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Review

System value and progress of CSP

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ABSTRACT

Concentrating solar power (CSP) offers the value proposition of being a baseload and dispatchable renewable energy technology. CSP significantly lags behind solar photovoltaic (PV) and wind power by cumulative capacity and cost for a number of reasons including the complicated nature of the technology and the traditional inability of the technology to be economically viable at smaller scales. The scaling limitation itself has prevented the technology from learning faster due to limited market share, which has inhibited the learning rate and continued to make CSP project financing difficult due to finance quantum risks.

CSP has limited but successful lifecycle experience due to the SEGS I–IX plants commissioned between 1985 and 1990 in California. More recently, the technology benefited from competitive tariffs before the adoption of PV and learning rates undermined its growth. PV (as with wind) now offers some of the lowest electricity generating rates of any technology. While this is valuable, the marginal value of intermittent renewables is roughly inversely proportional to their share of the electricity system as their capacity credit diminishes with each addition to capacity, all other things equal. CSP with storage has the ability to flexibly deliver electricity and to do so 24 h a day in the right conditions. CSP plants with up to 15 h of full-load storage have now been commissioned and are demonstrating initial evidence that they can deliver to expectation. Despite the proposed value of CSP, it is not penetrating the market as expected. The value of electricity has simply not been valued for instance in the U.S. market to date, which has valued renewable targets above capacity needs. Sunny developing countries have been identified as potential growth markets due to capacity constraints and the avoided cost of electricity. Most recently, China has embarked on the greatest capacity growth of CSP in the decision to commission around 5 GW of CSP within the next 5 years with 1.35 GW assigned to be online by the end of 2018. Even with this evolution, CSP will still significantly lag other renewables.

This review covers the system value and progress of CSP. An overall description of CSP and its value is followed by a broad review of CSP experience and research. A review of CSP in energy systems analysis is then provided to expose and quantify the marginal value of CSP. It is argued that improved quantification and accuracy in terms of energy systems analysis is an important step for CSP growth. The findings from the review show that CSP has potential to be the backbone of future electricity systems, but it needs to demonstrate value and acceptance to a broader audience than might be expected to achieve this.

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1. Introduction

Concentrating solar power (CSP) is a lesser known power generation technology entering into the growth phase of its technology life-cycle (Grobbelaar et al., 2014). The value of CSP is relatively well understood from a state-of-the-art point of view, but its value and potential in a power generation network is not as clear. The complexities arising from a rapid transition in electricity networks towards the use of intermittent energy resources and energy storage compound the need for systems based forecasting and knowledge. Contemporary CSP (with thermal storage) does not fit into currently defined conventional or renewable behavioral roles at a time when energy systems planning is just starting to deal with significant fractions of intermittent renewables (Pfenninger et al., 2014b). CSP could be the most valuable power generation technology of our time, yet thermo-economic scales and the related ability for the technology to learn could cause it to fall short significantly (IEA, 2014a).

1.1. Background

CSP is a class of power generation technology with several subtypes or variants that are distinctly different, but all share key attributes that label them as CSP technologies. CSP plants are characterized by the concentration of sunlight that is converted to high temperature thermal energy for direct or indirect operation of a heat engine and electricity generator. The initial conversion to thermal energy arguably enables the sensible and intrinsic potential for hybridization, addition of storage and the dual exploitation of electricity and thermal energy (heat).

CSP is a relatively immature technology compared with solar photovoltaic (PV) technology and most other electricity generating technologies. Total worldwide installed CSP capacity exceeded 1000 MW in late 2011 (IRENA, 2012a). By late 2013 it had more than doubled to around 3000 MW (NREL, 2013), and it reached almost 4800 MW at the end of 2015 (REN21, 2016). By comparison, PV has seen continued growth for a longer period of time with the worldwide installed capacity exceeding 67 GW in 2011 (IRENA, 2012b) and reaching about 227 GW at the end of 2015 (REN21, 2016).

A number of interrelated factors are generally attributed to the slower adoption of CSP. Primary amongst these is the historic and contemporary inability to scale modularly due to the thermo-economically driven inverse relationship between generating cost and plant size. The more recent addition of meaningful thermal storage offers a renewable solution to dispatchability with reasonably high availability. Yet the initial markets have not valued these attributes and instead have opted for lowest cost addition of renewables, which threatens a cost reduction and growth spiral typical of new technologies (IEA, 2014a). Several emerging economies, such as those of South Africa, Chile and Morocco, have been identified as ideal to move the technology forward (Teske et al., 2016). These countries have superior direct normal irradiation (DNI) solar resources over large areas as shown in Fig. 1 and tend to have growing capacity needs and/or high costs of reliable generation.

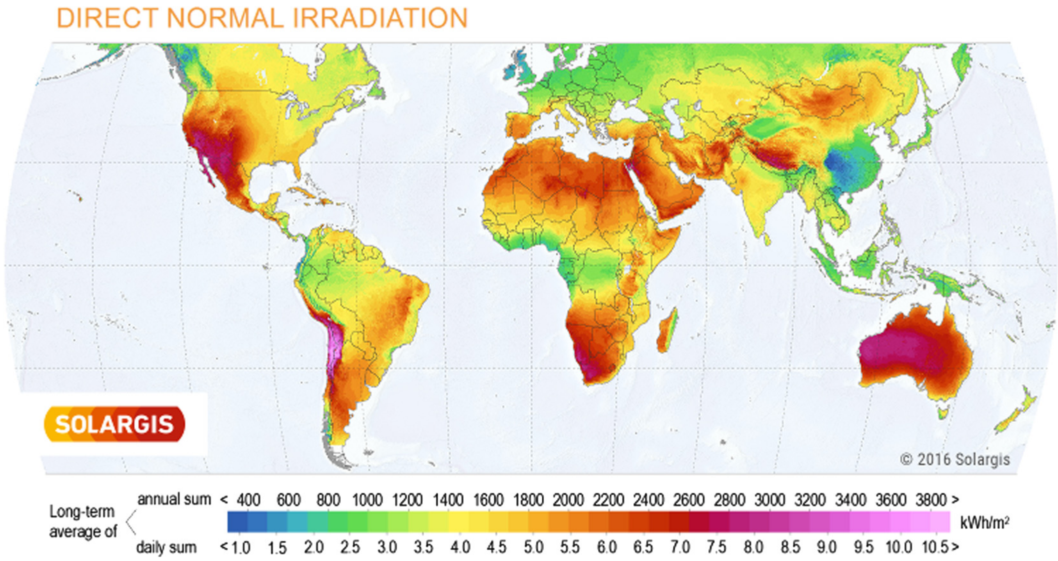


Fig. 1. Worldwide long term average annual DNI (Direct Normal Irradiation) (DNI Solar Map © 2016 Solargis).

Table 1
Primary energy supplies (adapted from de Rosa (2005)).

Source of energy	Amount (TW)
Solar	**173,000**
Direct reflection (Albedo)	52,000
Conversion to heat	78,000
Evaporation of water	39,000
Wind & waves	3600
Photosynthesis	40
Tides	**3**
Geothermal	**32**

South Africa presents an interesting recent case in CSP adoption. Fluri (2009) estimates the short term potential for CSP in South Africa based on an analysis of suitable land near existing transmission infrastructure to be in excess of 500 GW; that is more than an order of magnitude greater than the total generating capacity of Eskom, the South African state utility company. In 2011, the South African Integrated Resource Plan (IRP) was adopted as law (South African DoE, 2011), and CSP was implemented by the Renewable Energy Independent Power Producers Procurement (REIPPP) program (South African DoE, 2012). The initial plan included 1100 MW of CSP leading up to 2030, and a draft update in 2013 recommended 3300 MW; this draft update, however, never became law (South African DoE, 2013a). Initial rounds of the REIPPP program led to the deployment of 400 MW (200 MW in operation at the time of writing). A further 200 MW was approved of which a 100 MW plant has a signed power purchase agreement (PPA), and 450 MW has been allocated to preferred bidders (South African DoE, 2015). To date, CSP has controversially been eliminated in the newest version of South Africa's draft IRP, which defines new electricity generating capacity up to 2050 (South African DoE, 2016). If passed into law, only the approved projects are expected to proceed until such time as the IRP is revised again. It is not known if any of the 550 MW approved but without signed PPAs will proceed.

The next phase of CSP deployment seems to be coming from two quarters. The first of these is from emerging markets with electricity demand growth rates higher than South Africa, with similar or better solar resources and where the value of CSP is apparently greater due to the greater avoided or unserved cost of electricity. Countries within this quarter are led by Morocco, Chile and Namibia. The other quarter is China, which seems to have a completely different approach. As part of China's recently announced 13th 5 year plan, close to 1.35 GW of CSP in 20 projects

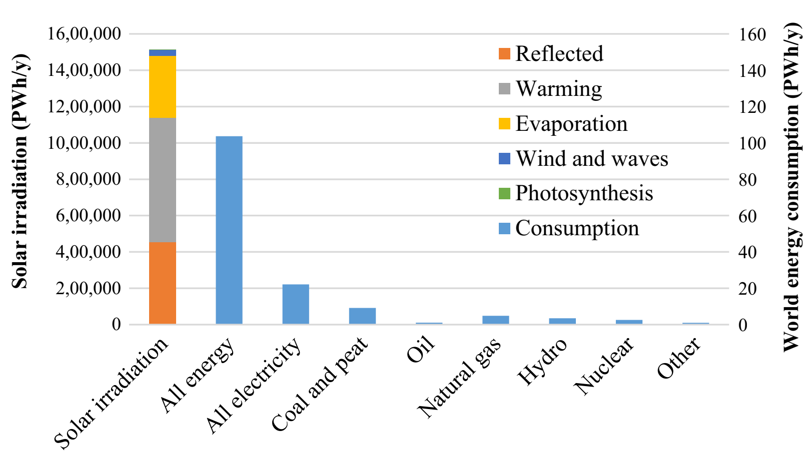


Fig. 2. Total world energy in 2011 by solar irradiation (left axis) and anthropogenic energy consumption (right axis) (adapted from de Rosa (2005) and IEA (2013)).

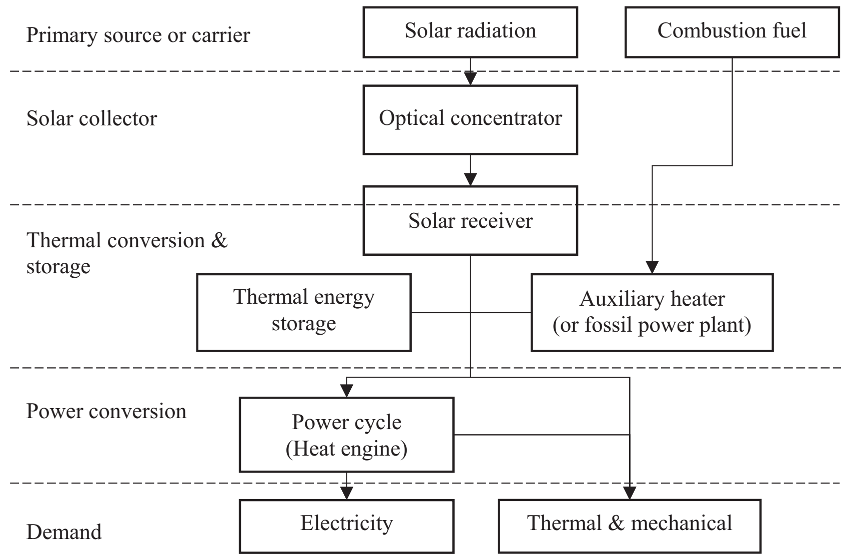


Fig. 3. Basic flow diagram for CSP systems (adapted from Stine and Geyer (2001)).

has been approved with a total of 5 GW expected in the next 5 years (CSPPLAZA, 2016). The initial 20 projects are considered to be commercial demonstration projects, and the configurations and maturity levels of these vary considerably. The scale of the near term plan for China relative to the cumulative history of CSP is illustrated in Fig. 5.

1.2. Solar energy in perspective

Solar energy is the source of most of Earth's ongoing primary energy supply as tabulated in Table 1. It is also the original energy source for most electrical power generation with the exception of nuclear power, geothermal and tidal based power generation.

Total global production of electricity in 2011 was 22,126 TW h (IEA, 2013). How this compares with global anthropogenic consumption of energy and annual solar energy irradiation is represented by Fig. 2. Electricity consumption represents about one fifth of anthropogenic energy consumption, which in turn is about 5 orders of magnitude lower than non-reflected solar energy irradiation. Provided solar power is valued and competitive, it offers the potential for energy and electricity far in excess of our needs. Trieb et al. (2009) assess the global CSP potential at almost 3,000,000 TW h per year; that is more than 130 times the 2011 world electricity production. The analysis considered areas where DNI exceeded 2200 kW h/m^2 annually and excluded areas used for other purposes or that were not suitable due to vegetation, water or terrain. The suitable areas add up to about 25,000,000 km^2. Just the very sunniest regions where the DNI exceeds 2700 kW h/m^2 per year provides a potential for about 460,000 TW h per year, or 20 times the 2011 world energy production.

While the stated potential of CSP vastly exceeds current worldwide needs, high DNI regions tend to be dry with significantly lower populations and population densities. More so than with PV, the best CSP locations are not coincidental with areas of significant electricity demand. Some capacity growth in good to excellent DNI areas is possible with minimal grid expansion in the short term. Notwithstanding other competing or adverse factors that will be discussed in this article, the urban areas of the U.S. South West areas offer significant growth potential. Considering Arizona as one example, in 2015 the state had a net summer electricity capacity slightly above 28 GW with total annual retail sales of about 77 TW h out of about 113 TW h net generation. In the same year, CSP net generation in the state was 719 GW h, less than 1% of total annual generation (U.S. Energy Information Administration, 2017a, 2017b). The majority of the population live in the Phoenix-to-Tucson southern part of the state where DNI is particularly high, implying a high potential for CSP without significant transmission needs beyond what already exists. Other isolated examples around the world with low to moderate new transmission needs include parts of the Mediterranean coast of North Africa and the Middle East. In order to participate in some of the larger urban areas proximate to moderate or better DNI areas, new transmission infrastructure will be required or CSP capacity will need to be located in lower DNI areas. China represents an interesting case where CSP plants are planned for locations where DNI barely exceeds 2000 kW h/m^2 per year with the bulk of the Chinese population located 500–1000 km to the east or south-east (Wang, 2016).

1.3. Overall definition of CSP

Solar thermal energy systems is a broad technology category involving the conversion of sunlight to thermal energy in order to supply thermal energy, electricity or both. CSP is a classification within solar thermal energy characterized by the increase of solar radiation flux density in order to achieve higher temperatures and efficiencies, primarily for making electricity production more feasible. Fig. 3 illustrates the basic elements and conversions involved from source to demand in CSP.

Solar thermal electricity (STE) is another term used for CSP but gives credit to non-concentrating technologies in addition to CSP. The only significant non-concentrating STE technology is the solar updraft tower (or solar chimney) technology which is comprehensively reviewed by Zhou and Xu (2016) and excluded in this CSP systems review.

Several key characteristics can be observed from the basic elements in the source-to-demand process in CSP. CSP has a relatively high number of distinct components, making it a complicated technology. This drawback, however, is offset by the fact that the technology offers versatility in application to suit demand. The conversion initially to thermal energy differentiates CSP from the other major renewable energy technologies such as hydropower, wind power and PV. This conversion process offers intrinsic com-

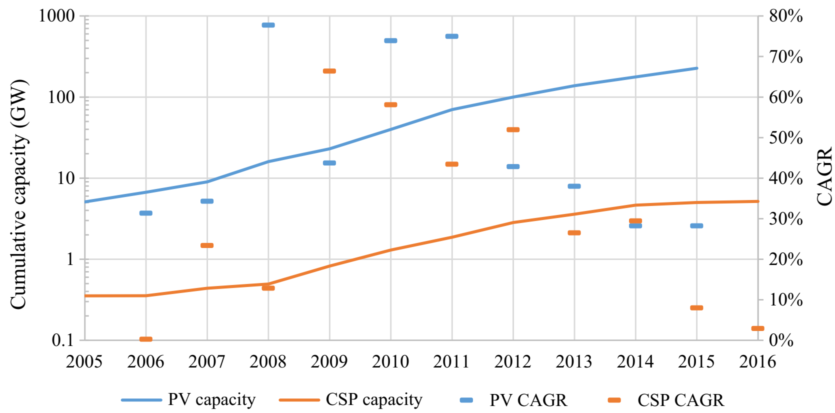


Fig. 4. Cumulative worldwide installed capacity (left axis, log scale) and compound annual growth rate (CAGR) (right axis) for PV and CSP.. *Sources:* adapted from REN21, NREL CSV download at NREL (2016)

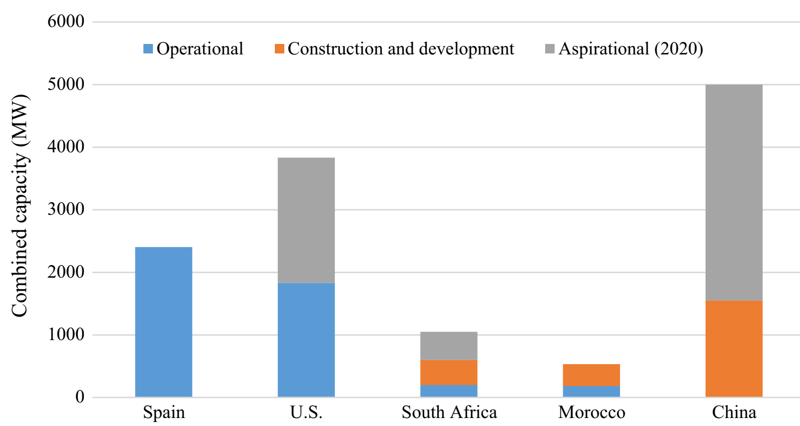


Fig. 5. Combined operating, construction and development, and aspirational CSP capacities for selected countries. "Aspirational (2020)" capacities are subjectively estimated from announcements or planned projects at risk up to about 2020. *Sources:* adapted from NREL (2016), SolarReserve (2016) and CSPPLAZA (2016).

patibility with thermal hybridization and thermal storage as illustrated in Fig. 3. Hybridization can take the form of auxiliary fossil fuel heating in CSP plants or augmentation of solar energy in existing or future conventional power plants. These various combinations allow for sharing of components or resources, theoretically offering cost advantages (IEA, 2014a). Thermal storage takes place prior to power conversion, thus enabling a cost tradeoff between the storage and downstream components which include the heat engine, generator and transmission equipment. This implies that storage does not proportionally add to the cost of a CSP plant; it can actually reduce the cost of power production in the case where the thermal storage is increased in exchange for a smaller turbine and generator.

1.4. Market adoption and value

While the history of CSP, at least by demonstration, goes back to before the turn of the twentieth century, it is a series of nine parabolic trough plants with a combined capacity of almost 400 MW in California commissioned in the late 1980 s that has provided the only proof of lifecycle performance to date. Most of these plants, known as the Solar Energy Generating Systems (SEGS) I–IX, are still operating today. The SEGS formed the reference for many more plants deployed mostly in Spain and the U.S. in recent times (IEA, 2014a, 2010). While the installed capacity of CSP increased by a factor of six over a four year period ending in 2013, the capacity growth rate of the technology is lagging expectations. Many resources are available that cover this history, perhaps most comprehensively and recently reviewed by Baharoon et al. (2015).

Fig. 4 presents a plot of the cumulative installed capacity and growth rate of CSP and PV over the last 10–11 years. The growth rate of CSP and PV present similar characteristics over this time; however, while 2016 is expected to be another good year for PV, CSP growth has stagnated. It is perhaps ironic that the 2016 cumulative capacity for CSP is currently known with some confidence. The limited number of large, capital intensive projects is relatively easy to track.

