, 90% for steel (incl alloying material) and copper, 70% for glass and silver and 0% for the remaining materials. The recycling flows are small during the build phase considered here, but is likely to increase to form the majority of the material requirements in the long term future where CSP capacity saturates.

3. Case study description and background assumptions

The two power plants chosen as cases in this study represent the two dominant CSP technologies, parabolic trough and central tower. These are, however, not directly comparable, since they are at different stages of commercialisation. The trough plant can be viewed as a design implemented on commercial scale, while the specific tower design is – although similar to existing commercial tower designs – not to be viewed as fully commercialized. A comparison of the main properties of the two plants is found in Table 1. The construction and materials needs for the different components of the CSP plants are given in Sections 3.3–3.6. For components that are not specific to the plant design, such as buildings and some parts of the steam cycles, the material choices are assumed to be identical for the two studied plants, if nothing else is specified.

3.1. Parabolic trough plant configuration

Parabolic trough fields are built up by Solar Collector Assemblies (SCAs), series of troughs of about 150 m length (Fig. 1). The plant selected to represent parabolic trough technology in this report is a 50 MW_e plant in Spain, “as it would be constructed today”, with data provided from manufacturer Cobra Energía [36]. The reflecting aperture area of each collector is assumed to be 12×5.77 m², with a mirror-aperture area factor of 1.10 [37,38]. The sunlight is concentrated on evacuated collector tubes in which heat is transferred to synthetic oil. The oil, a mixture of biphenyl and diphenyl, transfers the heat to the thermal cycle. Turbine operation can be smoothened and extended by heat storage in molten salt, a binary mixture of NaNO₃ and KNO₃. Economic assessments often find that large storage capacities are economically beneficial; for instance Herrmann et al. [39] have found the lowest levelized electricity cost at 12 h storage, but such capacities are rarely employed in present installations. The parabolic trough plant selected for this study has enough storage for 7.5 h operation without sunshine. The plant is assumed wet cooled.

3.2. Central tower plant configuration

Central tower plants (Fig. 2), also called central receiver plants, typically have a high tower with a large receiver on which light is focused by a field of mirrors, called heliostats. This study assesses

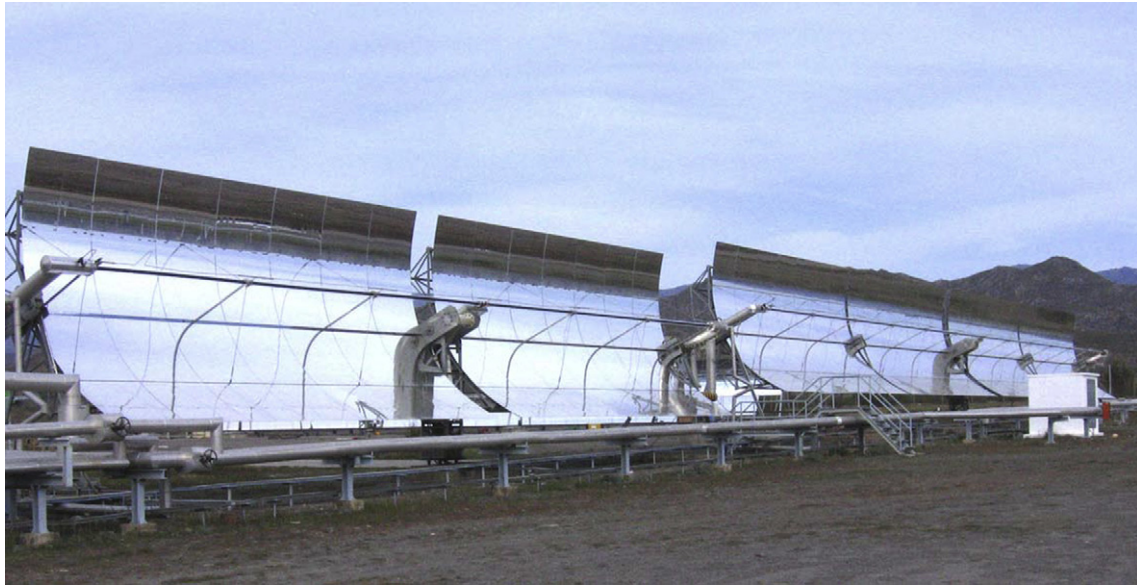


Fig. 1. Part of a parabolic trough assembly (Plataforma solar de Almería) similar to that chosen for this study.

the 100 MW_e eSolar conceptual molten salt tower design [40]. It uses small scale; flat heliostats of roughly 1 m² size, with individual tracking systems, each on an individual and mass produced steel frame structure. eSolar has demonstrated their design with the 5 MW_e direct steam Sierra SunTower demonstration plant. The molten salt design has a heliostat field very similar to the Sierra SunTower but larger towers and molten salt as heat transfer and storage medium. The central tower case study plant is dry (air) cooled.

3.3. Steam cycle equipment

Steam turbines and the piping, valves, tanks, pumps, heat exchangers, domes and other components constituting the steam cycles are the most complex part of the CSP plants. Viebahn et al. [24] show that the total material use of the entire steam cycle is typically a small part of CSP plant overall weight (<5%), but because of the high quality materials required, the composition is of importance. Steam turbines are commonly built with a high



Fig. 2. View of a solar tower plant (Sierra SunTower), similar to that chosen for this study. With permission from eSolar.

proportion of stainless 9%–12%–chromium steels, also containing molybdenum (Mo), manganese (Mn), nickel (Ni), vanadium (V), carbon and some other trace elements.

In this study, the steam turbine is assumed to be composed by 85.4% Fe, 13.0% Cr, 0.4% Ni, 0.13% Mn, 1.0% Mo and 0.06% V [41,42] (data also from an undisclosed steam turbine manufacturer). For the trough plant, steam cycle pipes and heat exchangers are assumed to be T22 low-chromium steel for high temperature (400 °C) applications and carbon steel for low temperatures. For the central tower plant, the heat exchangers are assumed to be built in 347H stainless steel for high temperatures, to withstand the molten salts, and carbon steel for low temperatures [43]. Steam pipes for the tower plant are assumed 12% Cr steel at high temperatures and carbon steel at low temperatures. Assumed data for key steam cycle components are given in Table 2. Some of the data on pipe weights are supplied by the plant manufacturers [36,40], for wet and dry cooling equipment by GEA [44].

3.4. Collectors

Mirrors are used for the collectors or heliostats of the solar plants. It is assumed that these use low-iron glass as substrate [47]. Raw materials used for the glass have approximately the

proportions: silica sand 73%, soda ash 13%, lime 8%, others 6%. The reflective coating is assumed to be silver, in a 100 nm thick layer.

Supporting steel structures for collectors/heliostats of both plants are assumed to be hot-dip galvanized steel. This material is mainly carbon steel (98% Fe, 1% C, 1% Mn) covered by a zinc layer of 100 µm [48]. The steel used for the parabolic trough absorber tubes is DIN 1.4541 stainless steel [49] with an approximated content of 18% Cr, 10.5% Ni and 0.4% Ti [50].

3.5. Heat transfer and storage

Large amounts of liquid media are used in both plants for transfer and sensible storage of heat. The tower plant uses molten salt for both purposes, while the trough plant collects heat by synthetic oil flowing through the absorber tubes and stores the heat in a separate system with molten salt. Figures for the amounts of thermal media used in the plant have been provided by plant manufacturers [36,40]. Material needs for the storage tanks have been estimated by using data for trough and tower plants in the report by [24] and scaled by Eq. (3) based on mass and density of the storage medium. When using nitrate salts there will be some level of decomposition to nitrite and other secondary products,

Table 3
Per GW and TWh/yr inventory for the two case plants of this study. The TWh/yr values are DNI-adjusted.

Material	Per GW (tons)		Per TWh/yr (tons)	
	Trough	Tower	Trough	Tower
<i>Construction</i>				
Aluminium (Metal)	0	11,000	0	2200
Cement	250,000	72,000	65,000	13,800
Chromium	2200	3700	570	710
Copper	3200	1400	840	260
Aluminium (Elemental)	740	12,000	180	2300
Fibreglass	310	0	82	0
Foam glass	2500	1800	640	340
Glass	130,000	110,000	31,000	21,000
Iron	650,000	393,000	170,000	75,000
KNO ₃	220,000	150,000	59,000	28,000
Lime	11,000	9400	2800	1800
Limestone	170,000	49,000	44,000	9400
Magnesium	3000	2600	730	500
Manganese	2000	5700	540	1100
Molybdenum	200	56	52	11
NaNO ₃	340,000	220,000	88,000	42,000
Nickel	940	1800	250	350
Niobium	0	140	0	26
Oil	44,000	0	12,000	0
Polypropylene	500	0	130	0
Rock	1,300,000	5,000,000	340,000	950,000
Rock wool	4700	3400	1200	650
Sand	1900	1400	490	260
Silicon sand	92,000	81,000	22,000	15,600
Silver	13	16	3.1	3.0
Soda ash	18,000	16,000	4600	3000
Steel	240,000	400,000	63,000	77,000
Titanium	25	0	6.5	0.00
Vanadium	1.9	1.7	0.48	0.33
Zinc	650	1400	170	260
<i>Operation and maintenance</i> (yearly, tons)				
Aluminium	0.78	1.40	0.20	0.27
Glass	140	240	35	46
Lime	11	20	3.0	3.9
Magnesium	3.2	5.7	0.83	1.09
Oil	2000	0	510	0
Silicon sand	98	180	26	34
Silver	0.0140	0.034	0.0037	0.0065
Soda ash	19	34	4.9	6.5
Steel	N/A	150	N/A	29
Water	12,000,000	160,000	3,200,000	31,000

mainly NO_x. This loss rate is claimed to be low [51], and due to lack of reliable data, it has not been included in the assessment.

The receiver, hot salt pipes and hot salt tank of the tower plant are assumed to be made of 347H stainless steel, while other molten salt pipes and the cold salt tank should be made of carbon steel [40,43]. The hot salt tank of the trough plant is assumed to be made of 316L stainless steel, while the oil pipes are low-Cr steel. Heat exchangers use stainless steel 347H (tower) or low-Cr (trough) steels for high temperatures and carbon steel for low temperatures (i.e. in the economizers).

3.6. Foundations and buildings

Concrete, rock and gravel are the most common materials on mass basis for the plants. Concrete is used for the solar field foundations, storage tanks, buildings and other miscellaneous structures. It is by approximation composed of 1/6 cement and 5/6 sand/rock, reinforced with rebar which is essentially 100% iron. Gravel is used in large quantities in the tower plant, to prepare the ground under the heliostat fields. Data on materials use for foundations, ground preparation and buildings are taken from plant manufacturers and supplemented by data from Viebahn et al. [24].

4. Material inventories

Aggregated inventories of materials used in the two types of solar plants are shown in Table 3. As indicated previously, the table should not be seen as a direct comparison of the two technologies in general, since the two case plants are at somewhat different stages of commercialisation. The reason that the tower plant requires less molten salt per TWh/yr capacity, despite a greater storage capacity, is because of the higher temperatures in the thermal cycle (higher ΔT). The difference in steel alloy use between the two case plants is due to different steel compositions, mainly because of varying steam cycle temperatures and heat transfer media (molten salts are significantly more corrosive than thermal oils).