Fig. 5 conceptually presents five key CSP markets with distinctly different adoption rates and only considers capacity installed, committed or that is considered aspirational over the next five years. The U.S. led the market initially and was well ahead of other markets until recently when Spain embarked on an ambitious but unsustainable growth in CSP capacity over a five year period. It is assumed that no further capacity will be added in Spain in the near future. Being more decentralized, the U.S. remains a prospective growth market, and it is assumed that the 2 GW proposed by SolarReserve (2016) may be feasible. While 1050 MW has been approved in South Africa, reaching that level remains uncertain, hence the divide between projects underway and aspirational additions. New capacity addition has dropped significantly leading up to and including 2016, but the Chinese plans in particular should result in an aggressive growth rate for the next few years.

The reasons for the lag in market adoption are explored from a system perspective in this article. Various other articles in this CSP

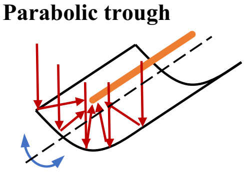
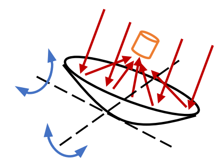
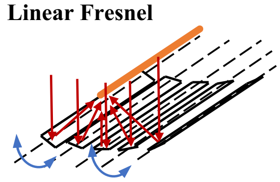
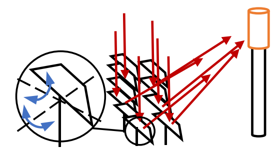
	Focus type	
Reflector type	Line focus (single axis, 2D concentrating)	Point focus (2 axis, 3D concentrating)
Continuous (continuously curved to axes)	**Parabolic trough** 	**Parabolic dish** 
Discrete (multiple, near flat)	**Linear Fresnel** 	**Central receiver** 

Fig. 6. Generally accepted CSP technology types (maroon arrows represent reflected sunlight, blue arrows with dashed line represent rotation axis, orange represents the receiver). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

focused special edition relate to CSP as a technology, whether in part or as a whole. As a technology, CSP is extremely complicated due to the number of components in a plant, let alone the combinations of CSP types, applications and installed environments. While complicated, the technology is likely not the key determinant in its successful adoption. Factors beyond the technology that relate to uncertainty and the unknown are likely as important if not more so. These factors are not complicated; rather they are complex. True systems exhibit complexity, and CSP is a complicated technology at the crossroads of many challenges and opportunities, thus placing it in a complex environment. This article strictly uses an epistemological definition of complicated vs. complex (Cilliers, 1998).

1.5. Objective

This article aims to provide a comprehensive review of the system value and progress of CSP worldwide. This review builds on the recently completed PhD dissertation by the corresponding author (Gauché, 2016a), which explores the system potential of CSP in South Africa. The reviews, methods and associated findings of the dissertation are incorporated in this article as a departure point and foundation. The review also extensively covers various studies and publications of peers, collaborators and the wider CSP and energy systems analysis community worldwide. The breadth of this topic prevents a deep review in any one area. Instead, the review attempts to provide a glimpse of the complexity of CSP's potential system role where science, technology, ecology, policy and sociology likely all fairly contribute to the success or failure of the technology. Where possible, other representative reviews of specific aspects of CSP are referred to with summary findings to avoid unnecessary duplication.

Compelling evidence of the breakthrough value of CSP has proved elusive. While the technology and its constituent components theoretically suggest a reasonable probability of becoming the single most important electricity generation technology (IEA, 2014a), and with many of the plants in operation demonstrating technical feasibility, CSP has yet to convincingly enter any market. System value is based on factors that reach beyond the performance and cost of the technology or of individual power plants. This review covers a number of areas in exploring the authors collective understanding and progress of this system value.

An overview of CSP is provided describing the various CSP types and configurations. The high level principles of CSP and a related

Fig. 7. Photo of Xina (front, under construction) and KaXu (rear, operating) parabolic trough plants in South Africa. *Source:* Photo supplied by Abengoa Solar.

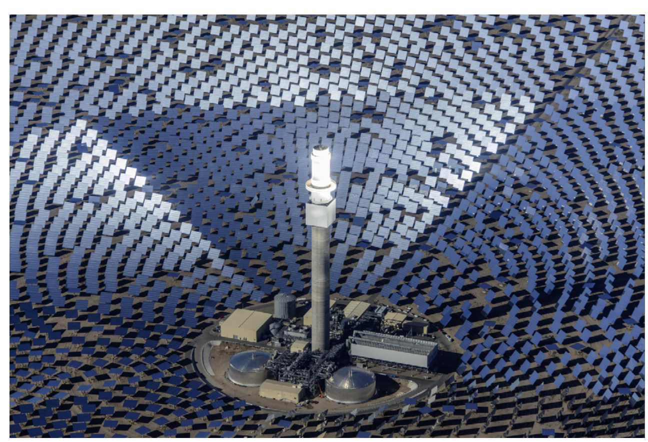


Fig. 8. Crescent Dunes CSP plant, a 110 MW central receiver plant with 10 full-load hours of storage. Image shows only part of the surround heliostat field with the power island in clear view showing the two molten salt tanks (front of tower) and air cooled condenser system (right of tower). *Source:* Photo supplied by SolarReserve.

performance scoping follows. The section concludes with the applications, history and current status of CSP globally. The systems role of CSP is then covered by looking at the current state of energy systems analysis, methods, studies and plans. CSP technology configurations and uses are considered in terms of the value

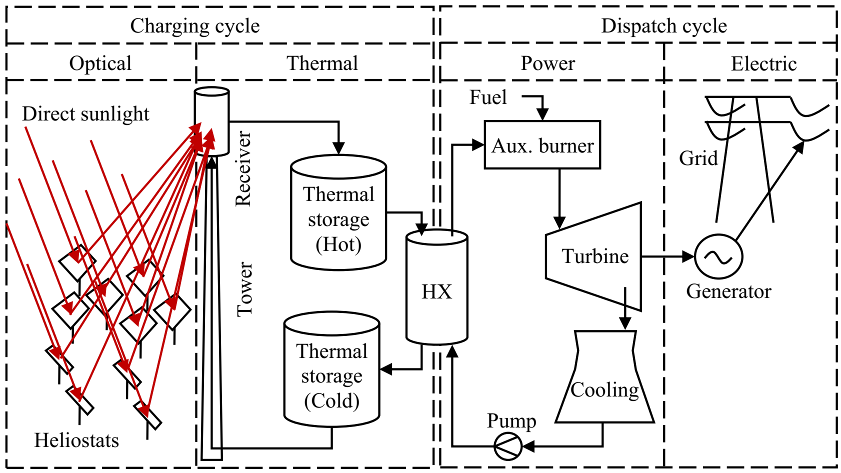


Fig. 9. Schematic layout of a central receiver CSP plant with storage.

and impacts to such systems. With CSP technology and the associated system value reviewed, a CSP technology outlook follows. This outlook considers advances and roadmaps in CSP technology development, energy systems analysis and a brief overview of where CSP research and development is done worldwide. The review wraps up with a discussion on the authors perspectives and outlook for CSP.

2. CSP overview

2.1. CSP technologies and configurations

There are four generally accepted CSP technology types; these are characterized by the method of concentrating sunlight by reflection onto a receiver as conceptually illustrated in Fig. 6.

Line focus CSP collectors focus concentrated sunlight on a linear receiver, typically a steel tube with an evacuated glass cover for insulation. The parabolic trough line focus system is to date the most commonly found CSP technology in operation. The simpler tracking of the sun and efficient use of the curved parabolic mirrors are clear advantages that have not been significantly challenged by the proposed alternative for line focus, the linear Fresnel reflector system. Line focus technologies have fundamental limits, particularly relating to the theoretical concentration ratio of 212:1 (Duffie and Beckman, 2006).

Point focus types are able to achieve far higher concentration ratios but require proportionally more effort in tracking accuracy. A continuously tracking paraboloid shaped reflector provides the highest concentration ratio and is theoretically the most efficient concentrator type maintaining high levels of efficiency at all times of day. To date, no large scale or scalable technologies have been developed to exploit this advantage commercially (REN21, 2016). Parabolic dish concentrators with Stirling engines have been successfully demonstrated and used for several decades, but lack of energy storage, cost and long term reliability are some of the reasons why the ideal solar concentrator is not in regular use.

The two CSP types that are dominant in the market are the parabolic trough (Fig. 7) and the central receiver (Fig. 8). The majority of CSP plants in operation are of the parabolic trough type. Parabolic trough plants brought into operation in the twenty-first century closely resemble the still operating SEGS plants with the exception of the addition of thermal energy storage. While proven and bankable, the state of the art parabolic trough technology has a practical operating temperature of around 390 °C and uses three working fluids. Thermal oil is used as the heat transfer fluid (HTF), molten salt is used for thermal storage, and water is used for the power cycle.

The state of the art central receiver based plants operate using two working fluids. Molten salt is utilized as both heat transfer and storage medium, and the power cycle is a superheated steam Rankine cycle as illustrated in Fig. 9. The first commercial plant of this type is the 20 MW Gemasolar plant in Spain developed by Torresol Energy, first operated in 2011. The receiver outlet temperature is 565 °C, and the storage capacity is rated to 15 h (NREL, 2011a). The higher operating temperature enables more compact and, hence, larger capacity storage. To date, only one other tower of this type has entered operational status: the 110 MW Crescent Dunes plant (Fig. 8) developed by SolarReserve (NREL, 2015a). Redstone is a similar SolarReserve plant in South Africa in advanced planning (NREL, 2015b) and is an approved project in the South African Renewable Energy Independent Power Producers Procurement (REIPPP) program.

The central receiver system uses multiple tracking mirrors called heliostats and approximates a point focus. While not able to achieve the highest efficiencies, this system is able to scale in size allowing for the use of efficient thermal storage and utility sized turbines operating at superheated levels (IEA, 2014a). Fig. 9 illustrates the basic layout of a state of the art central receiver system with a two-tank molten salt storage system and steam cycle.

2.2. Principles of a CSP plant

The central receiver system as illustrated in Fig. 9 is the reference for describing the energy conversion principles of a CSP plant. The system can be divided into a charging cycle and a dispatch cycle, where the only significant dependency between these two cycles is the charge level of the thermal storage. This system is selected as the reference due to its demonstration of the way forward for CSP overall, but the principles that follow are generally applicable to any CSP configuration, including handling advances in the technology intended to increase efficiency and performance.

The optical component is a solar collector system containing a field of heliostats that reflect incident DNI to a thermal receiver in the form of concentrated solar irradiation. The thermal receiver converts the optical energy to thermal energy, which is then stored in a high temperature container. Thermal energy is transferred through a heat exchanger (HX) to the dispatch cycle, which is generally a standard superheat steam cycle.

Presenting the following principles has a dual purpose. Firstly it serves as a high level mathematical framework for constraining the

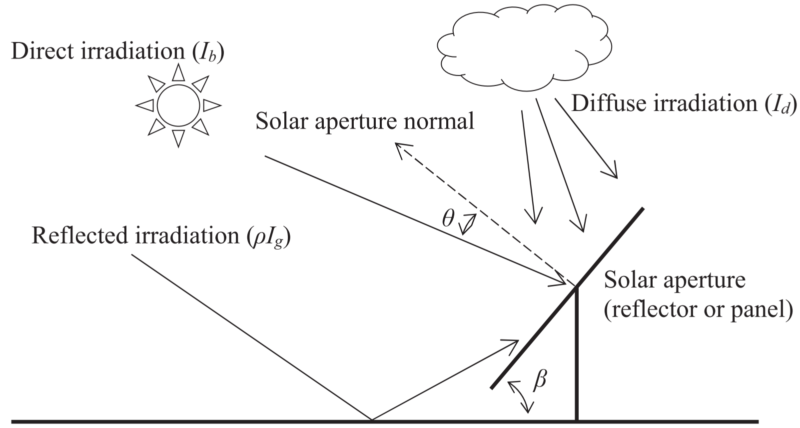


Fig. 10. Illustration of sunlight components onto a primary solar aperture that could represent a solar thermal collector, PV panel or CSP reflector (adapted from Auret (2015)).

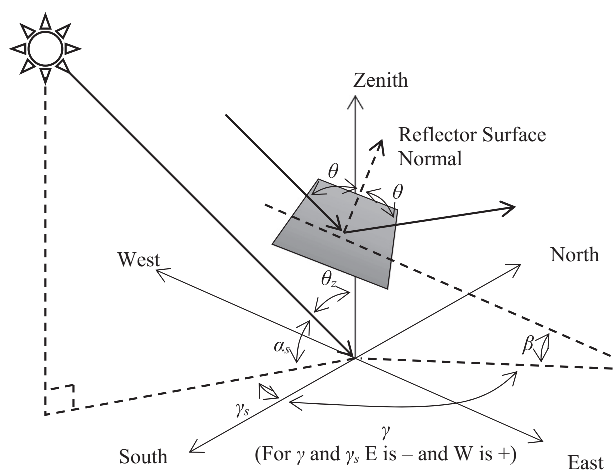


Fig. 11. Solar and reflector angles.

limits of the technology to a more general audience, and secondly these principles represent sufficiently the detail needed to evaluate CSP (and other solar energy technologies) in a system context. The majority of these principles come from two well regarded texts in the CSP community: a free online resource called "Power from the sun" (Stine and Geyer, 2001) and the well-known "Solar engineering of thermal processes" (Duffie and Beckman, 2006).

2.2.1. Optical conversion

Any of the known CSP, PV or solar thermal collector primary aperture areas can be geometrically related to the position of the sun per Fig. 10.

The total incident irradiation (I_t) for such a primary aperture surface per Stine and Geyer (2001) is

$$I_t = I_b \cos\theta + \left[I_d \left(\frac{1+\cos\beta}{2} \right) + \rho I_g \left(\frac{1-\cos\beta}{2} \right) \right] \tag{1}$$

where I_b represent beam irradiation (DNI), I_d represents diffuse horizontal irradiation (DHI), I_g represents global horizontal irradiation (GHI) and ρ is the effective ground reflectivity. The entire expression is relevant for non-concentrating solar collectors, but only the DNI component is relevant for any concentrating technologies per collector ignoring shading.

$$I_t = I_b \cos\theta \tag{2}$$

Direct sun-following concentrating trackers as used in concentrated PV (CPV) and parabolic dishes (such as Stirling dishes) benefit from zero cosine losses. For other CSP trackers, cosine losses and other losses associated with how they are arranged require further detail. All solar reflector (heliostat) field angles are described in Fig. 11 and relate the position of the sun relative to time, location and the angular position of an individual reflector.

The position of the sun is given by two components: Zenith angle (θ_z) and the angle of the sun relative to vertical. The compliment of this is the solar altitude angle (α_s) and solar azimuth angle (γ_s); the latter of which is the angle of the projection of the sun's rays relative to south. The position of the sun with respect to the observer can be determined with latitude (ϕ), date and solar time. Two terms relating to seasons and time remain: declination angle (δ), which is the angle of the zenith relative to the equator due to the tilted rotation axis of earth, and hour angle (ω), which is based on solar time, a conversion of solar time to an angle where 24 h = 360 ° and solar noon is 0 °.

Zenith angle is given as

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{3}$$

and solar azimuth is given as

$$\gamma_s = \text{sign}(\omega)\left|\cos^{-1}\frac{\cos\theta_z\sin\phi - \sin\delta}{\sin\theta_z\cos\phi}\right| \tag{4}$$

An approximation for the declination angle is given as

$$\delta = 0.006918 - 0.399912\cos B + 0.070257\sin B - 0.006758 \times \cos 2B + 0.000907\sin 2B - 0.002679\cos 3B + 0.00148\sin 3B \tag{5}$$

where B converts the day of the year to an angular value.

$$B = \frac{(n-1)360}{365} \tag{6}$$

Solar time accounts for the difference in longitude between the observer longitude (L_{loc}) and the longitude on which the local standard time (L_{st}) is based. Each 1 ° difference accounts for 4 min and the perturbations in the earth's rate of rotation. The sum of these two components is described by the equation of time (E)

$$\text{Solar time} = \text{Standard time} + 4(L_{st} - L_{loc}) + E \tag{7}$$

where the equation of time (E) is given as

$$E = 229.2(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \tag{8}$$

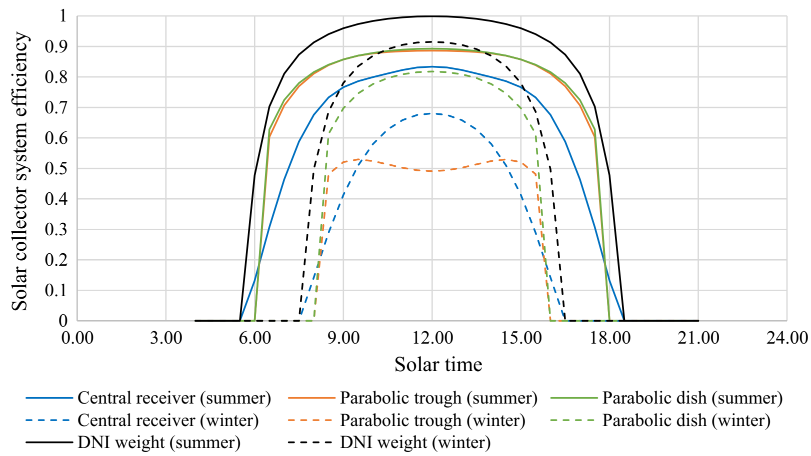


Fig. 12. Ideal DNI weighted CSP collector system efficiency comparison for a surround field central receiver system (blue), N-S aligned parabolic trough (orange) and multiple parabolic dish (green) at a latitude of 30° for mid-summer (solid line) and mid-winter (dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Information about the reflector surface is contained in these components: slope of heliostat (β); surface azimuth (γ), the direction of the slope relative to south; and angle of incidence and reflection (θ). A generalized equation for the position of the sun relative to the plane of interest is given as

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \quad (9)$$

which can be more conveniently represented by the zenith angle and solar azimuth angle by

$$\cos\theta = \cos\theta_z\cos\beta + \sin\theta_z\sin\beta\cos(\gamma_s - \gamma) \quad (10)$$

This reduces the cosine efficiency of any CSP reflector to a function of the position of the sun and the normal vector of the reflector. It is convenient both for illustrative purposes and also for simplifying systems analysis of CSP to separate the detailed optical system behavior from plant simulation. The integrated optical behavior based only on the position of the sun is sufficient for good systems analysis and is represented typically by a lookup table or simplified solar azimuth-zenith formulas.

For a parabolic trough plant that has collector rows in the typical north-south arrangement, the cosine efficiency is determined by setting the collector azimuth to east in the morning and west in the afternoon. The collector slope is set to the projection of the solar zenith angle in the plane normal to the rotation axis. Besides sunrise and sunset blocking, edge spillage, acceptance angle spillage and collector control, a parabolic trough's integrated collection potential is governed by this principle, and the derivation can be found in the referenced texts (Duffie and Beckman, 2006; Stine and Geyer, 2001). In the case of a central receiver system, the integrated optical performance requires consideration of each heliostat. Some of the more referenced methods to adjust each heliostat using (simplified) convolution methods include Delsol (Sandia, 2009) and HFLCAL (Schwarzbözl et al., 2009). For energy systems analysis, it is convenient to consider a surrounding heliostat field since the optical performance essentially reduces to being a function only of the solar zenith angle. The following polynomial derived by Gauché (2016a) has been used in various studies (Auret, 2015; Pfenninger et al., 2014a). This expression is not intended for plant design or yield, but it sufficiently describes daily to seasonal performance trends in energy systems analysis and includes typical losses associated with reflectivity, soiling and availability.

$$\eta_{optical} = 0.4254\theta_z^6 - 1.148\theta_z^5 + 0.3507\theta_z^4 + 0.755\theta_z^3 - 0.5918\theta_z^2 + 0.0816\theta_z + 0.832 \quad (11)$$

When accounting for atmospheric impacts to DNI on clear-sky reference days, the integrated efficiency of various collectors can be compared. Fig. 12 illustrates the DNI weighted performance of a surround central receiver heliostat field, a parabolic trough collector field and a field of parabolic dishes. This comparison is based on a latitude of 30 ° with mid-summer and mid-winter ideal days shown. In this example, parabolic trough and dish collection assumes that a sun altitude of 15 ° is required to overcome shading by adjacent collectors.

At this latitude, parabolic trough and dish systems perform well during summer relative to weighted DNI. In mid-winter, parabolic dishes continue to perform well relative to weighted DNI, but the parabolic trough system performance drops significantly. Central receiver optical systems have a generally lower optical efficiency than parabolic dishes but are more seasonally consistent than parabolic troughs. These behaviors are important both from a plant performance and systems performance point of view. In considering tradeoffs, the ability of these collector systems to be coupled with storage and also in pairing with high efficiency heat engines is critical. Before resuming with these realities, the SolarPACES 2013 keynote presentation of Karni (2013) made specific reference to the clear superiority of parabolic dish efficiency in terms of the first and second law of thermodynamics. Karni suggested that the CSP community might not be applying sufficient resources now to harness the optical superiority of the sun-facing paraboloid in CSP systems of the future.

2.2.2. Storage and solar multiple

The remainder of this section is based on the central receiver concept. Thermal energy storage permits a CSP plant to operate more flexibly at higher efficiency and a higher capacity factor. To do this, the solar field needs to be some multiple of that needed to get the turbine to its full rating on an ideal summer day. Even CSP plants with no thermal storage or auxiliary heating generally require an oversized solar field in order to allow the turbine to operate at its rated output for reasonable periods of time. The oversizing of the solar field is commonly referred to as the solar multiple (IEA, 2010; Trieb et al., 2009). The ability to size and optimize

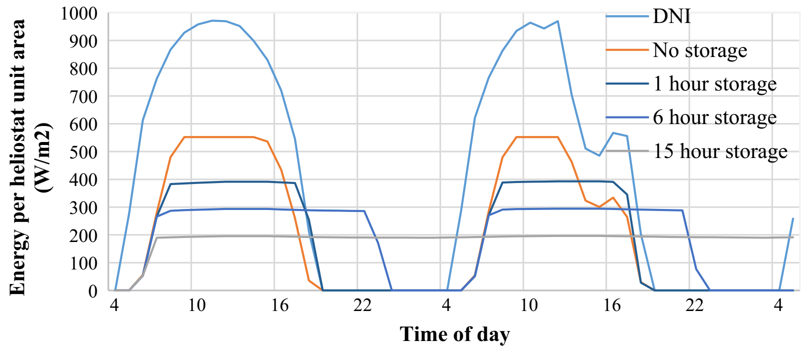


Fig. 13. Illustrative effect of solar multiple and storage in central receiver CSP plant.

the solar multiple is considered an additional advantage in an electricity system (IEA, 2010).

Sizing of components in a CSP plant for optimal design is a complicated process requiring many variables to be considered that are not included in this section. Fig. 13 illustrates a number of basic concepts for variations of the central receiver technology. Three primary variables impact the utilization of the cycle.

1. Collector size and rating: This is the optical component in the described cycle and refers to the effective aperture area of the reflector system and the associated rating of the receiver, which, if not sized appropriately, can limit full use of the reflector system.
2. Thermal storage rating: This is the thermal storage component, which is usually specified in multiples of full load turbine hours utilizable.
3. Turbine rating: This is the power component, the gross (or net) size of turbine power.

Hourly aggregated DNI is indicated relative to the collected thermal energy per unit area of a heliostat field for cases ranging from no storage to 15 storage hours over a two day period. In a system with no storage, energy needs to be used directly by the turbine. A solar multiple of unity means that the turbine can use all of the collected energy but will only do so under ideal conditions. This means that in reality it will always underperform, thereby underutilizing the capital investment of the turbine. Any solar multiple greater than unity will cause curtailment of the optical system, thus capping the energy potential as shown by the orange* line in Fig. 13 for the "no storage" case. All energy above this line will be unutilized. An increasing solar multiple will result, therefore, in a transfer of underutilization from the turbine to the optical (or collector) system. For efficient and practical operation, CSP plants without storage usually have solar multiples ranging from 1.1 to 1.5.

In a system with storage that never restricts the optical or power components, utilized energy is still capped, but all additional energy is stored for use when the need exceeds the collection. A short-duration example can be seen in Fig. 13 where performance on day two continues when solar irradiation dips for the case of a 1 h storage plant. The 15 h storage case shows continuous performance and would have a solar multiple of about 3–4. In a hypothetical case in which the energy storage has no constraints, all other capital is fully utilized.

In reality, energy storage cannot be unbounded due to the diurnal cycle whereby residual energy storage carried over to the next day results in another capital utilization constraint in conventional CSP. In the event that the marginal cost of energy storage is lower per kW h of delivered energy relative to the cost of the turbine, initially an increase in energy storage in exchange for turbine size will result in a lower cost of electricity. The rate of cost reduction will reduce at the point when residual storage starts to lead to curtailment of the collector system. From this point, marginal cost derivative will be positive, and the cost of energy will grow beyond the optimal storage size. These tradeoffs have been well studied at an individual plant level (Denholm et al., 2012; Jorgenson et al., 2013).

2.2.3. Electricity generation principles

CSP plant integration principles and primary performance indicators of CSP in a system are discussed using a simplified annual yield example. This example is simplified for the sake of bounding the capabilities of the technology and is a step towards the value of CSP.

A basic first order assessment can be performed to determine the capacity factor, efficiency, output and space needed of a CSP plant that utilizes its collector system at all times due to the inclusion of sufficient thermal energy storage:

$$C_f = \frac{E_{plant(y)}}{P_{net} \times 8760} \tag{12}$$

where C_f is the capacity factor of the plant defined by the actual annual electricity produced (E_{plant} as defined by Eq. (13)) from solar energy divided by the amount of power the plant is capable of delivering if it ran at net output (P_{net}) all year (8760 h). Subscript y denotes year.

$$E_{plant(y)} = I_{b(y)} A_{ref} \eta_{plant(y)} \tag{13}$$

where I_b is the long term average annual DNI, A_{ref} is the concentrator aperture area of the plant and η_{plant} is the total annual plant efficiency.

$$\eta_{plant(y)} = \eta_{optical(y)} \eta_{receiver(y)} \eta_{power(y)} \tag{14}$$

where $\eta_{optical}$, $\eta_{receiver}$, and η_{power} are the respective process efficiencies for collecting and concentrating sunlight, its conversion to thermal energy and its net conversion of power production, which incorporates the efficiency of thermal energy storage. In general, power conversion efficiency is related to the quality of energy, and thus temperature, of the thermal energy supply. Power conversion efficiency is limited theoretically by the Carnot efficiency and represented reasonably well in adapted form, referred to as the Novikov cycle (Curzon and Ahlborn, 1975; Novikov, 1958) shown in Fig. 14:

$$\eta_{power} \approx \eta_N = 1 - \sqrt{\frac{T_L}{T_H}} \tag{15}$$

* For interpretation of color in Fig. 13, the reader is referred to the web version of this article.

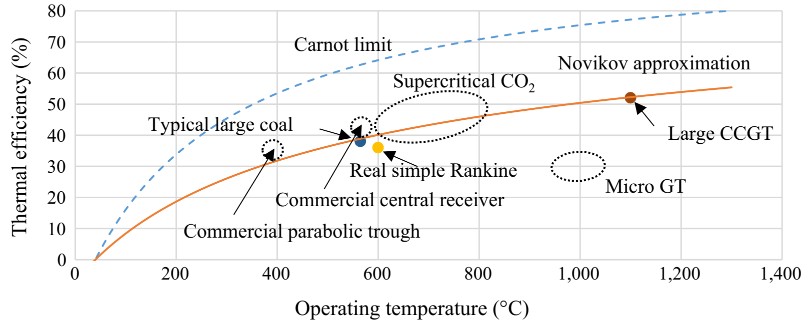


Fig. 14. Heat engine Carnot theoretical limit and Novikov practical approximation efficiencies with examples of actual power plants (dots) and CSP types. For CSP, the power plant efficiency without collector and conversion efficiencies is illustrated.

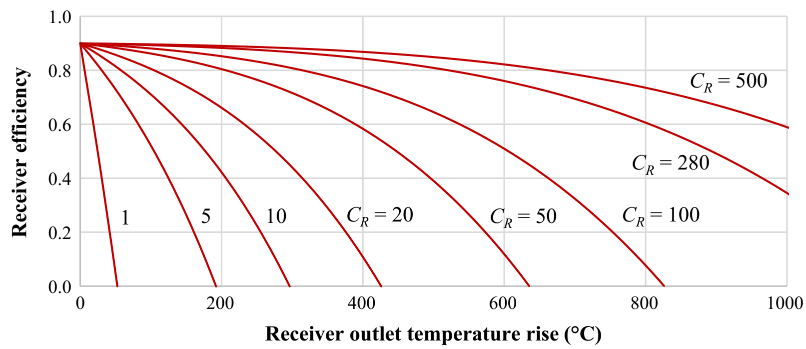


Fig. 15. Thermal receiver efficiency for various concentration ratios based on one illustrative reference condition where temperature is above ambient.

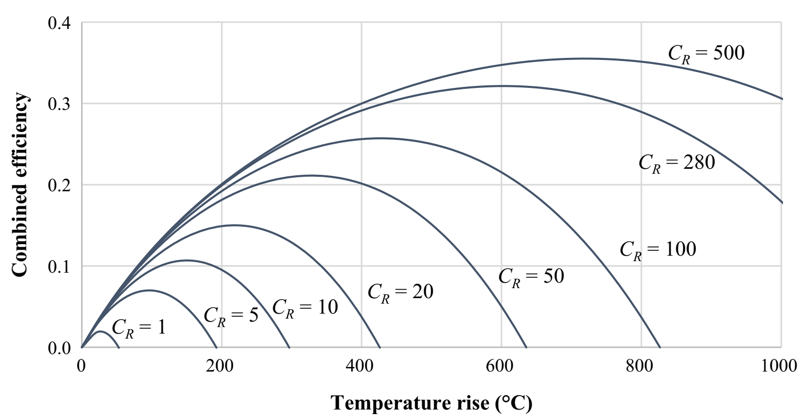


Fig. 16. Basic combined receiver and heat engine efficiency.

where T_L is the ambient temperature and T_H is the operating temperature entering the turbine.

The Novikov simplification isn't completely straightforward for CSP use and care is required in the accounting of efficiency when comparing conventional thermal plants to CSP. As can be seen in Fig. 14 actual CSP power plant efficiency is higher when removing the collector components which typically are accounted separately. Once the efficiency accounting is correctly approximated, the Novikov simplification allows for parametric analysis within CSP and between all thermal plants. As an example, a thermal power plant that operates at a working fluid temperature peak of 600 °C can operate at about 40% efficiency. Given that the Novikov approximation fairly represents thermal power plants based only on their operating temperatures, the simple and predictable correlation permits a high degree of flexibility in energy systems analysis. In this way, if a CSP roadmap predicts a rise in temperature over time, this can be linearly accommodated. This simplification is only relevant however for large efficient power plants, and part of the thermo-economic challenge in CSP is illustrated by adding micro-gas turbines, which despite recuperation, only slightly exceed 30% efficiency in ideal circumstances. The relevance of smaller-scale heat engines will discussed later.

Conversion of sunlight to high quality thermal energy requires suitably efficient solar thermal collectors. Solar thermal collectors are always exposed to the environment and will incur energy losses super-linearly to the increase in collector temperature output, all other things equal. Losses occur due to reflection, glazing absorption, convective heat transfer and thermal radiation – the latter terms being somewhat or significantly non-linear to the collected temperature. The use of insulating techniques such as selective absorption coatings, glazing and evacuation can help to a point.

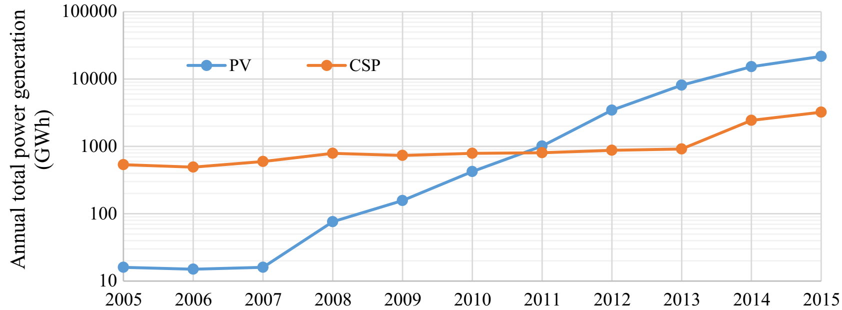


Fig. 17. Solar power generation at U.S. utility-scale facilities from 2005 to 2015.. *Source:* U.S. EIA

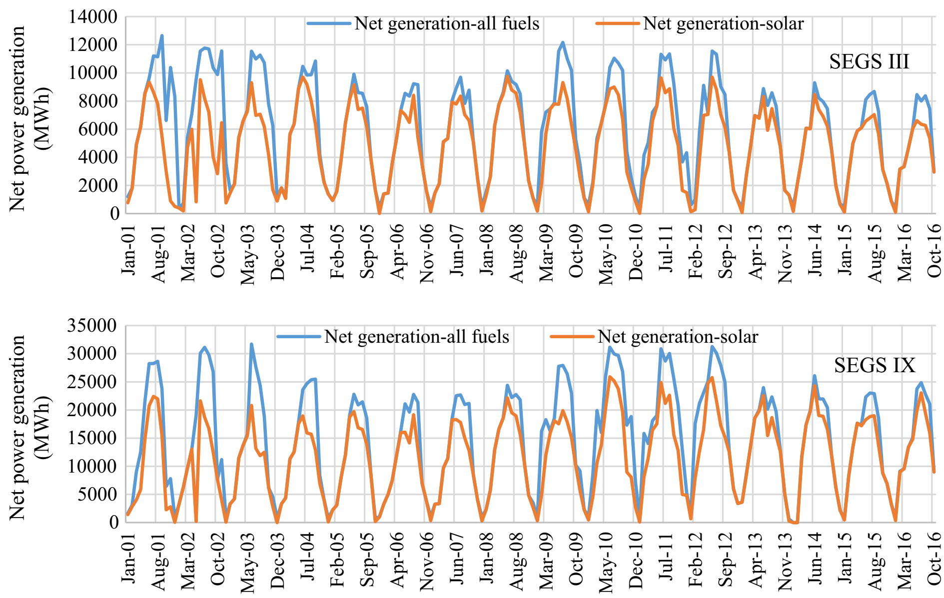


Fig. 18. Monthly net power production for SEGS III (top) and SEGS IX (bottom) from January 2001 to October 2016.. *Source:* U.S. Energy Information Administration

Table 2
Key plant features of two of the SEGS plants.

Plant	Technology	Net (and gross) turbine rating (MW)	Solar field output temperature (°C)	Start year
SEGS III	Parabolic trough	30 (33)	349	1985
SEGS IX	Parabolic trough	80 (89)	390	1990

The single most effective method in getting to very high temperatures is to substantially reduce the exposed receiving area of the collector (receiver). This is achieved by concentrating sunlight from a large primary aperture (usually a collection of reflector surfaces) to the receiver. Using the same example, a receiver delivering 600 °C to the heat engine needs to have a concentration ratio (C_R) of almost 500 in order to achieve an efficiency of 80%. Receiver efficiency can also be represented by temperature as shown in Fig. 15, analogous to the heat engine efficiency shown in Fig. 14.

The optical efficiency is a function of design, location and time as described earlier. For purposes of the example, an average annual optical efficiency of 60% will be assumed.

Fig. 16 plots the combined receiver and heat engine efficiency for this case. The first observation is that the two efficiencies trade-off against each other leading to optimal operating temperatures, all other things equal. The second important observation is that concentration ratio always increases plant efficiency, all other things equal.

Following the example, the optimal concentration ratio for a 600 °C receiver is about 280, resulting in a combined efficiency, $\eta_{plant} = 0.193$.

$$\eta_{plant} = 0.6 \times 0.76 \times 0.422 = 0.193 \tag{16}$$

For a CSP plant containing 1,000,000 m^2 of reflector surface in a location with a long term average annual DNI of 2800 kW h per m^2 per year, the annual solar-only power generation is

$$E = 2800 \times 1,000,000 \times 0.193 = 539,975,335 \text{ kW h} \tag{17}$$

If this CSP plant has a 100 MW output rating and produced this amount of power, the plant would have a capacity factor of

$$C_f = \frac{539,975,335}{100,000 \times 8760} = 61.6\% \tag{18}$$

A capacity factor of 61.6% represents a CSP plant with a significant amount of storage; this is typical of a small number of CRS plants representing the state of the art. If such a plant were also

Table 3
Key plant features of central receivers in the inertial category. *Source:* NREL SolarPACES database.

Plant	Country (and technology supplier)	Technology	Net (gross) turbine rating (MW)	Receiver temperature	Start year
PS10	Spain (Abengoa)	Direct saturated steam cavity receiver	11	250–300 °C	2007
PS20	Spain (Abengoa)	Direct saturated steam cavity receiver	20	250–300 °C	2009
Ivanpah	U.S. (BrightSource)	3 direct steam external receiver tower units	377 (392)	565 °C	2013
Khi Solar One	South Africa (Abengoa)	Direct steam – 3 cavity receivers, 2 h saturated steam storage	50	Unknown (superheated)	2016

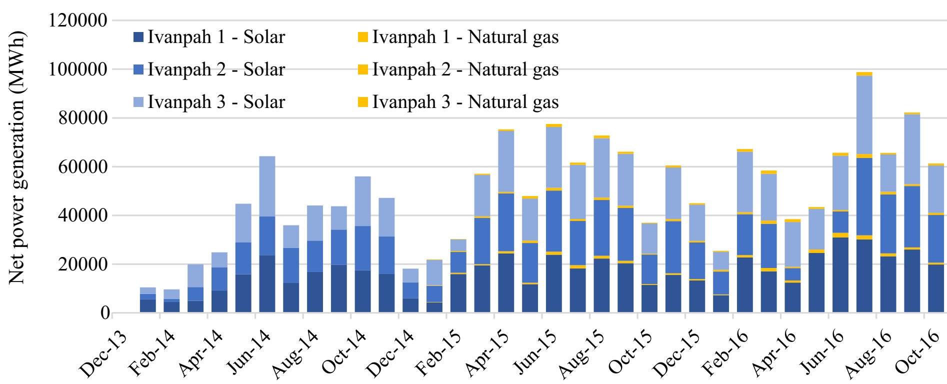


Fig. 19. Monthly cumulative net power production of the 3 Ivanpah units. *Source:* U.S. Energy Information Administration.

hybridized, it would represent a firm baseload power plant for a utility company. Such a plant would occupy about 5 km^2 of land, assuming typical current land usage for CRS plants (NREL, 2013; Ong et al., 2012). In a hypothetical scenario where such a plant is replicated in a distributed power network and is able to supply 81.4 TW h of electricity per year (20% of annual South African demand in 2030 per one scenario (WWF-SA, 2014)) at that capacity factor, 151 plants would be required, occupying 754 km^2 of land. This would represent 0.062% of South Africa's land surface.

2.3. CSP applications and configurations

With the high level principles of CSP described, but before reviewing the status and system value of CSP, a historic and contemporary review of the roles is given here. These CSP configurations are value or usage driven, and while examples of the technology configurations are provided, this section does not specifically distinguish CSP technology types.

2.3.1. Inertial CSP

Most of the early operating pilots and commercial plants lacked any significant thermal storage, typically relying on steam or oil accumulators for providing thermal inertia. The majority of these early plants were commissioned in the US, and most are still operating today. At the time, PV was not competitive at utility scale, and CSP with inertia demonstrated utility power capabilities. Fig. 17 is a plot of utility-scale solar power generated annually for PV and CSP between 2005 and 2015. Significant capacity growth in PV only started in 2007, and 2011 was the first year that PV produced more power than CSP (U.S. Energy Information Administration, 2016a).