A comparison with the findings of material use in the studies by García-Olivares [27] and Trieb [28] shows no great discrepancy in results. This work finds 240 t/MW as a reasonable number for steel

use in parabolic trough plants, compared to the 180 t/MW assumed by García-Olivares.

The material breakdown graphs showed in Fig. 3 illustrates where in the plants some of the bulk materials are used. The main use of most commodities is by far in the collector or heliostat fields. The main exception is cement in the tower plant since the heliostat support structure does not use concrete in anchoring. The heliostat field design does, however, include ground preparation with large amounts of gravel, meaning that site preparation is the dominating use of sand, rock and gravel. Molten salts are not included in the graphs; they are in both cases used 100% in the storage system. Aluminium is only used in significant amounts in the tower case.

5. Reserves and annual production of materials in comparison to CSP demand

This chapter discusses the relationship between material demands for CSP plants and the reserves and annual production of the corresponding materials. Table 4 shows the currently defined reserves, resources and annual production of the minerals and commodities required for the CSP plants.

Table 5 gives the ratio of material reserve figures (Table 4) to the amounts available as obtained from the inventory (Table 3). Most materials are widely available, and thus only materials found (from Table 4) to have relevant limits appear.

The values in Table 5 are significantly larger than the estimated 20,000 TWh/yr of 2009 total electricity production [53] i.e. all materials needed for the two types of CSP plant have a reserve that is significantly larger than what would be required if all electricity at current level was to be produced by CSP units.

Table 5 paints an inadequate picture, though, since other applications are currently using these materials. If we take the reserve life column from Table 4, the reserves for chromium, zinc, silver and copper will be exhausted at current mine rates before 2050. Chromium, zinc and copper appear to have significant room in their resource base for reserve expansion, but silver does not. As noted, additional silver reserves will come from yet-to-be-identified polymetallic deposits (mostly lead-zinc and copper) but this availability is difficult to know in advance. The other materials

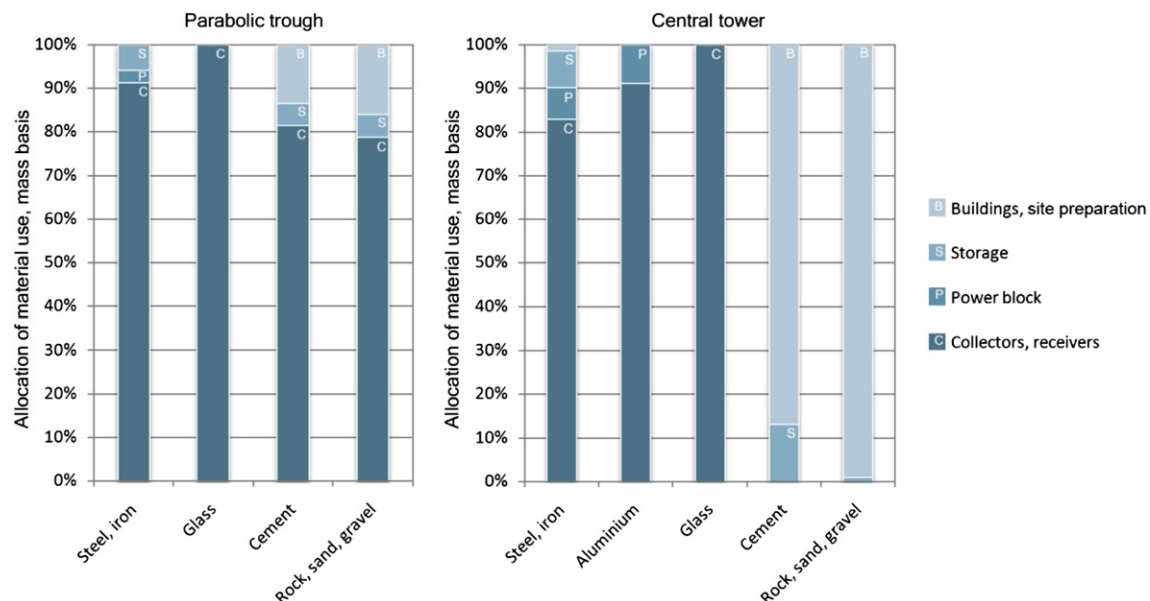


Fig. 3. Breakdown of bulk material mass distribution for the two CSP configurations, on mass basis.

Table 4

Reserves, resources and production of component materials (2010 values). The reserve life shows how many years the present reserves can supply the current demand before being exhausted.

	Reserve (Mtons)	Resource (Mtons)	Production (Mtons/yr)	Reserve life (years)
<i>Metals</i>				
Iron (Fe)	77,000	Abundant ^a	2300	33
Aluminium (Al)	32,000	Abundant	58	552
Titanium (Ti)	690	Abundant	6.3	110
Copper (Cu)	630	3000	16.2	39
Manganese (Mn)	630	Large ^b	13.0	48
Chromium (Cr)	350	12,000	22.0	16
Zinc (Zn)	250	1900	12.0	21
Nickel (Ni)	76	130	1.55	49
Vanadium (V)	14	63	0.056	250
Molybdenum (Mo)	9.8	14	0.23	43
Niobium (Nb)	3	Unknown	0.063	48
Silver (Ag)	0.54	Unknown ^c	0.022	25
Steel	Produced from Iron		1500	
<i>Minerals</i>				
Limestone	Abundant	Abundant		
Lime	Abundant	Abundant	280	
Silica Sand	Abundant	Abundant	120 ^e	
Soda ash	24,000	Abundant	46 ^f	522
Potash	9500	Abundant	26	365
Magnesium (Mg) ^d	2400	Abundant	5.6	429
Cement	Produced from limestone, etc.		2800	
Glass	Produced from silica sand, Mg salt		171 ^g	
Potassium nitrate	Produced from potash		33	
Sodium nitrate	Produced from soda ash		46	

^a Some materials are so abundant as to have no practical limit on their use.