Without storage, larger CSP units offer some relief to intermittence (such as cloud cover) due to thermal inertia. With some form of accumulation, either steam or oil, this inertia can keep the turbine running at reduced output between 30 min to a few hours. Examples are the original Solar Energy Generating Systems (SEGS) commissioned between 1985 and 1989 (Lotker, 1991). Besides lacking real competition at the time, the generation profile of inertial CSP has been valued in the south-western states where the electricity generation profile is significantly impacted by cooling demand. Baharoon et al. (2015) provide a thorough review of the history and performance of the SEGS plants. The monthly performance of two of these plants (somewhat randomly selected), namely SEGS III and SEGS IX, is shown in Fig. 18 from 2001 to October 2016, the most recent month recorded by the U.S. Energy Information Administration (2016b, 2016c). Table 2 provides a summary of the key features of these plants.

Both plants (as with the other seven) have proved the lifetime capabilities of inertial CSP. Luz, the developer, made incremental technology improvements over the span of the projects, and since then the plants have undergone operating and other changes to improve efficiency. Besides the daily generation profile, Fig. 18 also shows the seasonal characteristic of a parabolic trough plant located at around 35° latitude. In most years, the SEGS plants tend to drop output to zero for about 1 month in mid-winter, presumably coinciding with scheduled maintenance.

The first operating central receiver plants also generally fall in the category of inertial CSP. Table 3 lists four central receiver plants that all operate using direct steam receivers. While these plants do

Table 4
CSP configurations adapted from IEA (2010).

CSP configuration	Description
Intermediate load	With a small storage, the energy that would have been curtailed due to the slight oversizing of the collector system is instead captured for use during peak loads typically encountered in the evening. With a larger storage system, energy can be collected during the day and later serve electricity needs. The latter is referred to as delayed intermediate load
Baseload	With a large storage and a small turbine, this type offers the ability to produce power 24 h a day for continuous periods of time
Peak load	With both a large storage and turbine, this type is intended to serve peaking needs only

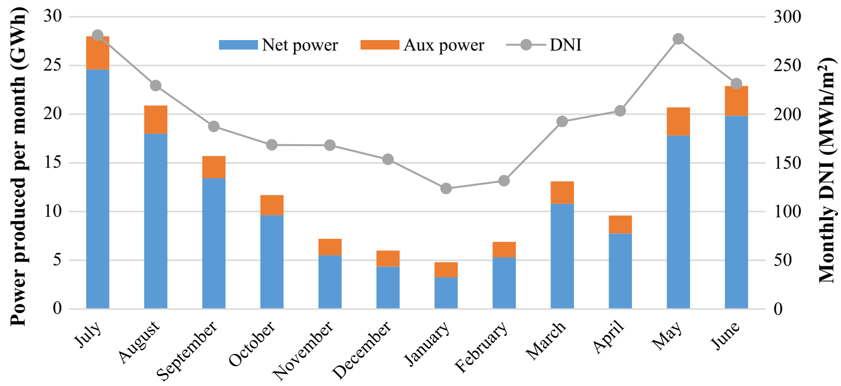


Fig. 20. Andasol 3 performance from 2013 to 2014 (reproduced from Dinter and Moller (2016)).

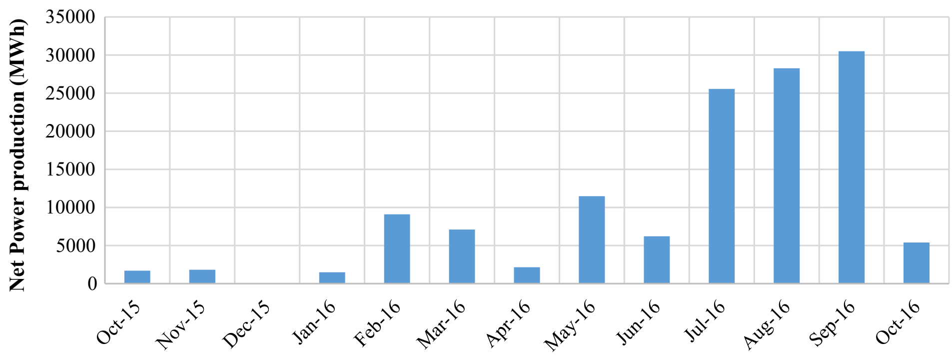


Fig. 21. Crescent Dunes 110 MW central receiver monthly cumulative power production. *Source:* U.S. Energy Information Administration.

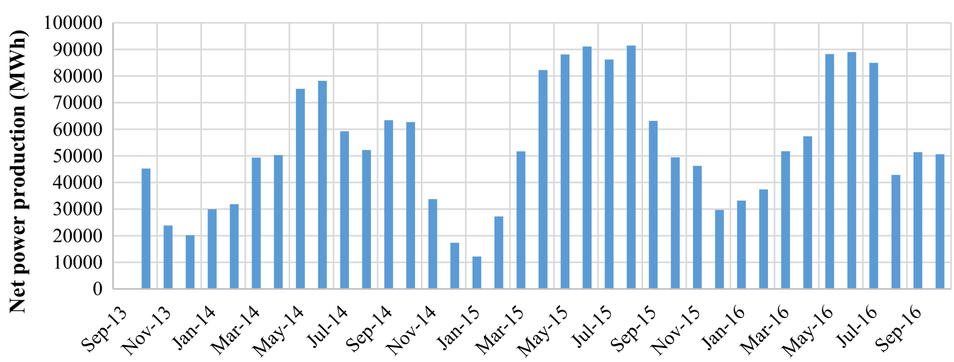


Fig. 22. Solana Generating Station (250 MW parabolic trough) monthly cumulative power production. *Source:* U.S. Energy Information Administration.

not have specific storage systems other than steam accumulators, to some extent they do demonstrate the value of higher winter output as shown over the first year of operation of the Ivanpah project (NREL, 2014) in Fig. 19 (U.S. Energy Information Administration, 2016d).

Ivanpah is completing 3 years of operation and has apparently achieved between 90% and 98% of modeled performance in the best months for each unit. BrightSource reportedly plan to be at full operation in 4 years (Smith, 2016). All 3 units experienced significant outages between May and August of 2016. Unit 2 had a main generator replacement, which resulted in no power production in May. During this time, the more popularly reported tower fire in unit 3 occurred, which reduced expected output during the month of May. In each case, the outages were limited time events and provide some evidence of the modular value of CSP where each unit works independently. Perhaps more interestingly is that the months of December 2015 and February 2016 show promise in the smaller performance drop that a surround heliostat field offers during winter compared with a parabolic trough.

2.3.2. CSP with storage

In this review, the use of the term CSP by default implies this category. CSP with storage is the evolution of the inertial value of CSP, recognizing the very high efficiency of thermal storage at large scale the associated cost benefit and the value of this storage to increasing penetrations of solar energy (Denholm et al., 2016). Thermal storage as an explicit and significant component of the plant changes the value of CSP significantly. The benefits of inertia are combined with the ability to drive the turbine almost continuously and to therefore begin to strive for a much higher degree of load following. All other aspects of inertial CSP are valid.

Within this configuration, several value based configurations have been proposed. Three of these adapted from the 2010 IEA CSP Roadmap (IEA, 2010) are listed in Table 4.

In all cases, supplying to these loads is not guaranteed cost-effectively, and if a plant requires a high degree of availability, it needs backup hybridization.

One of the earliest CSP plants in Spain that incorporated significant thermal storage is the Andasol 3 parabolic trough plant with a net output just below 50 MW and 7.5 h of full-load storage (Dinter and Gonzalez, 2013). Key performance characteristics of Andasol 3 reported over a 12 month period from 2013 to 2014 (Dinter and Moller, 2016) are shown in Fig. 20. While this parabolic trough performance dips in winter at a rate greater than the drop in monthly DNI, it does not drop as much as is shown in any of the SEGS plants. The use of three working fluids in a contemporary storage based parabolic trough plant is known to require higher auxiliary power for fluid pumping, an area of development and refinement within this CSP type.

Two more recent storage based CSP projects of interest are in the initial years of production as shown by monthly production figures in Fig. 21 (U.S. Energy Information Administration, 2016e) and Fig. 22 (U.S. Energy Information Administration, 2016f). Crescent Dunes is the single largest molten salt central receiver commissioned to date (NREL, 2015a). The monthly production figures of this plant show only progress towards full performance and little can be seen to reflect the seasonal behavior of the plant at this time. The Solana project is one of the biggest parabolic trough plants with storage and is demonstrating characteristics of the Andasol 3 plant in its ability to get through the winter period with reasonable performance.

2.3.3. Solar assisted power generation

CSP collectors can serve secondary roles in high availability thermal power plants. Various configurations have been proposed. Solar assisted power generation (SAPG) is also known as "solar boosting" or solar augmentation (Pierce et al., 2013). SAPG as a retrofit option to existing coal power plants or in new coal units is limited by several factors to augmenting in the region of 10–15% of coal use. The Kogan Creek solar booster in Australia was much anticipated but was apparently never completed. The addition of some solar heat to a more traditional power plant seems to have success, and the total capacity installed seems minor in comparison to the installed and operating capacity of regular CSP.

A notable difference perhaps is the Shams-1 project in the UAE. The Shams-1 parabolic trough plant is a fully hybrid plant that uses natural gas to boost the steam temperature to 540 °C during all operation. This hybridization offers the plant higher efficiency and reliability to the turbine. It is also a requirement that the plant offer guarantee capacity (IEA, 2014a). Shams-1 isn't necessarily a SAPG plant. Rather it is a full hybrid, but it is discussed here as the type of approach that might succeed in adoption where, as yet, solar boosting in the more traditional sense has not.

2.3.4. Hybridization, grid integration and scaling configurations

In CSP, hybridization usually implies that CSP components are the default power generation mode, distinct from SAPG. The most common form of hybridization present in many of the CSP plants already described is through the use of a backup combustion system intended to smooth out or extend the power production profile over a day. The amount of backup fuel is restricted based on the tariff structure of the project.

Hybridization with backup combustion can offer alternatives to purely renewable solutions by using biogas or by generation of fuels using solar heat. Hybridization with biogas offers a way to sparingly use biofuel resources while ongoing research investigates the production of hydrogen or syngas using concentrating solar collectors.

Fig. 23. GlassPoint PDO pilot. *Source:* GlassPoint website image used with permission.

Fig. 24. GlassPoint dust storm. *Source:* Glasspoint website image used with permission.

Hybridization with PV has also been proposed and is currently being implemented in various projects. Atacama-1 in Chile is a baseload solar power plant with PV and CSP. The CSP component is a 110 MW tower with 17.5 h of storage, making it one of the biggest CSP projects to date (NREL, 2016). The project includes a 100 MW PV plant, apparently based on the load profile required where the combined power at any time is the lowest cost. The co-location of such a hybrid setup is significantly influenced by the transmission limitations from the point of generation to the point of use, and it is argued that the connection and transmission costs can be shared when optimally operating such hybrids.

From a systems point of view, hybridization could be a matter of regional and grid-wide optimization where such co-location is not required. "Virtual hybridization" is the process of providing backup generation that is lowest cost for the system. For example, large open cycle gas turbine (OCGT) power plants that are relatively low cost to construct could be located near the source of backup fuel. This concept is explored in the following section.

Decentralization and being closer to the point of consumption has been another factor influencing CSP configurations, including Atacama-1. A very interesting development that demonstrates a number of values is the recently commissioned Sundrop farms CSP plant (NREL, 2016). This CSP plant uses a technology within a novel attempt at integrated resource agriculture. The 36 MWth system has a 1.5 MW_e steam turbine, heat from the plant can heat the greenhouses in winter and a desalination plant desalinates up to 250,000 m^3 of seawater per year. Aalborg CSP was the developer, and over 23,000 eSolar SCS5 modular heliostats provide over 51,000 m^2 of solar field aperture.

The ability to economically scale to smaller sizes is a clear advantage of PV, enabling economies of scale by selling into every possible market. No commercially sustainable alternatives have been demonstrated in CSP yet, arguably due to technology scaling limits but perhaps also because it has not yet demonstrated value in the market. In the range from 1 MW, all the way up towards 100 MW, steam turbine based CSP has not found lasting commercial traction. eSolar commenced with the SierraTowers as a commercial demonstrator (NREL, 2011b) and thereafter planned to scale up modularly using their small heliostat in an elegant modular system with molten salt storage and typically a 100 MW turbine (Tyner and Wasyluk, 2014). Several studies suggest that small heliostats offer greater potential, but the operation and maintenance of a system containing hundreds of thousands of heliostats is not proven. More recently, Vast Solar is in the commissioning phase of a 1.1 MW pilot also using small heliostats in modular tower configurations, but using more compact and efficient sodium receivers (NREL, 2016).

In the range of 100 kW–1 MW, the only immediately viable alternatives are air based micro gas turbines, typically in small central receiver plants and Stirling engines, which are typically in parabolic dish concentrators (known commonly as Stirling dishes). Whether due to efficiency, scaling or lack of storage options, these systems continue to elude commercial viability.

2.3.5. Indirect or non-electric CSP

A notable non-electric application of CST that is emerging is enhanced oil recovery (EOR), which typically makes use of steam to extract remaining oil in depleting oil wells. Such an example is the BrightSource Coalinga project (BrightSource, 2011), which was commissioned in 2011 and apparently operated for 3 years. In this case, it may have assisted BrightSource as a demonstration of its heliostat and receiver technology as a step towards the Ivanpah project.

GlassPoint has taken a different route by developing a solution specifically for such a process heat application and taking into account local conditions where EOR is applicable. Using almost standard commercially available greenhouses, GlassPoint has developed a parabolic trough technology that is more compact and lighter due to the removal of wind forces. The pressurized greenhouses nearly eliminate mirror soiling, and the height of the greenhouses allow for high performance even during severe dust storms (GlassPoint Solar, 2015). The GlassPoint 1 GW project under construction in Oman is one of the biggest CST projects ever built. If successful, this project and technology deserve to be noted for the level of disruption in the CSP environment (see Figs. 23 and 24).

Various other uses and combinations of CSP have been considered and researched; however outside of laboratory or pilot-scale projects, none have found any traction in the market or proven techno-economic feasibility. Other uses for CSP technology include high temperature process heat for metals, chemicals and production of fuel such as syngas and hydrogen.

2.4. Progress of technology maturity, operational performance and cost

A notable shortcoming of CSP is that it's slow and intermittent adoption, together with the evolution of multiple variants and re-integration more recently to include thermal storage in commercial plants, has resulted in relative little operational history and even less of this history in the public domain.

Feldman et al. (2016) explore the cost competitiveness between CSP and PV with batteries. In this study the actual learning rate of both technologies is investigated. The authors note that costs for CSP vary considerably based on configuration, location and other factors. Based only on parabolic trough plants installed in the U. S. and Spain, a learning rate of between 5% and 12% (with an average of 8.5%) is noted. This falls far short of the 40 year average learning rate for PV modules of 21%. The balance of system (BOS) for PV in the U.S. is in the region of 11%. The cost learning rate for batteries ranges considerably, depending on type and measure, but several recent studies suggest a rate in the region of 9% for Li-ion batteries. The outcome of the study is that in some categories, PV with batteries can compete with CSP. Estimates vary considerably, but it appears that PV with batteries will become competitive with CSP in 2030 for 3 h of storage. From 6 h of storage or more, CSP probabilistically remains the lowest cost solution.

Operation performance of parabolic trough plants without molten salt storage seems to be substantially proven based on the history of the SEGS plants. Baharoon et al. (2015) site various references that indicate ongoing refinements to these first commercially operated plants over many years. While a cost learning rate is reported for the SEGS plants, the first parabolic trough plants without storage in Spain do not seem to have directly benefited from the SEGS cost learnings (Feldman et al., 2016). Likely key factors for this lack of benefit are the combination of time lost with no new CSP capacity globally for 15 years and CSP being a new technology to Spain. Diekmann et al. (2016) provide a fairly updated analysis on the levelised cost of energy (LCOE) which correlates fairly closely for known tariffs for Noor II (parabolic trough) and Noor III (central receiver). LCOE values are expected to be in the range of US$ 0.12/kW h to US$ 0.15/kW h for good DNI areas in 2015, with central receivers being very slightly lower. The model forecasts that LCOE should drop to as low as US$ 0.07/kW h for central receivers and US$ 0.08/kW h for parabolic trough plants in favorable conditions and financing environments, noting that the cost of finance is a significant component of LCOE for CSP.

The operational performance of commercial CSP plants is particularly scarce with very little information pertaining to faults or failures reported in the public domain. The U.S. Energy Information Administration (EIA) is a valuable resource for disclosure of actual net power delivered to the grid for monthly, quarterly or annual aggregated values. The very large recent projects in the U.S. have begun to show operational experience as shown earlier, as have the first projects in South Africa. But the cumulative experience with high storage rated plants and the very limited cumulative experience of large central receivers are the precise experience indicators that talk to the contemporary value proposition of CSP, namely large, cost-effective, baseload-capable CSP.

Recently commissioned CSP plants have tended to struggle to reach full and reliable performance as illustrated by some examples in Section 2.3. Information access and knowledge transfer is very limited in the CSP industry and is perhaps a primary reason for stunted learning rates. Lack of knowledge transfer between developers, technology suppliers and for new countries seem to be key inhibitors.

2.5. Global status of CSP

The current decade (2010–2020) was anticipated to be a strong growth period for CSP in terms of capacity and cost roadmaps (IEA, 2010; Kolb et al., 2011). The reality is that by 2014, the growth rate declined significantly for a number of reasons. The relative over-supply of oil and gas (and most commodities) coupled with a continued growth in the adoption of PV at costs competitive enough to

Table 5
Central receiver projects. *Source:* Wang (2016).

No.	Investor	MW	HTF and storage hours
1	Qinghai Supcon Solar Technology	50	Molten salt, 6 h
2	Beijing Shouhang IHW Resources Saving Technology	100	Molten salt, 11 h
3	Northwest Engineering Corporation Limited of Power China	50	Molten salt, 6 h
4	Northwest Electric Power Design Institute of China Power Engineering Consulting Group	50	Molten salt, 8 h
5	Huanghe Hydropower Development Corporation	135	Water/steam, 3.7 h
6	China Three Gorges New Energy	100	Molten salt, 8 h
7	Dahua Engineering Management Company	50	Water/steam, 4 h
8	Yunmen Xinneng Solar Thermal Power Company	50	Molten salt, beam down, 6 h
9	Beijing Guohua Electric Power Co. Ltd.	100	Molten salt, 10 h

Table 6
Parabolic trough projects. *Source:* Wang (2016).

No.	Investor	MW	HTF and storage hours
1	Royal Tech CSP Limited	50	Thermal oil, 7 h
2	Shenzhen Gold Vanadium Energy Technology Co., Ltd	50	Molten salt, 15 h
3	Rayspower Energy Group Co., Ltd	50	Thermal oil, 7 h
4	Inner Mongolia Royal Tech New Energy	100	Thermal oil, 4 h
5	CGN Delingha Solar Energy Development	50	Thermal oil, 9 h
6	CECEP Gansu Wuwei Solar Energy Co., Ltd	100	Thermal oil, 7 h
7	Zhongyang Zhangjiakou Chabei Energy	64	Molten salt, 16 h

Table 7
Linear Fresnel projects. *Source:* Wang (2016).

No.	Investor	MW	HTF and storage hours
1	Lanzhou Dacheng Technology Co., Ltd	50	Molten salt, 13 h
2	Huaneng North United Power Co., Ltd	50	Thermal oil, 6 h
3	CITIC Zhangbei New Energy Development Co., Ltd	50	Water/steam, 14 h by concrete
4	Zhangbei Huaqiang TeraSolar Energy Company	50	Water/steam, 14 h by concrete

justify the technology as a fuel cost saver are arguably the foundation for CSP growth stalling. At around this time, emerging economies were anticipated to offer the next growth opportunity for CSP based on projects and plans already underway (IEA, 2014a). CSP has actually started to make a mark in emerging economies with at least strong starts in for example, South Africa, Morocco, India, Chile and China. In addition to the announced scale and number of commercial demonstration projects, the finalization of the next five year plan of China may be a quantum step for CSP (CSPPLAZA, 2016). The global status of CSP is summarized by considering only a few key countries and plans in order to offer context to the next section, which covers the system value of CSP.