^b Manganese resources are deemed “large” but are quite irregular with South Africa holding 75% and Ukraine holding 10% or more.

^c Silver resources will presumably be found with new polymetallic (Cu, Pb) deposits.

^d Magnesium salts, not magnesium metal are used for glass production.

^e Industrial silica sand (quartz sand) and gravel production.

^f This figure is including synthetic production.

^g Detailed value not found. Based on silica sand production, assuming all silica sand used for glass (silica comprising 70% of glass).

Sources: USGS Material Data Sheets [52] (Various authors).

in Table 5 still have enough ‘excess’ reserves at present mine rates to substitute all current electricity generation with CSP.

The current material constrained growth, G_{MC} , is shown in Table 6. The table is again filtered to show only materials with possibly relevant limits. The table shows generally high G_{MC} , i.e. the production rates are sufficient for a very rapid build-up of capacity for most materials. The most potentially rate constrained materials are the molten salts, silver, the alloy elements used for high

Table 5

Ratio of reserve of each material to the required amount for 1 TWh/yr capacity (DNI-adjusted), for materials with $S_{MC} \leq 1$ million TWh. Sorted by minimum value.

Material	Material constrained stock, S_{MC} by reserves (TWh/yr total capacity)	
	Parabolic trough	Central tower
Niobium	N/A	110,000
KNO ₃	160,000	340,000
Silver	170,000	180,000
Molybdenum	190,000	920,000
Nickel	310,000	220,000
NaNO ₃	270,000	570,000
Chromium	620,000	490,000
Manganese	1,200,000	570,000
Copper	750,000	2,400,000
Zinc	1,500,000	980,000

Table 6

Material constrained growth for solar plants showing most constrained materials ($G_{MC} < 50,000$ TWh/yr² for either plant, sorted by minimum value).

Materials	Material constrained growth, G_{MC} , TWh/yr ²	
	Parabolic trough	Central tower
NaNO ₃	520	1100
KNO ₃	560	1200
Nb	N/A	2400
Ni	6300	4500
Mo	4500	22,000
Si sand	4800	6900
Glass	5500	8100
Ag	6700	7600
Mg	7700	11,000
Soda ash	11,000	15,000
Mn	24,000	12,000
Fe	13,500	31,000
Cu	19,000	63,000
Al	320,000	25,000
Steel	36,000	30,000
Cr	39,000	31,000
Cement	43,000	200,000
Zn	70,000	46,000

temperature corrosion resistant steel (Nb, Mo, Cu, Ni), and glass along with the silicon sand and refractory magnesium used to produce it.

A comparison of materials needs for a strong CSP growth 2010–2050 with current annual commodity production is shown in Figs. 4–6. This can also be interpreted as the increase in

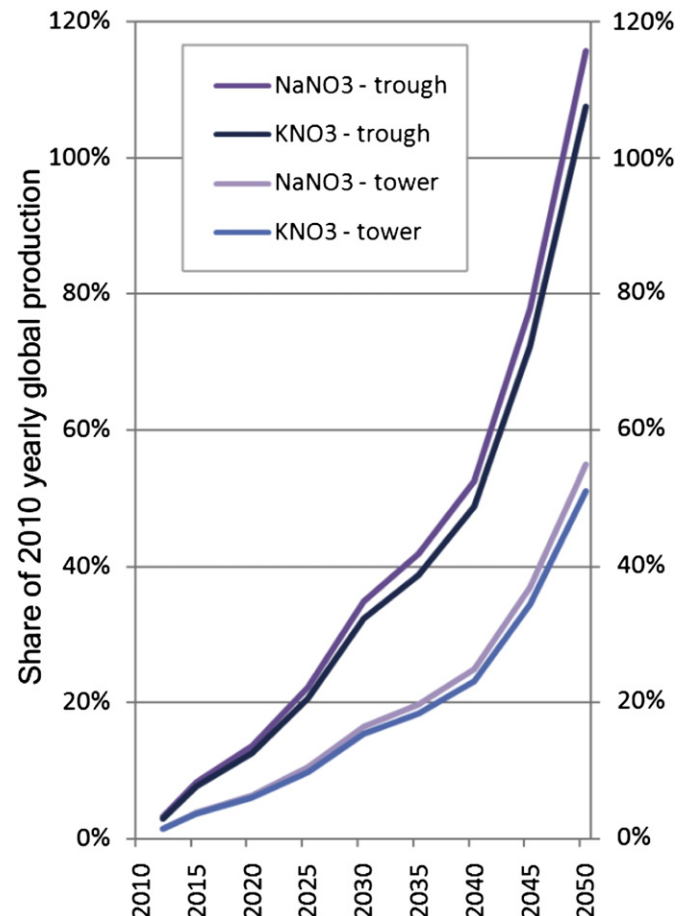


Fig. 4. Ratio of material needs to material production, yearly, for molten salts in parabolic trough and central tower plants. According to growth scenario (cf 2.1).