2.5.1. United States and Spain

The status and history of CSP in the U.S and the rapid adoption and equally rapid halt in Spain are well documented (IEA, 2014a). They are distinctly different markets, with the U.S. being more likely to grow CSP capacity in the near future. The combination of market, home grown R&D and collaboration with other countries has led to the establishment of various technology and project development companies. A significant majority of CSP capacity installed globally can somehow be related to a small number of CSP oriented companies from the U.S. or Spain (NREL, 2016). The sustainability of all these companies has been questioned in recent years due to project cancellation or other financially related issues; the most prominent over the last year has been the near bankruptcy of Abengoa (Abengoa, 2016).

2.5.2. China

The recently announced plans in China deserve first mention amongst the next followers. At the time of writing, about 1.35 GW of demonstration have been approved with tariffs of RMB 1.15 yaun/kW h (about US$ 172/MW h), and the overall plan is to complete 5 GW of capacity and achieve costs under RMB 0.8/kW h by the end of 2020. While impressive, this capacity should be placed in the context of being part of a project totaling 110 GW of solar power generation for the timeframe. Another major factor is that the typical DNI in the regions identified rarely reach 2000 kW h/m^2 per year, perhaps explaining the LCOE goals that are already apparently being achieved elsewhere. The first projects have been announced and include a variety of CSP types and configurations, some of which have not been attempted in commercial demonstration plants elsewhere.

By capacity, central receivers marginally exceed 50% with troughs at 34.4% and linear Fresnel just under 15%. The announced projects are listed in Tables 4–6. The notable technology departures from the state of the art include:

- A 50 MW beam down tower project with 6 h of molten salt storage.
- A prevalence of thermal oil as storage in parabolic trough plants.
- Four LFR projects of which two include concrete storage.

The degree of innovation in the announced projects perhaps makes sense in context of the local content plans. Chinese state-owned and private enterprises represent about 32% and 63% respectively with only around 5% from foreign enterprise. Ambitiously, all of these projects should in principle be put in operation before the end of 2018. If this occurs, the growth rate of CSP will be significant at least for a few years (see Table 7).

CSP is not new in China. Small-scale research and piloting has been ongoing since the 1980s with a 70 kW micro gas turbine based central receiver commissioned and tested with some success in 1995 through collaboration between Hohai University, the Weizmann Institute and related industrial participants (Jun et al., 2009). Chinese research and development in CSP is highly coordinated through the China National Solar Thermal Energy Alliance established in 2009 (Wang, 2016).

2.5.3. South Africa

The case for South Africa is perhaps a good example of the “canary in the coalmine” for CSP, particularly in recognizing the value of CSP. In a relatively short span of time (since 2011), this value was formally recognized in binding national plans during a phase of national capacity shortage to the present time where the national utility company claims to have significant excess electricity and all future CSP capacity (to 2050) is under threat. The South African electricity system has in recent times been referred to as a “canary in the coalmine” for being at the center of a polycrisis, where limited resources in all spheres of the economy threatened economic development without sufficient electricity capacity (Heun et al., 2010). Why this case is interesting will be explored in the next section covering the systems value of CSP. The status of CSP is summarized here.

After a few false starts to introduce Independent Power Producers (IPPs) in the previous decade, lessons learned were incorporated into the first Integrated Resource Plan (IRP) of 2010 (Department of Energy, 2011). The IRP is legislated to offer a man-

Table 8
Planned or allocated capacities in South Africa up to 2030. IRP 2010 is mandated (second column). IRP 2013 Update Base-case (third column) was not legislated and does not subtract capacities added in the interim. The allocated capacities of the REIPPP program to the end of 2016 are not relevant for non-renewables (fourth column). The IRP 2016 Update Base-case draft lists incremental capacities above what has been committed (fifth column).

Technology	IRP 2010 (MW)	IRP 2013 Update Base-case (draft) (MW)	Total allocated in REIPPPP (MW)	IRP 2016 Update Base-case to 2030 (draft) (MW)
Existing Coal	34,746	36,230	–	–
New Coal	6250	2450	–	5250
Combined cycle gas turbines	2370	3550	–	7320
Open cycle gas turbines	7330	7680	–	4512
Hydro Imports	4109	3000	–	1000
Hydro Domestic	700	690	–	Not specified
Pumped storage	2912	2900	–	Not specified
Nuclear	11,400	6660	–	0
Wind	9200	4360	2660	7000
PV	8400	9770	1899	4680
CSP	**1200**	**3300**	**600 + 450**	**0**
Small Hydro	Not specified	Not specified	19	Not specified
Biomass	Not specified	Not specified	16	Not specified
Biogas	Not specified	Not specified	0	Not specified
Landfill	Not specified	Not specified	18	250

Table 9
Implementation of CSP in South Africa through the REIPPP program based on best known information.

REIPPP round (Bid Window)	Project name and developer/ significant EPC or technology supplier	Capacity (Net) and storage hours	Technology	Tariff structure	Status and start year
1	KaXu Solar One, Abengoa & IDC	100 MW, 2.5 h	Parabolic trough with two-tank molten salt storage	Single tariff	Operational, 2015
1	Khi Solar One, Abengoa Solar & IDC	50 MW, 2 h	Direct steam central receiver with saturated steam storage	Single tariff	Operational, 2016
2	Bokpoort, ACWA Power/Sener,	50 MW, 9.3 h	Parabolic trough with two-tank molten salt storage	Single tariff	Operational, 2016
3	Xina Solar One, Abengoa Solar	100 MW, 5 h	Parabolic trough with two-tank molten salt storage	Two-tier tariff (2.7 × during evening peak)	2017 expected
3	Ilanga I, Emvelo & Cobra	100 MW, 4.5 h	Parabolic trough with two-tank molten salt storage	Two-tier tariff (2.7 × during evening peak)	Under construction, 2017 expected
3.5	Kathu Solar Park, Engie & Sener	100 MW, 4.5 h	Parabolic trough with two-tank molten salt storage	Two-tier tariff (2.7 × during evening peak)	Under construction, 2018 expected
3.5	Redstone Solar Thermal Power Plant, ACWA & SolarReserve	100 MW, 12 h	Central receiver with two-tank molten salt storage	Two-tier tariff (2.7 × during evening peak)	Under development, no PPA
5	Various preferred bidders	3 × 150 MW	Various	Unknown (two-tier tariff likely)	Unknown

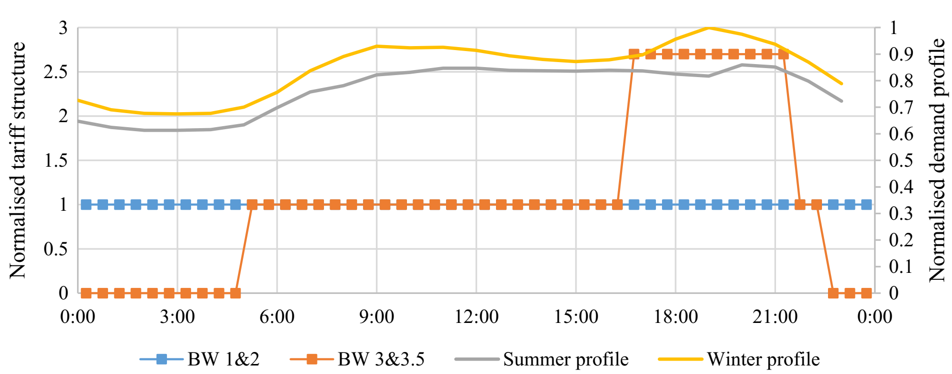


Fig. 25. PPA tariff structure evolution in the South African REIPPP. BW = Bid Window (left axis) and actual demand profiles for typical summer and winter day in 2010 normalized to the peak of the winter day (tight axis).

date whereby all parties are obliged to participate, and the IRP is implemented for utility renewables through the Renewable Energy Independent Power Producers Procurement (REIPPP) program (South African DoE, 2012). The IRP was updated as a draft in 2013 but never legislated (South African DoE, 2013b). A new update was released for public comment in December 2016 and is expected to be legislated in early 2017 (South African DoE, 2016). A summary of the South African plans is given in Table 8. An initial allocation of 1200 MW over 20 years was followed by an implementation program that increasingly recognized the value of CSP, getting to 600 MW allocated and an additional 450 MW approved well ahead of the 2030 deadline. The 2013 IRP draft

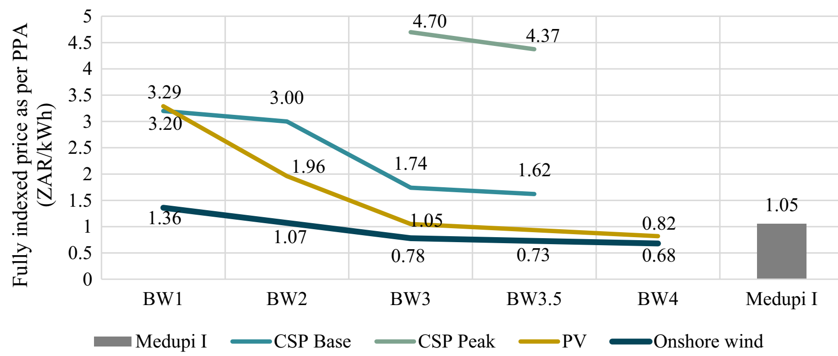


Fig. 26. PPA price evolution in the South African REIPPP program indexed to April 2014. Medupi I is a new 800 MW unit of a 4800 MW coal plant with industry estimated cost. BW = Bid Window.

Table 10
List of key items contributing to the value proposition of CSP.

Value proposition item	Description
Renewable and sustainable	• Low carbon footprint over lifecycle of the technology including low to zero carbon emissions during operation • Offers system resilience to fuel price fluctuations
Thermal energy storage	• Highest efficiency, large scale storage availability enables high capacity factor and/or capacity credit
Ramp rate, turndown limits and dispatchability	• In combination with storage, fast ramping enables good grid operator control and the ability to serve electricity in peak times, particularly the evening peak • Heat transfer by HTF or storage medium permits the faster ramp rate and turndown limit, usually constrained by combustion process
Inertial electricity	• The use of fairly traditional rotating heat engines offers voltage stability.
Hybrid and multi-use options	• The conversion from sunlight to centralized thermal energy allows for various combinations of energy inputs and/or energy uses to suit specific needs

update recognized the value of CSP even more, recommending 3300 MW in light of various factors including the uncertainty regarding the costs of nuclear power and the urgency at the time relating to the lack of capacity. The proposed 2016 Base-case update of the IRP has no CSP allocation beyond already approved allocations all the way to 2050.

The key factors relating to the apparent abandonment of CSP mostly relate to updated assumptions of renewable technology learning rates and a key assumption regarding the availability and cost of gas, noting that gas turbine capacity has vastly increased. To put this in context, most of South Africa's current peaking gas-turbine capacity plants use diesel, resulting in costs that are well above average CSP tariffs. Significantly reduced demand growth rate assumptions, the improved maintenance of existing coal power plants and the completion of two large coal plants, which will add 9600 MW, are also cited as factors that coincidentally also delay the addition of new nuclear capacity beyond the 2030 horizon.

Table 9 lists the CSP project rounds in South Africa. While legally mandated, the additional 550 MW of CSP yet to reach PPA status is all at risk, including the approved 100 MW Redstone project.

The introduction of the two-tier tariff structure more recently in the procurement program recognizes the avoided cost of electricity value in CSP. Fig. 25 illustrates this reward where a multiplier of 2.7 is given above the base tariff, noting also that the low demand period overnight gets no tariff.

Fig. 26 shows the evolution of actual average tariffs in the REIPPP program. When separating out the base and peak tariffs, CSP does demonstrate a priced-based learning evolution. PV and Wind exhibit significantly better learning rates, but a likely primary reason for this is the much higher capacity allocation with

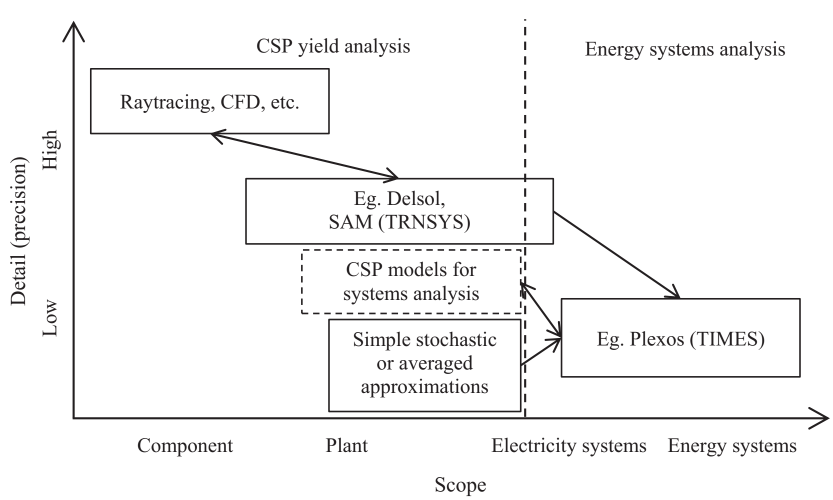


Fig. 27. Schematic representation of CSP yield analysis and an energy systems analysis in terms of precision and scope.

Table 11
List of 22 free (including free academic license) energy systems analysis tools indicating use, time resolution and sectors.

Tool	Organization	Open	Project Scale	Simulation/Opt.	Time res.	Sectors
BALMOREL	Collaborating Institutions	X	International	S, O	H	EG, ES, CHP
BCHP Screening Tool	Oak Ridge National Laboratory		Local community/single project	S, O	H	CHP
Calliope	ETH Zürich	X	Multi-scale	O	H, M	E
COMPOSE	Aalborg University		Local community/single project	O	H	EG, ES, CHP, T, Co
CP3T	Synapse Energy Economics, Inc	X	Multi-scale	Sc		EG
EnergyPLAN	Aalborg University		National/state/regional	S, O	H	EG, CHP, T, E
ENPEP-BALANCE	Argonne National Laboratory		National/state/regional	S, Sc	Y	EG, ES, CHP, T
ETEM	ORDECSYS	X	Local community/single project	S, O		EG, H
FreeGreenius	DLR		User dependent	S, O	H	EG, CHP
GCAM (previously MiniCAM)	Pacific Northwest National Laboratory		Global/international	S, O	Y*	EM, EG,
Invert	Vienna University of Technology/EEG		National/state/regional	S, Sc	Y	EG, H, T
LEAP	Stockholm Environment Institute		National/state/regional	S, Sc	Y	E
ORCED	Oak Ridge National Laboratory		National/state/regional	S, Sc, O	H	EG, H, T, ES
Osemosys	Collaborating Institutions	X	National/state/regional	S, O	D	E
PLEXOS	Energy Exemplar		National/state/regional	S, O	H,M	EG, ES
ReEDS	NREL		National/state/regional	S, O	Y**	E, ES
RETScreen	Natural Resources Canada		Multi-scale	S, IO	M	EG, H
SAM	NREL		User dependent	S, O	H	RE
SIVAEL	Danish TSO Energinet.dk		National/state/regional		H	EG, CHP
STREAM	Energy Analyses (Ea)		National/state/regional	S	H	
SWITCH	UC Berkeley	X	National/state/regional	S, O	H	EG, ES
Temoa	North Carolina State University	X	Single Region	O	Y***	E

S (simulation), Sc (scenario), O (optimization) *15 years, **17 annual time slices, ***multi-year, H (hour), D (day), M (month).
Sectors: EG (electricity generation), ES (electricity storage), CHP (cooling and heating power systems), H (heating), E (all energy sectors), T (transport), Co (cogeneration), EM (energy markets), RE (renewable energy sectors).

oversubscription in bidding, which has offered a very competitive environment for those technologies.

3. System value of CSP

The two-tier tariff structure in South Africa has been cited as evidence that the value proposition of CSP is indeed recognized in an electricity system (IEA, 2014a). In short, CSP claims to offer dispatchable electricity using renewable resources. The key elements of this value proposition are listed in Table 10.

These elements of the value proposition have been demonstrated to some degree in research and in commercially operating plants, but they do not themselves justify the selection of CSP capacity over any other alternatives. The ability to offer electricity at competitive prices based on time-of-day valuing ultimately needs to be demonstrated for any project or system plans.

- At a project level, CSP must be able to operate profitably within a tariff structure. In a simple structure, this implies LCOE must be lower than the tariff.
- To increase penetration in national or regional plans, CSP capacity needs to reduce the average system cost, and this implies continued demonstration of the learning rate of the technology and configuration optimization to maximize its use in the system.
- At a macroeconomic level, industrial participation, economic impact to grid and demand resilience, export of technology and electricity all need to be factored in.

3.1. CSP and systems analysis

Determining the value of CSP at any level requires analysis and simulation. There are two broad categories of analysis involving CSP that will be covered in this section:

1. Energy systems analysis: considers all generation in a grid connected system which typically needs to be optimized for capacity additions over many years into the future.
2. CSP yield analysis: considers the performance and yield from a CSP project.

Both of these categories have been evolving rapidly in recent years with only limited attention to ensuring suitable treatment either for CSP in the system or for system impacts on a CSP plant. Notably, energy systems analysis for multi-year planning has only very recently been taken seriously in reaction to the fast transition occurring with the adoption of significant fractions of intermittent renewables as well as recognition of other increasingly dynamic factors such as resource constraints and externality costs (Pfenninger et al., 2014b). Fig. 27 illustrates the basic contemporary relationships between various stages of simulation (see Table 11).

While somewhat generalized, the various analysis methods and studies, some of which will be covered in the next sub-section, exhibit the following characteristics as depicted in Fig. 27.

- Within a CSP yield analysis there has traditionally been relatively good feedback between a more detailed component analysis and a plant yield analysis, either directly linked within some form of multi-physics methods or by manual iteration.
- There seems to be a fairly clear mutually exclusive divide in expertise between a CSP yield analysis and an energy systems analysis with only a small number of experts or agencies that have expertise in both.
- As a result, several energy systems studies that explore the value of CSP have used CSP plant yield output as input to energy systems models, thereby essentially making the configuration and/or behavior static. Thus despite potentially detailed accuracy for the CSP plant yield analysis, the lack of system feedback potentially impacts the correct valuation of CSP. Given that the primary CSP value proposition relates to temporally linked dispatchability from storage, which is charged by independently temporally linked solar collection, it is likely that a significant portion of the value of CSP is lost.
- In several systems studies that do not specifically explore the value of CSP, the treatment of CSP and other renewables seems to vary considerably. In some instances, very simple approxima-

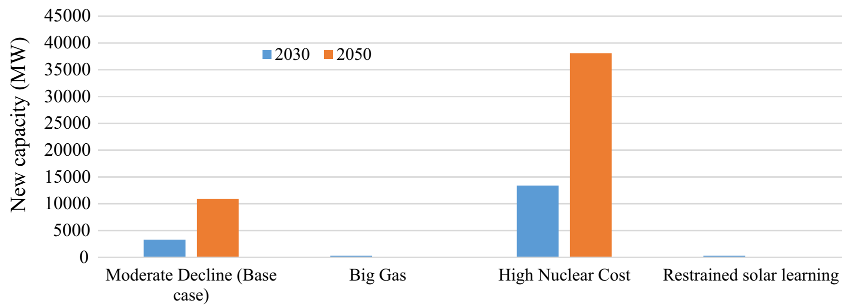


Fig. 28. CSP capacity allocation up to 2030 and 2050 based on the IRP 2013 draft update for the Base-case (Moderate Decline), Big Gas, High Nuclear Cost and Restrained Solar Learning.

tions are made to all generators, using only basic knowledge such as capacity factor, availability and capacity size. If additional treatment of renewable resources is factored in, CSP generators are often simplified using time slices or averaged behavior to capture seasonal effects. In these cases, the dispatch capability of CSP is again potentially lost.

- Appropriate CSP representation for energy systems analysis is an emerging research area and is recognized by experts in both categories. The typical requirements include appropriate spatial and temporal treatment of any given CSP capacity as well as for the system as a whole.

3.1.1. Energy systems analysis model review

Pfenninger et al. (2014b) present a comprehensive review of energy systems modeling relevant to the needs emerging in the twenty-first century. The review is centered on energy systems modeling for national and international energy policy.