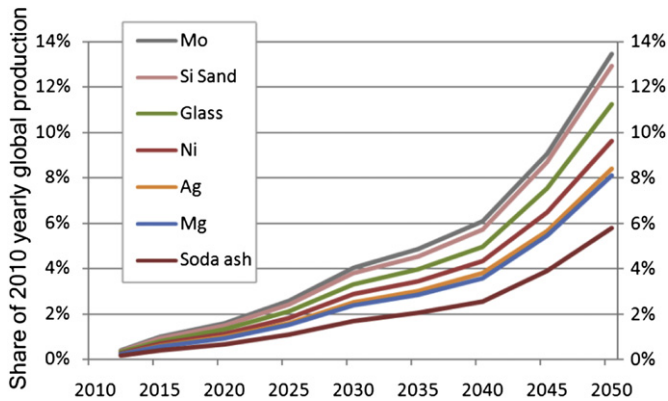


Fig. 5. Ratio of material needs to material production, yearly, for various materials in parabolic trough plants. According to growth scenario (cf 2.1).

yearly world production of materials that is required to make the CSP growth scenario possible without decrease in demand for other purposes. Only materials for which demand would reach at least 5% of worldwide production are included. The demand in this scenario compared to current production is significantly higher for molten salts than for other materials. Specifically for the trough plant, demand for both salts (NaNO_3 and KNO_3) is high in comparison to world production. Within two decades, CSP plants could become a big consumer of nitrate salts with 15–35% of the global market. Around mid-century, CSP plants could possibly use more than 10% of current world production of common materials such as nickel, glass and silica sand. The 10% level is reached already 2035–2040 for niobium in tower plants.

In summary, the thermal salts would quickly require attention to manufacturing and extraction capacity while CSP demand for all other materials would remain a small part of the annual production for several decades, with none reaching 10% before 2030 if constant production is assumed.

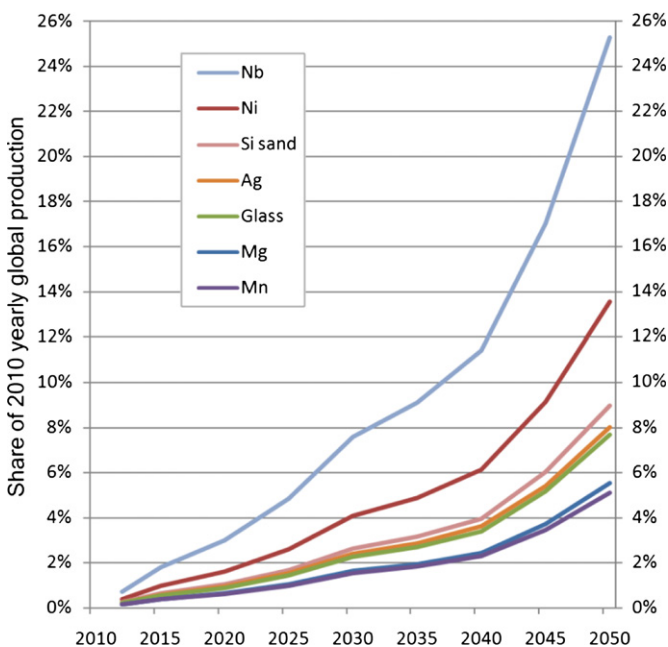


Fig. 6. Ratio of material needs to material production, yearly, for various materials in central tower plants. According to growth scenario (cf 2.1).

6. Production constraints, market impact and substitution of critical materials

The actual possibility for constraints to arise for each material will depend on whether CSP represents a net new demand for the material, how easily material supply can be increased and substitution options for the materials in CSP designs or in their other applications if necessary. This chapter discusses these factors for the set of materials identified as having the largest requirement relative to their supply: Glass and its constituents, the steel alloy elements, silver, and the thermal salts.

6.1. Glass, magnesium and silicon sand

As shown above, a large diffusion of the CSP technology will eventually require a large input of glass, and glass related compounds (Si sand, soda, refractory magnesium). The material constituents of these components are widely available, and adding more manufacturing capacity for such common components is unlikely to present a problem. Should there somehow be difficulties, there are possible ways to reduce or substitute the glass, such as using thin glass, aluminium-based or polymer-based reflector designs [47]. With large material supplies, little barrier to increasing manufacturing, and the possibility of substitution, these components will not restrain CSP in any way.

6.2. Steel alloy elements

The elements that are alloyed with steel for enhanced corrosion resistance and strength at high temperature (Cr, Ni, Zn, Mg, Mo, Mb, Nb, V) would be required in large quantities for a CSP build-up. The use of high temperature steel in CSP would however presumably substitute the use of the same alloys in other thermal electricity production sites. The net effect of CSP on the demand for these materials themselves is therefore unclear. Even if CSP growth was not a substitute for other thermal technologies and thus did not reduce steel demand for other energy purposes, it would not require more than 5% of the current output of any of the materials for several decades, with the exception of niobium.

The highest material needs relative to production are for niobium and molybdenum. Molybdenum (as well as chromium) is classed as having notably poor substitutability in thermal steels [54]. Molybdenum availability could be an issue because the reserve life of Mo is 43 years, while the resource base is not significantly larger than the reserves. The importance of niobium (for molten salt pipes in the tower design) is however debatable. It can be omitted if other steels are used, possibly in combination with coatings to protect the steel surface from corrosion (for non heat transfer applications).

Although a large number of alloys may be substituted for one another, it would be difficult to fully substitute high temperature steel alloys in general by either using other materials or by less material intense designs. Given the uncertain net impact on demand for these materials, the generally low requirements relative to production and the long timescale involved, steel alloy elements are unlikely to be a constraining issue for CSP. Molybdenum is the most likely candidate should issues arise.

6.3. Silver

The use of silver in mirrors for CSP requires a closer look as it is difficult to substitute, would constitute a large new demand for silver and the metal is potentially constrained in rate and available reserves. As Fig. 7 shows, there has been a significant supply deficit in terms of the difference between silver mining and fabrication

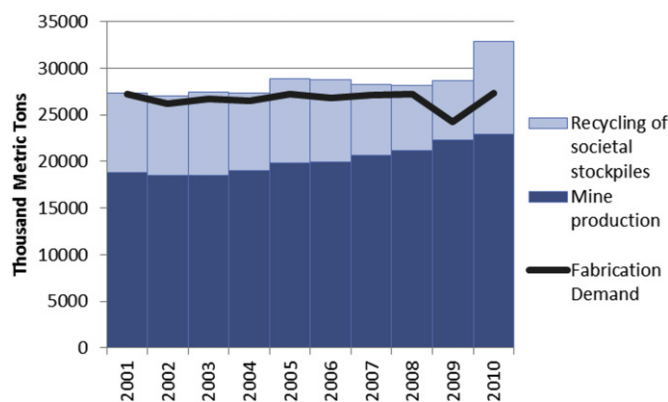


Fig. 7. Silver supply and demand [55,56].

demand for more than a decade. This deficit has been filled by drawing down government stockpiles and by recycling scrap and jewellery.

The dwindling use of silver in photography has been offset by the increase in electronic, photovoltaic, medical and nanomaterial demand, applications which have a high ability to pay for silver and which do not typically result in a recyclable stock [55,56]. The industrial demand for silver is thus very competitive at present, and represents 55% of fabrication demand and 75% of mine supply. The remaining demand is for new jewellery, coins, silverware and bullion.

Diminishing recycled silver supplies may be difficult to compensate through mining; roughly two thirds of silver production occurs as a by-product of mining other base metals, predominantly copper and lead [56]. Furthermore, silver has been mined for thousands of years, and there is not a large potential for new primary silver mines. This situation implies that the mine supply response to higher prices would be muted for silver. There is thus a potential for a large increase in price that all prospective silver users should be considering in strategic plans.

Reducing silver use for mirrors is a difficult challenge since it is already applied in extremely thin layers of about 100 nm. Alternative materials for reflective coating have been investigated, but none offer the same broadband reflection qualities [57]. The silver layer thickness could possibly be slightly reduced but there are durability and manufacturing issues strongly prohibiting layers thinner than about 50 nm [58]. A possible substitute is to instead use aluminium as reflective layer, on an aluminium substrate with a covering layer of oxides or polymer to protect from corrosion. Changing from silver to aluminium reflectors typically decreases the maximum reflectivity from ~95% to ~90% [59]. This decrease could be compensated by scaling up the reflector area which would increase the use of other less constrained materials and degrade the plant economics, but would not rule out feasibility. As silver is a small component of cost, the silver price would have to increase by multiples to make the increased reflector area needed for aluminium mirrors a cost-effective substitution.

6.4. Thermal salts

The use of thermal salts for storage would represent a significant new demand for the nitrate compounds and is difficult to substitute. The material requirement would exceed the total current production capacities for KNO_3 as well as NaNO_3 at roughly 500 and 1000 TWh/yr capacity addition for the trough and tower plants respectively. In an aggressive adoption scenario, this could occur before mid-century. The relative proportion of K and Na salts can be

adjusted somewhat and calcium salts are being tested as a possible component/substitute, but for a given salt composition, there is an almost linear relationship between the desired amount of thermal storage and the necessary mass of salt. If thermal storage is desired for CSP, there is therefore no foreseeable possibility to substitute this demand, with the technologies analysed in this work. The molten salt use per unit energy can be reduced by employing mixtures that store heat by phase change [60] or substituted by concrete storages. The large availability of the primary elements involved indicates that there should be a good scope for a supply response for molten salts, but it is difficult to say at what speed and cost.

7. Discussion and implications

The results of this work should be viewed as order of magnitude estimates of material availability for large diffusion of CSP technologies. Thus, rather than exact predictions and forecasts, it is useful to check for 'show-stoppers' and for judging the worst case backdrop situation, since it covers neither expected efficiency increases in power plants nor increases in ultimate reserves and resources from improved technology, increased prices or new discoveries.

In terms of the plants, the main sources of error in this work are lacking or insufficient data for some components and in data as basis for the estimates for scaling of thermal components. It is also an open question as to what degree the chosen power plant designs are representative for the total potential stock. One specific difficulty is assessment of the use of materials such as copper, aluminium and rare metals in turbines, generators and electric motors. These are typically complex components and precise data on metal composition is not readily available. It is unlikely that motors and generators contain more copper than the wiring in the collector fields (for which there is good data) viewing the weights of these components compared to the sheer weight of the wiring. This notion has been confirmed by an expert from industry.

The long run availability of resources is not something that can be known with certainty. Tilton [61] gives a comprehensive overview of the factors and reasons underlying this issue. The crux of the matter is that the supply-demand balance of materials is a complex process, with many feedbacks on both sides. 'Reserve' and 'resource' figures will change over time based on the price evolution of the material, the development of extraction technology and the success of exploration efforts in uncovering heretofore unknown deposits. Conversely, high prices or impending shortages of a commodity will induce efforts at minimization or substitution, and technological change can alter demand exogenously (e.g. through the emergence of a competitor technology).

8. Conclusions

This study has compared the material demands for construction and large-scale application of existing or near-term Concentrating Solar Power (CSP) technology with the present available production and reserves of those materials. In conclusion, there is no material that sets any relevant limit on how much of the two studied CSP types could be built in the foreseeable future, based on available reserves. The reserves of every required material are many times higher than what would be required to substitute all electricity generation with CSP. Current usage patterns would indicate that the current reserves of zinc, chromium, silver and copper will be consumed with or without CSP by mid-century. The possibility of replacing these reserves for silver is unclear. The material flows in operation, with the exception of water, are negligible compared to

the construction phase. The impact of water use is a complex question and highly specific to the particular region, it has been outside the scope of this study.