Energy systems modeling emerged during the second part of the twentieth century to primarily focus on energy security and cost. The more recent emphasis on climate change and the resulting interest in renewable resources for the provision of energy has led to challenges relating to the intermittent nature of renewable technologies. Greater temporal and spatial information is needed in modeling, which was not previously a concern in energy systems.

The TIMES (The Integrated MARKAL-EFOM System) model platform, developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program) (Loulou and Labriet, 2008), is a widely used modeling platform that has been broadly adapted and emulated from open source versions such as OSeMOSYS (Howells et al., 2011) to the commercially sold PLEXOS power systems platform (Energy Exemplar, 2015).

The TIMES model uses a so-called bottom-up approach whereby technologies in the system are described in as much detail as needed in order to optimize energy systems over time. The primary drawback is that complexity in the models cause very long computation times. This is often resolved by simplifying the model and also simulating only a single or several representative time slices. The ability to deal with forecasting, scenarios and contingencies add to the computational burden in such physically-described models. There is a wide range of modeling tools developed to address specific challenges in energy systems analysis. A list of twenty-two free tools is presented in Table 10.

Pfenninger et al. (2014b) categorizes four challenges of emerging approaches in energy systems analysis.

1. Resolving time and space is becoming increasingly important and requires improved models but also better access to spatial-temporal information.
2. Addressing uncertainty and the future requires that scenario analysis emphasize predictive methods rather than technical accuracy in order to achieve better predictions.
3. Handing optimization across scales.
4. Incorporation of behavioral and social factors.

In this review, a case is made that the real systems value of CSP requires attention to all four categories. More attention is given to the first two, however. Time and space resolution is not just important for a particular project, but may be even more important at the system level. What also becomes evident here, perhaps illustrated by the recent proposed update of the South African plans, is that uncertainties beyond the technology are more difficult to resolve and may have greater impacts to the growth rate of CSP than actual technology advancements. To illustrate this point, the energy system scenario optimization performed for the South African IRP draft update of 2013 considers a variety of contingent scenarios, of which 3 additional scenarios to the Base-case are shown in Fig. 28. The only scenario that relates directly to CSP techno-economics is the fourth one: Restrained solar learning. In the event that CSP does not achieve the learning rates assumed in the Base-case, then it does not succeed. The same happens however if CSP advances but large supplies of low-cost gas are obtained. In the case of high cost nuclear, noting that the cost assumption changes from \$5800/kW to \$7000/kW for overnight capital costs of nuclear power, CSP allocation jumps to become the single biggest contributor to power generation in the country by 2050 with over 38,000 MW required.

3.1.2. CSP yield analysis model review

Ho (2008) provides a comprehensive review of CSP system and component analysis methods and models used by Sandia National Laboratories, illustrating a fairly long history of modeling capabilities built up in the U.S. Most of these models focus on detailed aspects of CSP technology, and many of the codes have been superseded or are used mostly in the Sandia Laboratory environment. The Solar Advisor Model (SAM), now called the System Advisor Model (Gilman and Dobos, 2012), is listed as the remaining CSP system modeling tool used by Sandia National Laboratories and National Renewable Energy Laboratory (NREL).

SAM is free to download and use for any purpose and has been used extensively in the analysis of CSP plants and energy systems around the world. SAM performs technical and financial simulations of many renewable technologies and comprehensively covers CSP technology variants. It uses hourly solar and weather data and is able to perform parametric and optimization simulations. SAM uses the TRNSYS (Klein et al., 2010; Fiksel and Thornton, 1995) transient thermodynamic simulation algorithm developed at the

University of Wisconsin in 1975. It also incorporates several older models reported in Ho (2008).

SAM has several limitations. The first is that it is not developed to be a systems simulation tool and needs to be used in conjunction with other tools for energy systems analysis. While it is free to use worldwide, its algorithms are largely proprietary or not directly accessible making it difficult to use with confidence.

Optical analysis methods to simulate the sun, atmosphere, reflector surfaces, tracking mechanism behavior and receiver flux qualities is a major development area in CSP. Numerical ray tracing methods, typically using Monte Carlo methods to fully describe individual or multiple optical elements, give the most detailed results but require longer computational time. Two freely available ray tracing tools are the proprietary SolTrace (NREL, 2011c) and open source Tonatiuh (Blanco, 2011).

Heliostat field performance prediction and optimization has traditionally been done by simpler analytical or hybrid methods. Delsol 3 (Sandia, 2009), developed by Sandia National Laboratories, is one of the most sighted tools using analytical approximations and is also used as the heliostat field optimization tool in SAM.

The aforementioned tools and methods are perhaps amongst the most commonly used in academic research while many other tools and methods are developed in-house or developed commercially. Particularly at the point of developing an actual project, design analysis requires a high degree of accuracy down to discrete handling of transient behavior in materials. In order to facilitate higher confidence and predictability for bankability of projects, the guiSmo (guideline for CSP performance modeling) project was established under the framework of SolarPACES in 2010 (Eck and Barros, 2010). The intention of these guidelines is not to prescribe how to model a CSP plant, but to specify minimum requirements considered important in CSP yield analysis. For instance, it recommends a time step of 10 min as a suitable compromise between transient accuracy and switching processes. This recommendation also aims to promote standardization between meteorological products (data), calculation time steps and reporting time steps for post-processing. A first of its kind, this guideline has been released in draft form and is due to be published as a complete first version (Hirsch et al., 2016).

3.1.3. Solar and weather resource data

For solar and wind energy system modeling and plant design, information about the resource needs to be sufficiently granular to factor in time of day changes. Solar data in increments of 1 h is used as a standard for energy systems analysis with significant renewable energy capacity and for early feasibility for individual projects. As recommended in the guiSmo project, 10 min intervals are required for a more accurate yield analysis in future. Due to significant annual deviations in actual conditions, a timeframe of typically thirty years is considered necessary for reliable modeling, particularly for bankability of expensive projects. It is difficult to obtain information for longer terms and also usually too computationally intensive. The typical meteorological year (TMY) method, in which twelve statistically representative chronological months are stitched together for a specific location (Wilcox and Marion, 2008), is the standard used for producing a typical year of meteorological data that enables more convenient analysis. For large renewable energy projects, lenders require expert analysis to understand the output of plants for typical and extreme years. TMY P50 and P90 are datasets to test the probability that a plant will deliver a certain annual output 50% and 90% of the time (Dobos et al., 2012; Vignola et al., 2011).

For energy systems analysis, it is likely that having access to data from a higher number of spatially distributed locations is more advantageous than the sub-hourly temporal resolution. Provided characteristics of the solar resource are representative, while being able to demonstrate sufficiently low error bias when aggregated over a day or longer periods, the value of CSP capacity at any one location can be satisfactorily assessed. Another important consideration in energy systems analysis is that TMY data sets cannot capture the correct system behavior when accounting for coincidental factors relating to weather and solar resource. This does create a dilemma for advances in energy systems analysis where there is a need for a longer historical time series in order to suitably assess anomalous years. Related to this is the paradox that longer historic time-series aiming to increase the validity of a model increasingly deviate from the forecasting timeframe for which the model is intended.

3.2. Recent CSP value studies

Beyond the most popular energy and CSP systems models, a number of methods have been published in some form, particularly during the last decade. This section covers key studies where CSP has been included to some degree in systems analysis.

The global potential of CSP has been expressed using a wide range of model detail. Trieb et al. (2009) use a spatial-GIS approach, suggesting that CSP can potentially supply 3,000,000 TWH per year, vastly exceeding the world electricity consumption. More recently, the value of CSP has been tested using an hourly spatial-temporal method to determine the optimal contribution in four key world regions. Pfenninger et al. (2014a) use the CSP model developed for this dissertation and report that well configured systems can satisfy baseload needs with little to no backup generation at costs approaching $ 0.06/kW h by 2030.

Fluri (2009) reports on the South African CSP potential using a similar method to Trieb et al. (2009) but limited to locations close to the existing transmission system. This study confirms that the short term potential vastly exceeds the current and future electricity needs of South Africa.

Several studies under the banner of the DESERTEC project (Trieb et al., 2012; Viebahn et al., 2011) present a case for solar electricity imports from the Middle East and North Africa (MENA). The authors claim that less than 0.2% of suitable CSP land is sufficient to supply 15% of the 2050 European electricity demand. The referenced studies are spatial-GIS based, but multiple agencies have considered the DESERTEC concept or parts thereof using linear programing with varying degree of spatial and temporal resolution.

REMix-CEM (Renewable Energy Mix-Capacity Expansion Model) by the German Aerospace Centre (DLR) appears to be one of the first models to transcend the energy systems domain of linear optimization, employing CSP in some detail in the case of Jordan (Fichter et al., 2014; Trieb et al., 2013). The CSP model is quite detailed and incorporates part-load and environmental impacts to performance. Cost is optimized for the entire energy system containing capital and operating costs for all technologies. The outcome is that a significant amount of CSP in a renewable mix results in Jordan continuing its economic growth while becoming energy secure.

Mileva et al. (2013) present simulation results that demonstrate the value of reaching SunShot (Gary et al., 2011; U.S. Department of Energy, 2012) cost goals for solar energy technology. The authors use a multi-nodal abbreviated time series model called SWITCH, developed by Fripp (2008), for energy systems modeling in California. SWITCH comprehensively considers multiple demand areas, technologies, transmission, costs and reliability. The model relies on SAM to perform the CSP simulations, perhaps explaining why the CSP plant configurations are limited in the publication.

Multiple studies have been conducted by NREL to evaluate the potential of CSP in the USA, particularly in the Southwest. Almost without exception, SAM is used to provide CSP modeling for a limited number of CSP configurations into linear modeling. Nevertheless, the studies point to clear advantages of CSP when cost are realized and PV saturation starts to occur (Denholm et al., 2012; Denholm and Hand, 2011).

Several South African policy driven energy systems analyses have incorporated CSP over the last decade. The majority of these use a variant of TIMES modeling (Miketa and Merven, 2013; South African DoE, 2013c, 2011). Most, if not all, energy systems models use simplified capacity factor based assumptions for technologies, stochastic single-node environmental parameters and typical time slices for intra-week or seasonal behavior. No references to full spatial-temporal models have been found for South African energy planning.

Ummel (2013a, 2013b) performs wind, PV and CSP spatial-temporal modeling for a future South African energy system and uses SAM to produce the outputs of a set CSP plant configuration with 6 h of storage replicated in a detailed spatial distribution. The performance of the CSP fleet appears to be exogenous to the system model, which in turn is simplified to a single node aggregation. Ummel suggests that improved spatiotemporal efforts will result in significant economic gain.

A multi institutional German-South African project considered the highly urbanized region of Gauteng in a holistic study that assumed energy to be the key element in its sustainable transformation (Eltrop and Annegarn, 2013). Within this project, CSP was included endogenously using a comprehensive and fairly detailed self-developed CSP model applied in a TIMES model for the greater project and reported in various publications (Telsnig et al., 2013; Tomaschek et al., 2015). As with most TIMES models, time slices were used, but it seems that greater emphasis was placed on the use of temporal solar resource data than has been applied in other South African TIMES models. A key limitation of this study seems to have been access to good solar and weather data with only two sites used, one of which was outside of the study region (Upington) and one in Gauteng.

Auret (2015) developed a spatial-temporal model of the South African electricity system based on the 2010 IRP and several scenarios proposed in the 2013 draft IRP Update. This bottom-up model treats the operation of all power generation technologies and plants endogenously based on system and IPP operator tariff structures and behaviors. Annual demand is based on the IRP and shaped hourly based on the 2010 Eskom demand data. Auret is critical of CSP's ability to deliver on the promise that the proponents of the technology usually suggest; this is due primarily to current tariff structures, not technology limitations. WWF South Africa (WWF-SA) commissioned a study exploring the feasibility of a high renewable scenario for 2030. These results also confirm that CSP is technically capable of fulfilling the value proposition provided that it operates to the needs of the system. When it does so, CSP offers a particularly valuable resilience to the electrical system in that it results in a system significantly less dependent on fuel price or demand fluctuations (Gauché et al., 2016, 2015).

3.3. Progress in measuring value of CSP in the system

A number of value measures have been used in electricity plant yield and system analysis in the methods and studies discussed in this section. Some of the reduced value measures include LCOE, capacity factor, capacity credit (the fraction of capacity associated with reducing the highest point of load duration) and cost comparison to avoided costs. None of these measures are ideal and the use of production cost optimization for electricity systems is increasingly regarded as a necessity for systems that expect a high renewable penetration (Denholm et al., 2016).

In their recent study exploring the competitiveness of PV plus batteries with CSP, Feldman et al. (2016) comprehensively investigate technology learning rates and apply these in various scenarios and configurations over time. The study suggests that CSP remains the better option over time when storage size is large. The authors however acknowledge that the comparison is limited as it doesn't account for value of electricity. While system configurations were selected to produce similar performance as an attempt to force parity value, even this is limited due to the characteristic differences in storage. CSP storage is restricted to a CSP plant but has very high efficiency while battery storage is flexible and can be located anywhere in the electrical network, but has lower efficiency. Determination of value is complex and requires detailed simulation for optimized dispatch. Jorgenson et al. (2013) investigate the value of CSP using a production cost model in an energy systems analysis platform. The authors determine the value of CSP by dividing the cost of the avoided electricity by the amount of electricity produced by CSP. This produces a marginal value of CSP that can be compared directly with LCOE.

The concept of marginal value has also been defined by Gauché (2016a) for generalized use in production cost energy systems analysis. The resulting marginal value of electricity (MVOE) accounts for all system costs, including the cost of the marginally adjusted or added capacity, thereby resulting in a net marginal value where a positive result implies that the marginal change was beneficial to the system. This MVOE is similar to value measures in other studies and is a derived measure from an energy systems model. Its definition and use is explored by comparison with LCOE. The standard method to determine the cost of alternative power generation technologies is by the LCOE (IRENA, 2015).

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{19}$$

where the investment cost is in year t, M_t is the operating and maintenance cost in year t, F_t is the fuel cost in year t, E_t is the electricity produced in year t, r is the discount rate, and n is the lifetime of the plant.

LCOE remains the most popular indicator to evaluate costs of alternatives. From the point of view of developers and investors of projects, this NPV based approach works well as it allows for direct assessment of investment potential when revenue is well understood, such as by a guaranteed 20 year PPA. LCOE remains the best-known metric for setting technology development goals such as is the case in the SunShot program of the U.S. DoE. The SunShot program does recognize the limitations of LCOE and sets additional requirements such as reaching certain capacity factor levels.

Annual system cost, the cost summation enumerator of the LCOE formula, can be represented by

$$\begin{aligned} \text{System cost}_{year} = & \sum_{p,o=1}^{n} \left(MF_{(p,o)} + MV_{(p,o)} + F_{(p,o)} \right) \\ & + \sum_{p,n=1}^{m} \left(I_{(p,n)} + MF_{(p,n)} + MV_{(p,n)} + F_{(p,n)} \right) \\ & + UE_u \end{aligned} \tag{20}$$

where the subscript p,o represents all older power capacity or infrastructure, and p,n represents all power capacity or other infrastructure with outstanding investment debt; U is the economic cost of unserved electricity per kW h, and E_u is the annual cumulative unserved electricity (kW h). The separation of the older and newer investments is intended to offer convenience, and the first summation term can serve as an overall term for removing all costs that are not expected to be influenced in the MVOE analysis. It should be noted that in an appropriately sensitive system analysis, all generators are likely to change behavior. For instance, the addition of a CSP plant is likely to alter the fuel consumption of an old peaking

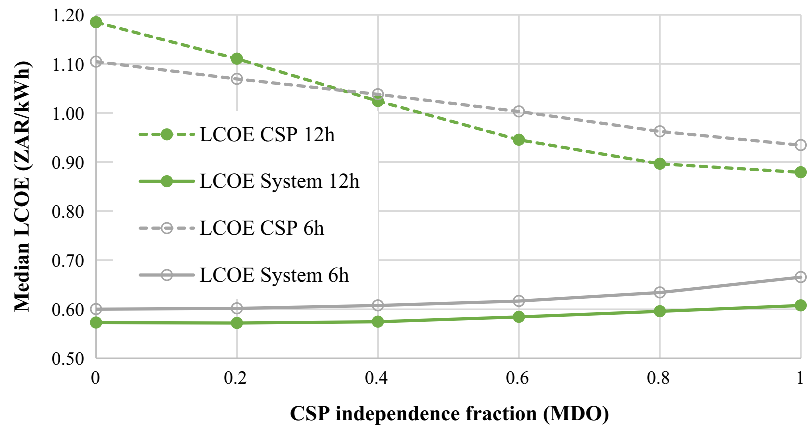


Fig. 29. LCOE of the CSP fleet and the whole system for CSP plants with 6 or 12 storage hours as a function of system independence fraction (or MDO = Minimum demand override).

Table 12
Example of MVOE using the WWF-SA 2030 scenario where all CSP capacity is compared between IPP mode and Slave mode.

	Unit	IPP (Independent)	Slave (System dependent)
MDO value	–	1.0	0.0
LCOE (system)	ZAR/kW h	0.607	0.572
LCOE (CSP)	ZAR/kW h	0.878	1.185
Capacity factor (CSP)	–	0.628	0.466
Annual power generation (system)	TW h	413.254	411.203
Annual power generation (CSP)	TW h	43.995	32.640
MVOE (CSP)	ZAR/kW h	–	0.479
"Apparent" LCOE (CSP)	ZAR/kW h	0.878	0.706

plant in the network, and the change in fuel cost of that old plant needs to be factored in.

Using the LCOE definition as an example, the system LCOE becomes

$$\mathrm{LCOE}_{system} = \frac{\sum_{t=1}^{n} \frac{\text{System cost}_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_d}{(1+r)^t}} \tag{21}$$

where E_d is the annual system demand (kW h), not annual system generation. The use of demand is coupled with the concept of adding the cost of unserved electricity to system cost. The result is a system-wide economically meaningful cost of electricity. With this cost established, the associated MVOE is defined and is therefore sensitive to the demand-side cost. MVOE simply allocates the difference between system LCOE values of two scenarios multiplied inversely to the proportion of electricity generated due only to the difference relative to system demand.

$$MVOE_{\Delta C} = \frac{E_d}{E_{\Delta C}}\left(\mathrm{LCOE}_{system} - \mathrm{LCOE}_{system+\Delta C}\right) \tag{22}$$

where subscript ΔC is any change in the system, such as the addition of a single CSP plant. MVOE aims to provide a unit based equivalent to LCOE, attributable down to the level of just the change. Because cost is already factored into the system model, MVOE is the net value of the change and can be associated with profitability or subsidy of that change.

The usefulness of MVOE is illustrated by considering a sensitivity test of the WWF-SA 2030 scenario where the operating behavior of a national fleet of CSP plants is changed from a flat-tariff IPP operating mode to a fully system operator driven mode, which could be referred to as "slave mode" (Gauché et al., 2016). Slave mode tends to reduce the achieved capacity factor of CSP by serving the system with the highest possible capacity credit. This drives up the LCOE of CSP while dropping the system LCOE as shown in Fig. 29.

From Fig. 29 it is clear that the sacrificial (slave) use of CSP is beneficial to the system, but the degree of this is not quantified. The fact that the system cost drops even while the CSP cost increases should imply that the positive MVOE change exceeds the change to the LCOE of CSP. This is indeed confirmed by MVOE analysis per Table 12.

While slave mode increases the CSP LCOE to ZAR1.19/kW h, the MVOE of this change is ZAR0.48/kW h, resulting in an "apparent" LCOE of ZAR0.71/kW h, which is significantly lower than the actual CSP LCOE of ZAR0.88/kW h in IPP mode. This relatively simple value measure can be used for various purposes, including the development of innovative incentive structures in PPAs that encourage the value of CSP to be exploited. MVOE can, amongst others things, assess the value of:

- New tariff structures
- Changing operating behavior of one or more plants or all capacity within a technology type
- Switching a project from PV to CSP (as one example of any new capacity tradeoff)
- Seeking the best placement of one or more projects in a system context. It should be noted that while system optimization could also be done to achieve this, MVOE can assign value credit to the placed capacities.