The production rates of most materials are also sufficient to enable a massive growth rate in installed CSP capacity. Despite the fact that there is little issue of material scarcity in an absolute sense, some components and materials required for large-scale CSP adoption will stretch current production and manufacturing capacities. Nitrate salts and silver, both crucial in the present design of CSP plants, could face supply shortage and increased prices in the coming few decades. With the growth scenario applied in this work, CSP plants could be consuming 15–35% of the global nitrate production within two decades. The silver use in CSP plants could be problematic both in the short term because of higher costs due to a potential supply shortage that could arise irrespective of CSP growth, and in the long term because of reserve limitations. Issues with glass and some steel alloys would be comparatively minor and are not likely to arise for several decades, if at all. Finally, these factors will only apply during a rapid increase in installed capacity. Operational material flows are negligible and the material flows available from decommissioning older units will be largely recyclable. Over the medium and long term, as CSP capacity saturates, the net amount of new material required will decrease towards that required to make up for losses in recycling.

For silver, there is some potential for substitution, although with negative effects on plant costs. Silver use can already be substituted by aluminized reflectors but with a corresponding about 5% decrease in collector field efficiency. There are potential substitutes for the steel alloys used, by selecting other steel types or through using coatings instead to protect steel from corrosion. The nitrate salts have little potential for substitution but have a large potential for a supply response.

With technology improvements, increase in extraction and production capacity of strategic materials and research into substitution, materials availability will not hinder CSP from replacing all of today's fossil fuelled electricity generation. The most important challenges concerning materials for CSP in the coming decades, will be to scale up nitrate salt production and develop good substitutes for silver in reflective surfaces. These issues may affect the cost of CSP on the margin, but are not particularly severe.

References

- [1] Bhandari R, Stadler I. Grid parity analysis of solar photovoltaic systems in Germany using experience curves. *Solar Energy* 2009;83:1634–44.
- [2] EASAC. Concentrating solar power: its potential contribution to a sustainable energy future. European Academies Science Advisory Council; 2011.
- [3] Hernández-Moro J, Martínez-Duart JM. CSP electricity cost evolution and grid parities based on the IEA roadmaps. *Energy Policy*; 2011.
- [4] Lund PD. Boosting new renewable technologies towards grid parity – economic and policy aspects. *Renewable Energy* 2011;36:2776–84.
- [5] CSPToday. CSP world plant locations, [CSPToday.com](http://www.csptoday.com); 2011.
- [6] CSPToday. India map 2012, http://www.csptoday.com/india/pdf/CSP_IndiaMap_V2.pdf; 2012.
- [7] Iberdrola. Iberdrola engineering starts up the Kuraymat power plant in Egypt, with a total capacity of 150 megawatts – press release. Available from: http://www.iberdrola.es/webibd/corporativa/iberdrola?IDPAG=ENMODPRENAC11&URLPAG=/gc/prod/en/comunicacion/notasprensa/110705_NP_01_Kuraymat.html; 2011, 05 Jul.
- [8] Jacobson MZ, Delucchi MA. Providing all global energy with wind, water, and solar power, part I: technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 2011;39:1154–69.
- [9] Kleijn R, Van Der Voet E. Resource constraints in a hydrogen economy based on renewable energy sources: an exploration. *Renewable and Sustainable Energy Reviews* 2010;14:2784–95.
- [10] Kleijn R, Voet E v d, Kramer GJ, Oers L v, Giesen C v d. Metal requirements of low-carbon power generation. *Energy* 2011;36:5640–8.
- [11] Lund PD. Upfront resource requirements for large-scale exploitation schemes of new renewable technologies. *Renewable Energy* 2007;32:442–58.
- [12] Andersson BA, Råde I. Metal resource constraints for electric-vehicle batteries. *Transportation Research Part D* 2001;6:297–324.
- [13] Gruber PW, Medina PA, Keoleian GA, Kesler SE, Everson MP, Wallington TJ. Global lithium availability: a constraint for electric vehicles? *Journal of Industrial Ecology* 2011;15:760–75.
- [14] Kushnir D, Sandén BA. The time dimension and lithium resource constraints for electric vehicles. *Resources Policy* 2012;37:93–103.
- [15] Andersson BA. Materials availability for large-scale thin-film photovoltaics, progress in photovoltaics: research and applications, vol. 8; 2000. pp. 61–76.
- [16] Andersson BA, Azar C, Holmberg J, Karlsson S. Material constraints for thin-film solar cells. *Energy* 1998;23:407–11.
- [17] Candelise C, Spiers JF, Gross RJK. Materials availability for thin film (TF) PV technologies development: a real concern? *Renewable and Sustainable Energy Reviews* 2011;15:4972–81.
- [18] Feltrin A, Freundlich A. Material considerations for terawatt level deployment of photovoltaics. *Renewable Energy* 2008;33:180–5.
- [19] Green MA. Price and supply constraints on Te and in photovoltaics. In: Conference record of the IEEE photovoltaic specialists conference; 2010. p. 550–5.
- [20] Green MA. Ag requirements for silicon wafer-based solar cells, progress in photovoltaics: research and applications, vol. 19; 2011. pp. 911–916.
- [21] Wadia C, Alivisatos AP, Kammen DM. Materials availability expands the opportunity for large-scale photovoltaics deployment. *Environmental Science and Technology* 2009;43:2072–7.
- [22] Burkhardt JJ, Heath GA, Turchi CS. Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives. *Environmental Science & Technology* 2011;45:2457–64.
- [23] Lechón Y, de la Rúa C, Saez R. Life cycle environmental impacts of electricity production by solar thermal power plants in Spain. *Journal of Solar Energy Engineering* 2008;130:021012–7.
- [24] Viebahn P, Kronshage S, Trieb F, Lechón Y. NEEDS RS 1a – D12.2 final report on technical data, costs, and life cycle inventories of solar thermal power plants. DLR/CIEMAT/Sixth Framework Programme; 2008.
- [25] May N. Eco-balance of a solar electricity transmission from north Africa to Europe. Diploma thesis. Technical University of Braunschweig and German Aerospace Center (DLR); 2005.
- [26] Weinreb G. Technical, ecological and economic analysis of solar thermal power towers. University of Stuttgart; 1999.
- [27] García-Olivares A, Ballabrera-Poy J, García-Ladona E, Turiel A. A global renewable mix with proven technologies and common materials. *Energy Policy* 2012;41:561–74.
- [28] Trieb F, Schillings C, Pregger T, O'Sullivan M. Solar electricity imports from the middle east and north Africa to Europe. *Energy Policy* 2012;42:341–53.
- [29] USGS. Principles of a resource/reserve classification for minerals. *Geological Survey Circular* 1980;831.
- [30] Greenpeace, SolarPACES, and ESTELA. Concentrating solar power global outlook 09; 2009.
- [31] IEA. Technology roadmap concentrating solar power. Paris: International Energy Agency; 2010.
- [32] Pacala S, Socolow R. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* 13 august 2004;305:968–72.
- [33] Pihl E, Heyne S, Thunman H, Johnsson F. Highly efficient electricity generation from biomass by integration and hybridization with combined cycle gas turbine (CCGT) plants for natural gas. *Energy* 2010;35:4042–52.
- [34] Trieb F, Schillings C, O'Sullivan M, Pregger T, Hoyer-Klick C. Global potential of concentrating solar power, presented at the SolarPACES 2009. Berlin; 2009.
- [35] Kearney A. Solar thermal electricity 2025. ESTELA; June 2010.
- [36] Doyle Gutiérrez L, Cobra Energia. Personal communication, e-mail. 2011.
- [37] Akyol S, Ahrens S, Jahr F, Rehberger C, Lüpfer E. Cost impact model for using polymer film based lightweight mirror construction in CSP plant. presented at the SolarPACES 2010, Perpignan, France; 2010.
- [38] Kearney DW. Parabolic trough collector overview, presented at the parabolic trough workshop 2007. Golden, CO, USA: NREL; 2007.
- [39] Herrmann U, Kelly B, Price H. Two-tank molten salt storage for parabolic trough solar power plants. *Energy* 2004;29:883–93.
- [40] eSolar. Personal communication (undisclosed person), mail. 2011.
- [41] Bloch HP. A practical guide to steam turbine technology. McGraw-Hill; 1995.
- [42] Klueh RL, Harries DR. MONO₃ high-chromium ferritic and martensitic steels for nuclear applications. Ch 2: development of high (7–12%) chromium martensitic steels. ASTM Standards and Engineering Digital Library; 2001.
- [43] Moore R, Vernon M, Ho CK, Siegel NP, Kolb GJ. Design considerations for concentrating solar power tower systems employing molten salt. Albuquerque, New Mexico and Livermore, California: Sandia National Laboratories; 2010.
- [44] GEA heat exchangers. Personal communication, e-mail. 2011.
- [45] García-Sobrinos G, Salvador-Villá I, Serradilla-Echarri J. Tower of power. Available from: <http://www.asce.org/Content.aspx?id=28974&ccs>; 2010.
- [46] Flagsol-gmbh. Important progress in construction of andasol 3 solar power plant: turbine and generator installed. Available from: http://www.flagsol-gmbh.com/flagsol/company/news/2010_09_20.html; 2010, Oct 14.
- [47] Kennedy CE. Advances in concentrating solar power collectors: mirrors and solar selective coatings. In: Presented at the 21st international vacuum web coating conference. Scottsdale, Arizona; 2007.
- [48] Nucor-Fastener. Hot dip galvanizing – technical data sheet, http://www.nucor-fastener.com/Files/PDFs/TechDataSheets/TDS_007_Hot_Dip_Galvanizing.pdf; 2011.
- [49] Schott. Schott PTR 70 receiver – setting the benchmark. Schott Solar; 2011.

- [50] M-WOITE. DIN 1.4541 steel specification, <http://www.m-woite.de/en/materials/14541.shtml>; 2011.
- [51] Mar RW, Swearingen JC. Material issues in solar thermal energy systems. *Solar Energy Materials* 1981;5.
- [52] USGS (various authors). Minerals commodity summaries. U.S. Geological Survey National Minerals Information Center; 2011.
- [53] IEA World. Energy outlook 2011. Paris: International Energy Agency; 2011.
- [54] Morley N, Eatherly D. Ensuring material availability for the UK economy. London: E. Agency/BERR; 2008.
- [55] Klapwijk P, Walker P, Ryan P, Newman P, Meader N, Tankard W, et al. World silver survey 2010. Washington, DC: The Silver Institute; 2010.
- [56] Hilliard HE. USGS mineral commodity summaries – silver. U.S. Geological Survey National Minerals Information Center; 2011.
- [57] Jaworske DA. Reflectivity of silver and silver-coated substrates from 25degC to 800degC [for solar collectors]. In: Energy conversion engineering conference, 1997. IECEC-97, proceedings of the 32nd intersociety, vol. 1; 1997. p. 407–11.
- [58] Peters PN, Sisk RC, Brown Y, Gregory JC, Nag PK, Christl L. Measurements of the optical properties of thin films of silver and silver oxide. Marshall Space Flight Center, NASA; Feb 1995.
- [59] Fend T, Hoffschmidt B, Jorgensen G, Küster H, Krüger D, Pitz-Paal R, et al. Comparative assessment of solar concentrator materials. *Solar Energy* 2003; 74:149–55.
- [60] Oró E, Gil A, de Gracia A, Boer D, Cabeza LF. Comparative life cycle assessment of thermal energy storage systems for solar power plants. *Renewable Energy* 2012;44:166–73.
- [61] Tilton JE. On borrowed time? Assessing the threat of mineral depletion. Washington, D.C: RFF Press; 2003.