The MVOE method offers a fully systemic value and is therefore indifferent to categorized roles and costs in electricity systems. This may be an important consideration for CSP where value is currently described by roles such as baseload and peaking. MVOE could potentially uncover a greater overall role in electricity systems, a concept further explored in the final section.

4. Technology and systems outlook

Technology advances are discussed in context of energy systems analysis and not directly based on the expertise and skills of the CSP industry. Three categories of future development for CSP are identified here that ultimately need to be considered as dependent on each other for CSP deployment to grow rapidly over the next two to three decades.

1. CSP technology at a fundamental and component level is briefly covered in context of overall research trends and in consideration of the needs of energy systems.
2. CSP technology integration pathways highlight some areas that need to be resolved at the intersection between technology, environment and the energy system.
3. Systems integration outlook considers advancements needed to better comprehend and accommodate CSP in the system.

4.1. CSP technology outlook

A subjective listing of options that could be feasible for CSP in the near to longer term is summarized in Table 13. These options are based on cumulative experiences and opinions from a technology and systems value perspective. Other articles in this special edition will cover specific CSP types and technology advances in more detail.

The CSP technology outlook items listed are required to reduce cost of CSP plants by reducing plant footprint, capital cost and resource consumption. Of particular importance to CSP is a lower reliance on water consumption. By increasing temperatures through considering alternative working fluids and generators, dry cooling becomes more feasible above and beyond advances in dry and hybrid cooling techniques.

4.2. CSP technology integration pathways

The complicated nature of CSP makes a listing of all component integration options in the future infeasible. Table 14 provides a list of some example integration topics that relate to the technology in context of the environment and use that may require development or consideration.

4.3. Systems and grid integration

Understanding and realizing the system value of CSP will require significant growth in research and development, particularly if factors external to the technology play as significant a role as has been suggested. Improving the treatment of CSP in energy systems analysis could be arguably as important as the development of the technology and plant yield analysis.

Parameter modeling is enjoying more attention in CSP and is becoming fairly common at component level. The ability to parameterize CSP technologies into energy systems analysis tools appropriately will be a requirement for the correct evaluation of CSP, perhaps more necessary to address than for any other power generation technology. In energy systems analysis, conventional power plants are more predictable, thus easier to accommodate, while intermittent renewables such as PV and Wind tend to operate passively to the system, which also simplifies their treatment. Agüera-Pérez et al. (2016) point out the importance of comprehending 10 min averaged wind impacts vs. wind gust impacts but offer a statistical method to sufficiently account for the impact of wind. Various other recent investigations consider parameter models as an important development area for cost optimization (Blackmon, 2013; Emes et al., 2015). Similarly, other atmospheric conditions that impact plant performance such as atmospheric attenuation and cloud cover are topics enjoying attention but with much still to be done. A single tower 100 MW central receiver plant with 12 or more hours of storage could experience losses in excess of 10% (Gauché, 2016a). While various empirical models have existed for some time (Pitman and Vant-Hull, 1984), experimental measurements for attenuation are scarce, and without the presentation of satisfactory measurement techniques, reanaly-

Table 13
Near, mid and long term incremental CSP technology commercialization roadmap options based on views of the authors.

Technology area	Near-term (5 year)	Mid-term (5–15 years)	Long-term (15–30 years)
Reflector materials	• Lower lifecycle cost for solar mirrors	• Advanced solar mirrors • Reflector film	• Smart reflector surfaces
Concentrators	• Wireless heliostats • Increase use of sensors and autonomy • Very low cost parabolic trough for molten salt • Modular CSP units	• Resurgence of Linear Fresnel and/or Linear mirrors • Autonomy for most services • Beam down towers	• Micro paraboloid (dish) • Lifecycle autonomy
Receivers	• Selective coatings • Air receivers • Improved experience	• Particle receivers	• Receivers for micro paraboloid concentrators
Storage	• Advanced molten salt • Thermoclines • Concrete (lower temperature) • Target 10+ hours of storage	• Particle storage • Lower cost thermoclines • Initial thermo-chemical • Thermal storage graduates from CSP as renewable system balancing technology • Target 15 h storage	• Thermo-chemical for seasonal storage (fuels) • Target: Transportable fuels enable crossing the diurnal (24 h) cycle
HTF	• Advanced molten salt • Early potential for Sodium and air	• Liquid metals • Particles • Air	
Working fluids	• Air	• Supercritical CO_2	• Some abandonment from direct CSP
Generators	• CSP optimized steam generators for daily thermal cycling, which requires different thinking to conventional power generation	• Breyton and combined cycle • Supercritical CO_2	• "Solid state" (thermoelectric, thermovoltaic, CPV with storage) • Separation from CSP with generation from solar thermal generated fuels
Water consumption	• Improved and optimized dry and hybrid cooling	• Completely "dry" cycles and water reduction for mirror washing	• Continued improvements in reflector washing

Table 14
List of some CSP technology integration considerations based on views of the authors.

Integration topic	Summary of development issues and/or needs
CSP and PV (or other) hybrids	• Exploring the benefits and issues around projects containing CSP and PV for cost reduction and increased end-user value. This is already being implemented at large scale in Atecama-1 and in a smaller scale pilot that will test the integration of CSP with PV and batteries (Cocco et al., 2016; Petrollese and Cocco, 2016)
Weather and atmospheric variances	• Reflector systems remain the single highest cost component in a CSP plant, and their costs are primarily impacted by survivability and performance in wind. Two key areas of development are (1) to optimize reflector systems for specific conditions and (2) to reduce wind as a factor by more integrative methods • Dust and particles carried by wind also impact reflector performance and lifetime. Composition and participle size vary by region, and methods to determine ways to measure and mitigate for these are needed (Sansom et al., 2015) • Atmospheric attenuation impacts the feasibility of large scale central receiver systems. In some locations, short focal distance line focus systems may always be the ideal choice, but smaller scale modular towers could emerge to compete in areas with higher attenuation
Reduction in auxiliary energy needs	• Line-focus systems in particular have higher parasitic energy needs. These include pumping and freeze-protection heating of HTF and storage mediums
Modularity and standardization	• Conventional thermal power plants have evolved based on thermo-economic optimization where larger turbines are more efficient and cost-effective. Long focal distances (for central receivers) or long HTF transport distances (for line focus systems) tend to cause a techno-economic tradeoff with large heat engines. Modularity at various levels and scales has been explored and will remain an important research area. The development of better suited heat engines (or generators in general) has been a topic of research for decades and has evolved from considering air Brayton cycles and, more recently, supercritical CO_2 Brayton cycles. If suitable smaller-scale solutions in the range of 100 kW–10 MW become commercially feasible, this may significantly alter the development and adoption of CSP • The evolution of methods and technologies towards standardization will be required to reach higher volumes, an important aspect of cost reduction • Similar to standardization, industrial engineering techniques to explore more rapid deployment of CSP plants will likely play an important role. The ability to provide the highest degree of factory pre-assembly while being practically implementable will be important for speed of commissioning and cost • Seeking opportunities beyond integrated CSP could assist commoditization of CSP technologies. The CO_2 Brayton cycle is considered to be a potential modular solution for CSP and nuclear power. Similarly, CSP storage solutions could be modularized and adopted in high renewable systems where frequent curtailment is experienced in order to stabilize grids • In general, more standard power-block components for CSP could lead to significant cost reductions • Design standards to accommodate environmental conditions such as wind that have a high impact on CSP capital cost. These design standards need to factor in variances in local conditions such that commodity components can sufficiently cover lowest costs for plants
Automation	• A higher rate of adoption of CSP will likely require more emphasis on autonomy throughout the lifecycle of a plant. Besides the economic value of high volume manufacturing, the rate of advancement in microelectronics and mechatronics is likely to be significantly beneficial to the operating and maintenance of CSP plants • Onsite labor is not the most efficient use of resources and the cost of CSP construction will need to reduce by shifting employment to factory based manufacturing for sustained productivity of labor

sis of older data or attempts to derive attenuation by other means such as DNI occurs (Ballestrín and Marzo, 2012; Goebel et al., 2011; Sengupta and Wagner, 2012).

Similar to parameter modeling, probability modeling is a topic that has been relevant in CSP techno-economic and yield studies (Ho et al., 2011). Probability modeling also has a potentially signif-

Table 15
Bottom-up data recommended for energy systems analysis.

Data type	Use	Preferred format	Availability and status
Solar irradiation (DNI)	CSP yield	H, SH, 1	High quality satellite derived is commercial available (limited academic availability) (Ineichen 2013)
Solar irradiation (GHI, DHI)	PV yield	H, SH, 1	High quality satellite derived is commercial. Significant free data from measurement stations
Ambient temperature and humidity	Thermal plant efficiency and water use	H, LH, 2	Widely available. Humidity only required for systems where evaporative cooling significant
Wind speed for CSP	Collector system performance	H, SH, 2	Widely available for measurement stations, but high quality spatiotemporal datasets not as common
Wind speed for wind power	Wind power yield	H, SH, 1	Limited commercial and free data sets for spatiotemporal modeling
Atmospheric attenuation	CSP plant scaling and technology choice	A, SL, 2	Generally not available. Models use approximations
River, reservoir, ocean flows and temperatures	Source or sink for thermal or water power	H-A, 1–2	Generally obtainable depending on need
Demand (grid-wide)	Regional and national planning	H, SL, 1	Freely available in some countries
Demand (localized)	Transmission and generator placement planning	H, SL, 1	Freely available in some countries, but can be difficult to source
Transmission system	Transmission and generator placement planning	Network	Can be confidential. Transmission systems of regions and power pools are approximated and provided commercially in Plexos

Preferred (minimum) format: H = hourly, D = daily, M = monthly, A = annual/average, SH = high spatial resolution, SL = low spatial resolution, 1 = first order impact, 2 = second order impact.

Table 16
Top-down and other data potentially applicable to energy systems analysis.

Data type	Comment
Demand forecasting	A function of economic growth of the region of interest, which itself is a function of the cost and availability of electricity
User behavior changes	The availability and price of electricity, amongst infinite other reasons, will change the demand level and shape of demand. Some of these changes are lasting, such as the avoided grid supply of installing domestic PV
Cost and availability of fuel	Real term cost adjustments to fossil and nuclear fuels have a first order impact on energy systems analysis. Price inelasticity of fuel makes it hard to forecast cost due to volatility between supply and demand
Learning rate of technology	The cost at any given time of each technology is as important as cost of fuel from a systems point of view. Learning rates need to be converted to cost, which requires knowledge of capacity adoption, thereby creating a dependency loop in the modeling process which is impossible to resolve without simplification

icant role to play in energy systems analysis, particularly in treatment of scenario forecasting where ambiguity regarding availability and cost of fuels is particularly relevant.

As with technology integration, systems and grid integration research and planning is reliant on data pertaining to the system environment. Two primary types of data are needed: Bottom-up data is data that can generally be measured in the system or environment such as weather, solar and wind resources. In the near-term, demand can also be considered in this category. Table 15 lists and describes typical bottom-up data types.

Top-down and/or systems-dynamic data types are required for good energy systems analysis, but the ability to factor these in is usually understood to be complex and therefore more difficult to accommodate in models. Examples of such data not typically used in CSP yield analysis are given in Table 16.

4.4. State of research: SolarPACES (2016)

The annual SolarPACES conference (SolarPACES, 2016) is the primary research gathering for the CSP community. The system value of CSP as presented in this review is wrapped up with a high level review of research statistics from the SolarPACES (2016) conference held in Abu Dhabi in October 2016. Fig. 30 and Table 17 summarize the technology based research trends (Gauché, 2016b; Hinkley, 2016; Zarza, 2016). Interestingly, receiver research for central receivers was a significantly popular topic, much of it centering on the ability to collect and store energy suitable for supercritical CO_2 power cycles.

Fig. 31 presents a subjective count of papers (presented as oral or poster) and presentations given (without paper, but significant to this review) at SolarPACES (2016).

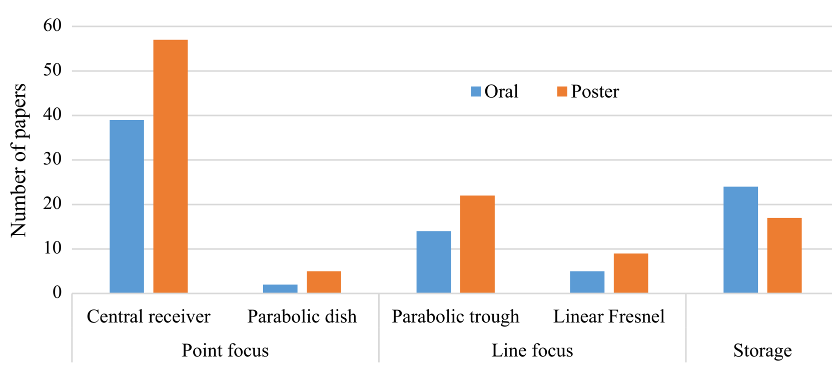


Fig. 30. Estimated breakdown of papers at SolarPACES (2016) based on closing session trends.

Table 17
Noted technology trends in research at SolarPACES (2016).

Topic	Summary of noted trends
Central receiver	• Fractionally the greatest representation in terms of orals and posters • Receivers represented almost 50% on component basis • Heliostats represented 28% on component basis, mostly theoretical research including field layout methods • Heat transfer (and working) fluids in order: molten salt (16), particle (14), air (10), liquid metal (3), water (2) and supercritical CO_2 (2) • Significant research aiming at increasing temperatures, targeting supercritical steam and CO_2. Very little technical research in air Brayton cycle
Parabolic trough	• H_2 levels in HTF circuit and receivers: Modelling, detection and monitoring sensor development • The bulk of other papers relate to simulation methods and development of new collectors • Only two papers on operational experience
Linear Fresnel	• All theoretical studies with little to no experimental results • Key development in the area of improved secondary reflectors for the receiver in anticipation of molten salt
Storage	• A key milestone is the operational status of the U.S. based 110 MWe, 10 h storage, Crescent Dunes plant with about 1.1 GW he (electric equivalent) in storage is comparable to the global cumulative battery storage capacity of 1.5 GW he in 2015 • Thermocline thermal storage research is resurging and represented widely in terms of configuration and research facilities • Molten salt evolutionary research in terms of stability, chemistry, additives or combining with thermoclines • Phase change materials (PCM) for latent heat storage and thermochemical storage represent the bulk of the remainder

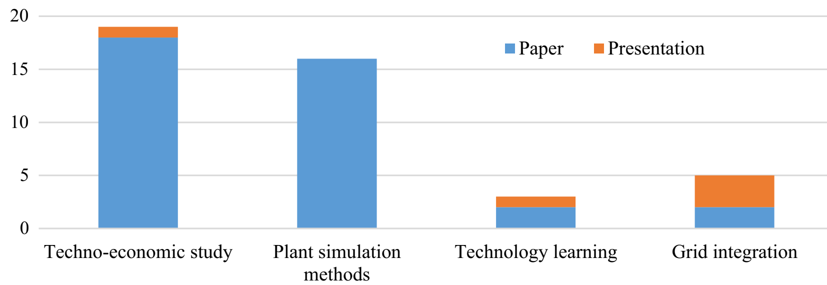


Fig. 31. Estimated breakdown of papers or presentations representing various aspects of CSP plant techno-economics, learning and grid integration.

While the SolarPACES conference is a scientific, peer review conference oriented more towards CSP technology advances, it is also one of the only global venues for aspects related to grid integration and technology learning forecasts of CSP. A healthy number of papers submitted in 2016 relate to plant-level techno-economics and simulation methods. Simulation methods or studies that did not relate to a plant level were not included in Fig. 32. Topics related to technology learning and grid integration were very limited; only four papers with any substantive contribution could be found, and only a further four presentations were given relating to these topics, of which three were plenary presentations.

5. Discussion and conclusion

Adoption of CSP as a valuable contribution to regional and national electricity systems has not occurred at the rate expected a decade ago (IEA, 2014a). CSP as a technology and its role in the energy system has been reviewed showing that while advances are occurring, these need to continue on all fronts. Exploring the potential limitations, importance and relevance of CSP, beyond CSP as a technology, and beyond its part of a designed electricity system, is perhaps worth considering. These broader aspects are generally of a more complex nature and discussed in order to provide final context to the conclusions.

5.1. Policy research, planning and roadmaps

CSP needs to continue to improve and demonstrate its value proposition, but adoption of the technology is also strongly reliant on higher level social and political decisions in our future. Scholten and Bosman (2016) consider the implications of purely renewable energy based systems in the future, noting that regions and countries have varying levels and types of renewable energy resources. Their study uses thought experiments to consider various scenarios. Two primary findings from these experiments are that (a) countries face a “make” (self-generation) or “buy” (import) decision and (b) electricity becomes the more dominant carrier of energy, which implies greater emphasis on infrastructure and management. With these primary findings, two scenarios emerge: a “Continental scenario” comprises more centralized networks fol-

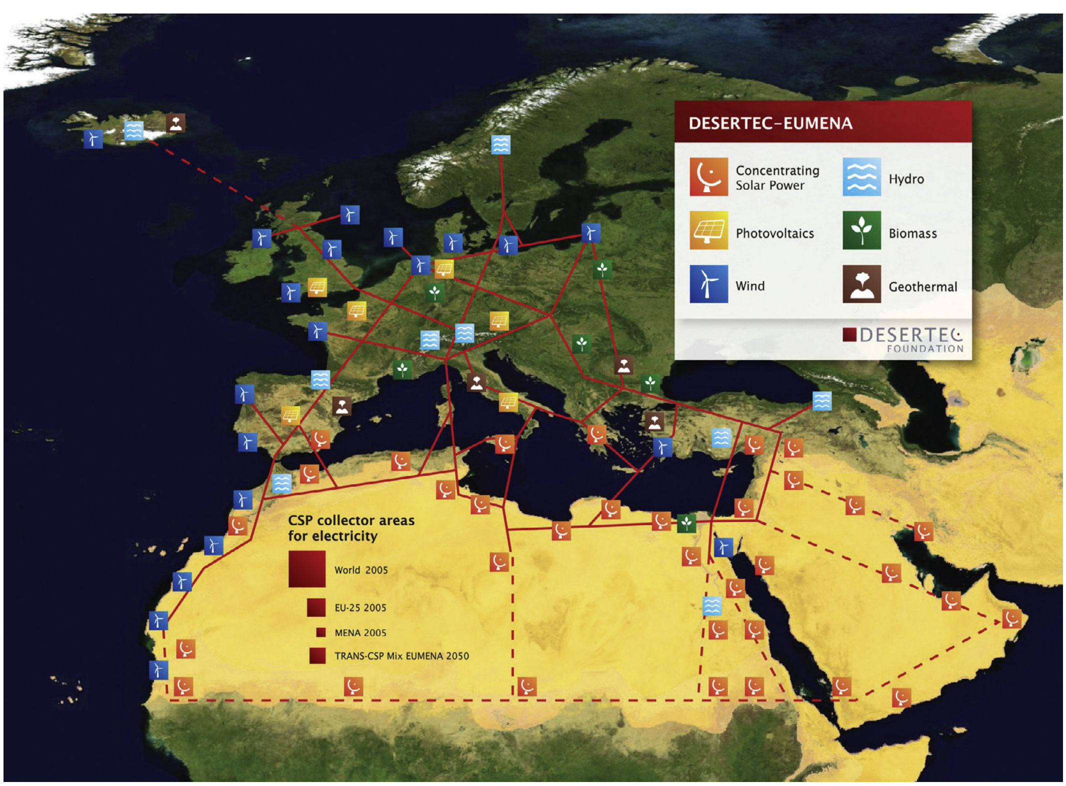


Fig. 32. DESERTEC EU-MENA Map: Sketch of possible infrastructure for a sustainable supply of power to Europe, the Middle East and North Africa (EU-MENA). *Source:* DESERTEC Foundation, www.desertec.org.

lowing a buy decision; whereas a "National scenario" follows a make decision with decentralized networks. There are a few implications relative to traditional fossil-fuel systems.

1. A shift from access to resources towards infrastructure management.
2. A shift in strategic leverage from producers to consumers while countries need to provide balancing and storage services.
3. A decrease in geopolitical concerns, provided countries become 'prosumer countries' where they increase their self-reliance.

The outcome towards a high renewable society is likely a mixture between the Continental and National models. The Desertec initiative mentioned in the systems analysis section and illustrated in Fig. 32 offers a vision of what could be possible in the EUMENA region. The implementation of CSP in such a configuration apparently could offer significant macroeconomic advantages to both the developing regions of North Africa, the Middle East and to the developed countries of Europe. While the Desertec Foundation has evolved with new partners and sponsors, the concept continues to stimulate strategic energy systems research.

Papaefthymiou and Dragoon (2016) offer a comprehensive policy recommendation for a migration towards 100% renewable systems based on considering all aspects of energy systems from resource to user. The authors break the evolution into three development regimes: near-term, representing about 10% adoption of renewables; mid-term, representing around 50%; and long-term. The initial regime requires a high degree of planning and forecasting. An integrative approach where energy storage is important at all points in the system, from primary resource to end user, is considered of primary importance towards the end goal. The challenge however is the significant and appropriate policy that is needed to enable the required behaviors in going beyond 10% adoption levels. These behaviors include implementation of expanded transmission systems, implementing smart grid technologies and efficient use of surplus generation. This evolution is complex and needs to start now.

The International Renewable Energy Agency (IRENA) (2016) presents a roadmap to increase the contribution of renewables by 2030, including a "doubling" option. The roadmap suggests that the "doubling" net benefit will be 15 times more than the cost. CSP is indicated as having the highest growth rate in the event of a doubling of plans, but this is from a very low base of 1% worldwide generation, which is lower than the 2014 edition of the roadmap.

The International Energy Agency (IEA) recognizes a number of values for energy storage (IEA, 2014b). These uses include improving energy system resource efficiency, increasing the use of renewable resources, increasing energy access remotely, and greater reliability and resilience of electricity grids. The use of molten salts is recognized as being in the demonstration to deployment phase of maturity. While recognition is given to the contribution made by CSP in terms of energy storage, CSP as a technology isn't clearly indicated as a significant storage contributor. The value of CSP at increasing renewable penetration is presented in case study for the U.S (Mehos et al., 2015).

The IEA Solar Thermal Electricity Technology Roadmap of 2014 (IEA, 2014a) suggests that CSP can still contribute the largest share of electricity worldwide by 2050 despite the slower than expected growth since the previous version of the roadmap (IEA, 2010). This recognizes the increasingly limited value of PV due to saturation at some point despite current popularity.

5.2. Social and environmental considerations

While social and environmental considerations might be understood as separate topics, in CSP these topics are closely linked because of social perceptions, the relative newness of the technology and the industrial natured appearance of a CSP plant. As with all power generation technologies, CSP has social and environmental impacts, all of which need to be measured, monitored and mitigated for. While a review of actual impacts is out of scope here, it needs to be recognized that such perceptions have likely been instrumental in one or more CSP project cancellations and likely have been a cause of the slower than expected uptake of the technology. It is therefore important that more research and experience is gained in these areas, firstly to more correctly represent the overall impacts of the technology but also to honestly place CSP squarely in the category of a "must have" sustainable energy solution.

Although literature on the environmental impact of CSP is limited and often expressed as life-cycle analyses, the first research on the topic dates back to 1982 where avian mortality was measured at Solar One in California (McCrary et al., 1986). To date, the most prominent concerns, namely the impacts on birdlife, water usage and land impacts associated with CSP, have been reported on for numerous U.S. CSP plants (Bracken et al., 2015; Hernandez et al., 2014; Walston Jr. et al., 2015).

Hernandez et al. (2014) broadly look at the environmental impacts of utility scale solar energy (USSE), noting that the rapid adoption thereof requires careful attention, but once correctly managed, USSE is able to become a key renewable to mitigate climate change. In a separate study, Hernandez et al. (2015) find that the amount of suitable existing developed areas within the state of California would be more than able to accommodate the state's

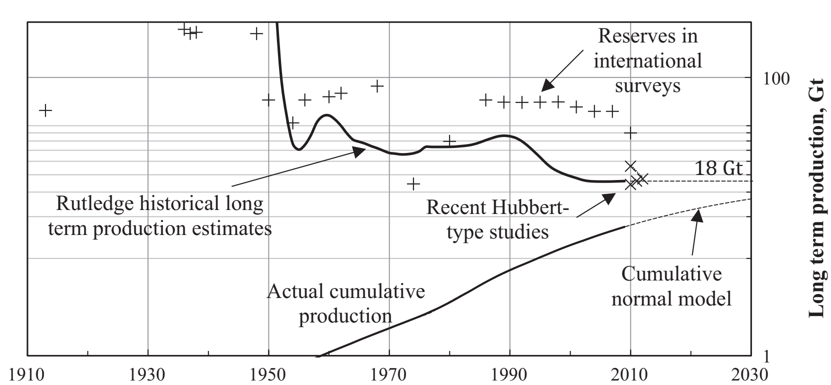


Fig. 33. Estimates of long term (ultimate) coal production in Africa (mostly South Africa) showing international survey values as well as historical estimates to the cumulative normal model. Actual and modelled cumulative production is also shown, as are all recent Hubbert-style predictions (data and model adapted and used with permission by Dave Rutledge).

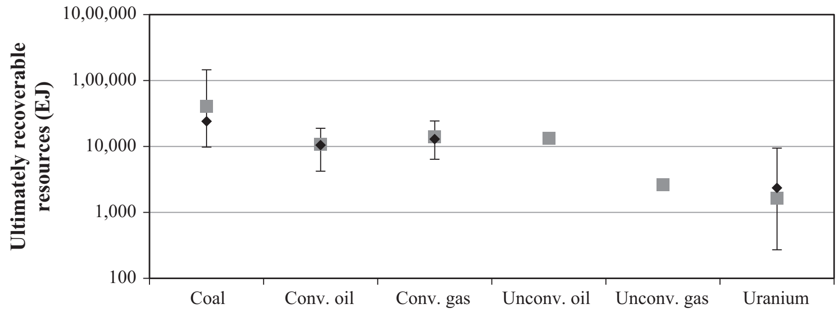


Fig. 34. Worldwide ultimately recoverable resources (URRs) of various conventional energy resources adapted from Dale (2012). Grey squares represent mean values and the range represents 5th percentile and 95th percentile; black diamonds represent the median value of the estimates.

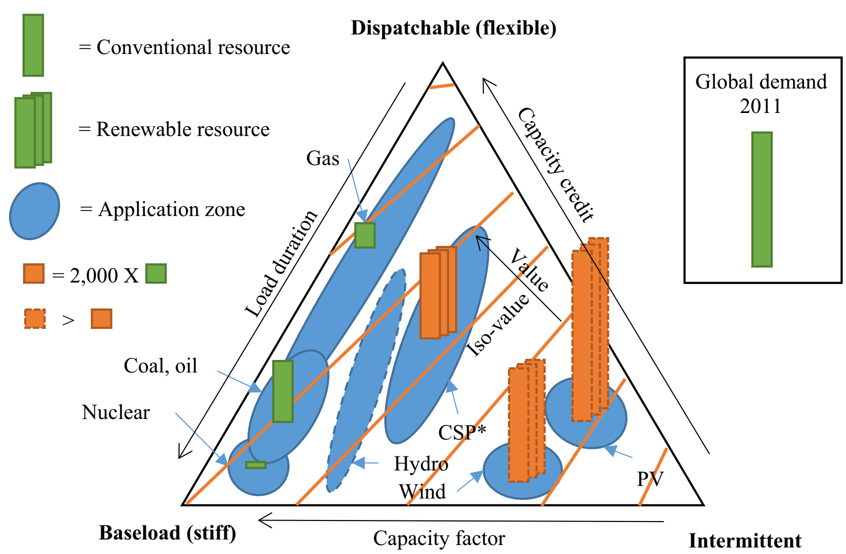


Fig. 35. Qualitative positioning of typical primary resource and generator electricity options in regions where CSP is likely applicable. Bar heights indicate electricity equivalent potential per year, assuming equal annual demand for 50 years for conventional fuels. Depth-stacked bars for renewables indicate the perpetual nature of the resource. Orange bars are ≥2000 times the value of green bars for the same height. Blue zones infer range of applicability (not size) of a resource/generator type. *CSP range is for 12–15 h storage plants. Global 2011 electricity demand height is scaled relative to bar heights in the triangle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

need of electricity using small and utility scale solar energy. Rudman et al. (2016) presents initial survey based findings of the impact of USSE in South Africa as part of a larger study using mixed methods. The survey was conducted by interviewing experts in various sectors relating to USSE, including environmental practitioners and developers. While impacts are recognized, these were considered manageable, and the cumulative impact with the growth of USSE needs to be better understood.

Moore and Hackett (2016) present a very interesting and comprehensive social review of CSP which focusses on the concept of 'place-making. The 'place-making' process is inherently subjective and multifaceted and the acknowledgement of this process helps to explain public perception about places. These authors argue that improved participatory practices are needed to more appropriately design technologies and that broad public acceptance is not a problem. Interestingly, a disproportionate fraction of people in opposition to solar energy are involved in the siting process of projects.

Ultimately, an understanding of the tradeoffs between the benefits of deploying CSP as a renewable energy technology and possible social- and environmental impacts would help to facilitate positive attitudes towards the technology (Moore and Hackett, 2016). Similar to learning needed for cost and performance optimization of CSP, studies investigating the management of environmental impacts increases social learning to benefit the acceptance of CSP by the end user of the electricity. Such studies should thus be encouraged to explore the diversity of technological configurations in different environmental and social contexts.

5.3. Global energy perspective

A number of recent international publications have looked at coal reserves worldwide. The authors use Hubbert style forecasting, which has proved reliable at predicting peak and ultimate production of oil in mature or depleted regions. Hubbert analysis uses historical production information fitted to a normal distribution curve or similar. If sufficient production has occurred, particularly at the point where the rate of production increase starts to wane, peak and ultimate production quantities and dates are predictable with higher accuracy than geological exploration estimates predict (Hubbert, 1956).

Rutledge (2011) developed a model that uses the better of a logistic or cumulative normal model for all coal regions and the world as a whole. Rutledge (2013) makes his data and models available to others, and the results have been re-processed in Patzek and Croft (2010) use a multi-Hubbert cycle analysis to determine a global coal production forecast. Mohr and Evans (2009) also perform Hubbert style analysis on world coal, incorporating an iterative supply and demand method in an attempt to replicate real world conditions. Hartnady (2010) works on a similar model which examines the (South) African coal resource question in detail. Hartnady (2012) revises his previous estimate based on updated data from Rutledge (Rutledge, 2011). All of the authors' current ultimate estimates are shown in Fig. 33 indicated using the symbol "×".

Similar trends exist in the other coal regions of the world. When examining these models for exhausted coal or oil regions there is little doubt that they predict peak and ultimate production more accurately than geological estimations do. These models show predictability when other regions can make up for demand, but it is not known how the models will behave for world production or production of later maturing regions as there may be no motivation to cease production of sub-economic resources. On the other hand, this hindsight model is indifferent to supply and demand mechanisms and even handles significant occurrences well, such as war and cartel interference. In the event of approaching sub-economic resource levels, one would speculate that alternatives would by then have succeeded to enter the market.

Dale (2012) reports a meta-analysis of all major non-renewable sources. The methodology includes statistical analysis on a large set of resource estimates that the author was able to obtain. Fig. 34 is a re-creation of the results, and as would be expected in such work, the range on each type is large. Ranges are not shown for unconventional oil and gas due to insufficient estimates.

A qualitative positioning of electricity options for regions where CSP is applicable is presented in Fig. 35. The figure positions the primary energy generation technologies known today, divides the global median expected ultimately recoverable resource (URR) for each conventional fuel equally over the next 50 years and compares by bar-height for the electricity equivalent for that type per year. In the case for renewables, these bar heights are perpetual and accordingly indicated by the depth stacking, noting that the wind and PV resource potentials are not quantitatively scaled. While resource availability is globally represented, the figure aims to illustrate resource and technology application where CSP is relevant directly or by grid connection.

The figure only presents relative positioning of non-hybrid generation where energy storage is included prior to the production of electricity, either in the form of the energy resource or as part of the conversion to power process. The non-hybrid representation helps to delineate resource constrained power generation from sustainable resource power generation. Storage after the point of electricity generation is also omitted, given that it can largely be seen in the category of "all other things equal", which is generally applicable to any point in the system. System based storage such as pumped storage is omitted and the value of any generation option is conceptually illustrated using "iso-value" lines noting that this value is a marginal concept specific to any given scenario. Hydro is provided illustratively without resource estimate for several reasons but primarily because it is largely already adopted in the applicable regions.

The more traditional concept of baseload, mid-merit and peaking generation, which primarily considers the tradeoffs between two vectors, capacity factor and cost, is replaced by the concept of value, which is represented by three categories of generation: baseload, dispatchable and intermittent. These three categories and their relationships are described.

Baseload power is defined similarly to its classic role, that is, of providing a relatively constant output of electricity based on a typically low instantaneous daily, seasonal or annual system demand. The difference to classic baseload being that it is evolving to factor in residual demand after removal of intermittent generation. A key risk for baseload is that if renewable based intermittent generation capacity growth steepens the residual demand curve to the point of pushing down the long duration demand despite demand growth, underutilization will occur. Intermittent power is power generation based on intermittent energy resources in the time-frame of usually less than one year and usually above 1 s where the generation technology itself has practically no inertia. Wind and PV power are the most common in this category. Dispatchable power serves the residual demand gap when baseload and intermittent power cannot do so by capacity or availability or ramping. Typically, dispatchable generation is fast ramping and highly available.

The distinction between these three categories is not elementary, but each pairing comparison does reveal a primary differentiator. Capacity factor is a primary differentiator between baseload and intermittent generation. Neither is particularly effective at serving power that serves the shape of demand and in fact, separately or together, tend to exaggerate the normalized shape of residual demand. All other things equal, the system is adversely affected when their combined capacity exceeds long duration load significantly. Capacity credit is a primary differentiator between intermittent and dispatchable generation. While both categories exhibit lower capacity factors, the value gradient rises steeply towards dispatchable options. The related impact is that the addition of pure intermittent generation has very little reciprocal value to the capacity needs of dispatchable generation and tends to adversely reduce the capacity factor of dispatchable generation, all other things equal. This capacity factor reduction is positive to the system in the event that the cost or availability risk of its resource increases above the marginal capital recovery cost. Load duration is a primary differentiator between baseload and dispatchable generation. This essentially defines the classic power system that is now undergoing change due to the adoption of more sustainable options. The relationship between these is a cumulative one where a tradeoff between capital and fuel cost leads to an optimized system up to a point at which the cost (direct or indirect or avoided external) of including the intermittent vector leads to better cost alternatives.

As defined, CSP is not distinctly associated with any of these categories. CSP is put forward as being a renewable alternative to baseload and dispatchable power generation where, based on current alternatives, it falls short when not considering hybridization or technology advances. In some configurations and plants built, CSP has no thermal storage, and other than thermal inertia it does not exhibit obvious advantages over other intermittent options. The versatility of the technology and its relative newness create a distinct identity crisis. CSP has a distinct advantage the moment that its cost exceeds the value threshold. In scenarios considering supply security due to capacity shortage, current CSP costs warrant its adoption without subsidy (Silinga and Gauché, 2014). In scenarios where availability and associated costs of fuel are a concern within the next 15 years, CSP appears to provide for robust systems that are resilient to fuel cost and demand fluctuations (Gauché et al., 2016).

The value of electricity is a function of residual demand where residual demand is a function of what has already been supplied in the system (per definition) and changes in behavior at the point of consumption. All other things equal, the orange "iso-value" lines in Fig. 35 depict a reasonably traditional concept of the value of electricity. Fully dispatchable and available generation is by far the most valuable and usually the most expensive.

The final point to make is that the median estimates for conventional energy resources do not support 50 years of electricity generation to satisfy just a 2011 annual demand (ignoring demand growth). On the other hand, renewable resources are plentiful, but power generation value is limited. Ignoring other storage options, CSP conceptually exhibits much higher value. The definition of value will change (moving the iso-value lines) when the system changes. As example, if low cost batteries begin to play a more significant role, the value gradient will reduce and thereby diminish the value of both baseload and dispatch capacities. In general, CSP will face a variety of emerging and maturing competing threats and complementing opportunities. As example, PV undermines CSP today, with studies indicating that the "Duck Curve" presents an opportunity (Denholm et al., 2016). The reality of our future is that we are likely faced with many inflection points that are too complex to understand by comparing to individual factors and a continuous systemic understanding of value will be required to predict the value of CSP and to preempt its evolution.

5.4. Conclusion

CSP capacity worldwide has grown to around 5 GW, much of this capacity installed in the last decade. In some years the growth rate has been impressive, closely matching that of PV; yet CSP has not done quite as well. Other than the emerging plans in China, CSP has recently been under threat of stalling as it did in the 1990s. While significant experience has been gained from the SEGS plants commissioned in the 1980s and mostly still running today, the technology learning didn't fully translate in the recent growth phase. This suggests that CSP as a technology needs to keep increasing capacity continuously in order to fulfil its value. Additionally, CSP knowledge transfer between developers needs to be encouraged or enforced to achieve maximum performance without delay with each new plant if CSP is to survive. This means that a new CSP plant needs to be constructed in less than 2 years and should perform at full performance almost immediately.

From a resource point of view, there is little doubt about the potential of CSP. There is also growing evidence that technically CSP performs to its promise. This means that it does efficiently store energy for extended use, potentially offering a high capacity factor and/or high capacity credit electricity. Techno-economically, CSP needs to reduce its average generating cost to penetrate more of the market. There is evidence that cost learning occurs once a significant number of similar plants are commissioned and research roadmaps present many tangible future cost reduction options.

This review points to a number of hurdles beyond the technology that CSP needs to overcome in order to realize a sustained capacity growth rate. It is not clear if any one hurdle is higher than the others, rather it seems they all need to be cleared. These six hurdles are:

1. Increased cumulative operating experience at plant level for CSP with storage.
2. The ability to learn, thereby following the cost learning curve, in part by a sustained growth rate and by shared learnings between developers.
3. Improving the technology to make bankability easier, in the form of operating experience but also by other means such as modularity to reduce the quantum of upfront cost.
4. The ability to prove systems and integration value by demonstration and by refined systems analysis.
5. Social and environmental acceptance by factoring in all complexities and societal feedback.
6. Conviction through the form of policy recognizing the energy security value of CSP where it is part of an important sustainable energy system, well ahead of the risk of conventional resource extraction decline.

Most of these hurdles require some form of intervention. As example, the current gap in knowledge transfer between parties that blocks the progress of the technology is unlikely to resolve by itself given the cost and confidentiality required by a single project.

Energy systems analysis is a rapidly growing and evolving research area, roughly coinciding with the adoption of utility-scale solar energy. The greatest difficulty with energy systems analysis relates to the infinite complexity of a very representative model that can robustly forecast the future. CSP finds itself in somewhat of an identity crisis at the same time. In isolation, it isn't quite renewable, nor is it completely baseload or a guaranteed dispatch solution. The ideal behavior and configuration of CSP in a system may reveal higher value. Should this value exist, then system parameters should play a stronger role in the evolution of the technology and research investment decisions.

When applying sufficient parameter sensitivity to CSP in a systems analysis model as attempted in the WWF-SA scenarios (Gauché et al., 2016), a high capacity of CSP in the system led to a lowest cost system, with highest cost resilience to changes in demand. Well located, proportioned and operated CSP in the system shows the ability to reach high renewable levels while relying only infrequently on operating backup generators. If true, CSP does not need to be one of the three corners of Fig. 35; it can compete as the backbone of future electricity grids while being supported by two or three of those corners. Over time this becomes increasingly relevant as the conventional idea of baseload power disappears, being replaced by renewable-generated fuels and other network storage systems. If CSP does not manage to show a sustained growth rate, resource constraints suggest that renewable based fuels and storage will be of greater importance, and this might imply a less cost-optimal system scenario than one in which CSP succeeds with a sustained growth rate.

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