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CSP-Referenzkraftwerk

Konzeptstudie CSP-Referenzkraftwerk mit Salzschmelze „Made in Germany“

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1. Einleitung

Dies ist die deutsche Fassung des Abschlussberichts zum Projekt „CSP-Referenzkraftwerk mit Salzschmelze Made in Germany“. Er ist entsprechend den Vorgaben des Zuwendungsgebers aufgebaut.
Da die Ergebnisse in erster Linie international verbreitet werden sollen, wurde ein ausführlicher Bericht zu den technischen Details in englischer Sprache verfasst. Dieser englische Bericht enthält viele Details zu den Ergebnissen, die in Kapitel 7 des vorliegenden Dokuments nicht nochmals in deutscher Sprache im vollen Umfang wiederholt werden. Stattdessen enthält Kapitel 7 nur kurze Zusammenfassungen der Ergebnisse aus den Unter-Arbeitspaketen. Für weitere Details werden die Leser daher auf den englischen Bericht verwiesen.

2. Aufgabenstellung

Solarthermische Kraftwerke (CSP) ermöglichen durch die Integration von thermischen Speichern und – ggfs. einer fossilen Hybridisierung eine von der fluktuierenden Sonnenstrahlung entkoppelte und somit bedarfsgerechte Stromerzeugung sowie eine Grundlastfähigkeit des Kraftwerkes. Sie tragen damit in idealer Weise zur Erzeugungssicherheit und – bei künftig erhöhten Solaranteilen – zur Entlastung der Stromnetze bei.
Im Vorhaben wird eine Konzeptstudie für ein CSP-Kraftwerk mit Salzschmelze von der deutschen CSP-Industrie erstellt, das das Potential hat, als zukünftige Referenz den Stand der Technik, nämlich Parabolrinnentechnologie mit Thermoöl als Wärmeträgerfluid, abzulösen. Dabei wird ein Referenzkraftwerk für die Salzturmtechnologie definiert. Wesentliches Ziel der Konzeptstudie ist es, ein CSP-Kraftwerk zu definieren, das dem Stand der Technik aus technischer, ökonomischer und ökologischer Sicht überlegen ist, dessen Subsysteme von deutschen Herstellern angeboten werden, und bei dem trotz innovativen Technologieeinsatzes eine Finanzierbarkeit sichergestellt werden kann. Dies soll durch eine gesamtheitliche Optimierung der Kraftwerkstechnik erreicht werden. Es wird erwartet, dass ein solches System das Marktpotenzial aufweist, vielfach in nahezu gleicher Bauweise implementiert zu werden, und durch sehr günstige „total cost of ownership" gekennzeichnet ist. Zudem wird besonderer Wert auf kurzfristig realisierbare Anlagentechnik gelegt. Trotzdem steht die weitere Kostenreduktion im Vergleich zur heutigen Salzturmtechnologie im Mittelpunkt, um einen Standard für die nächste Generation von Salzturmkraftwerken zu definieren.
Die Konzeptstudie bietet den teilnehmenden Unternehmen ein hervorragendes Akquisitionswerkzeug im Kontakt mit zukünftigen Kunden, die CSP-Kraftwerke ausschreiben wollen. Wenn die in dieser Konzeptstudie definierten Spezifikationen der Referenzkraftwerke von den Kunden als Vorlage verwendet werden, wird gewährleistet, dass es zu technisch sinnvollen Ausschreibungen kommt, die von den Projektpartnern kompetent angeboten werden können.

2.1. Wissenschaftliche und/ oder technische Arbeitsziele des Vorhabens

Das wissenschaftlich/technische Ziel des Vorhabens ist die Definition eines Referenzkraftwerkes für die nächste Generation von Salzturmkraftwerken. Hierzu wird die Kraftwerkstechnik aus technischer und ökonomischer Sicht optimiert.

Zur Erreichung dieser übergeordneten Ziele werden im Einzelnen die folgenden wissenschaftlich/technischen Ziele verfolgt:

- gemeinsame Machbarkeitsstudie von Industrie und Wissenschaft: Kompetenz-Bündelung und Heben von Synergie-Effekten
- Referenz für zukünftige CSP-Projekte / Ausschreibungen
- Referenz für Entwicklung und Vermarktung von Komponenten
- Fokussierung, Schaffung kritischer Stückzahlen für Komponenten (Heliostaten, Receiver, TES-Komponenten, …)
- Außenwirkung, Förderung der Kooperation von CSP-Unternehmen & Wissenschaft, Unterstützung im Markt / Markteintritt
- Auf Basis der Anlagenkonzepte wird ein Gesamtprozessmodell erstellt. Dieses wird als Basis für energetische Jahresertragsberechnungen genutzt und um anschließend wirtschaftliche Betrachtungen durchzuführen.
- Techno-ökonomische Analyse zur optimalen maximalen Prozesstemperatur des solaren Hochtemperaturkreislaufes. Erarbeitung eines optimierten Anlagenkonzeptes für Solarturm.
- Technische Risikoanalyse der eingesetzten Komponenten im Anlagenkonzept.
- Bewertung der „Bankability“ der Anlagenkonzepte.

3. Voraussetzungen für das Vorhaben

Die folgenden Abschnitte beschreiben die beteiligten Projektpartner und die von ihnen bei der Durchführung geleiteten Arbeitspakete. Da es sich um ein Verbundvorhaben handelt und die Arbeitspakete in der Regel nicht von einem einzelnen Projektpartner bearbeitet wurden, heißt das nicht, dass jeweils die anderen Partner nicht in den betreffenden Arbeitspakten involviert waren.

Deutsches Zentrum für Luft und Raumfahrt e.V. (DLR)
Es waren zwei DLR Institute an dem Projekt beteiligt, das Institut für Solarforschung und das Institut für Technische Thermodynamik.
Das **Institut für Solarforschung** gehört zu den international führenden Forschungs- und Entwicklungsinstitutionen im Bereich solarthermischer Kraftwerke. An den Standorten Köln, Stuttgart, Almeria und Jülich arbeiten derzeit etwa 120 Angestellte an der Weiterentwicklung konzentrierender Solartechnologien. Neben der Technologieentwicklung werden Marktstudien, Wirtschaftlichkeits- und Machbarkeitsstudien für solarthermische Kraftwerke in der Mittelmeerregion durchgeführt. Weiterhin betreibt das Institut eigene Versuchsanlagen, u. a. das Solarturm-Versuchskraftwerk in Jülich. Das DLR koordiniert das Projektkonsortium HPS 2 zur Erstellung der Flüssigsalz-Versuchsanlage in Evora.
Das **Institut für Technische Thermodynamik** des DLR in Köln, Stuttgart und Ulm, arbeitet an der Nutzbarmachung von hocheffizienten Energiewandlungstechnologien und an technischen Lösungen zur Einführung erneuerbarer Energieträger. Technologien zur Hochtemperaturwärmespeicherung sind dabei einer der Entwicklungsschwerpunkte. Dies beinhaltet die Entwicklung von Flüssigsalzspeichern inkl. der relevanten Materialfragestellungen.
Das DLR hatte die Gesamt-Projektleitung, sowie die Leitung der folgenden Arbeitspakete:

- AP 1: Projektkoordination
- AP 4: Techno-ökonomische Analyse
- AP 6: Roadmap und Berichtsfassung

MAN Energy Solutions SE (MAN)
MAN Energy Solutions SE gehört zu den Weltmarktführern von Solar-Dampfturbinen. In den letzten Jahren wurden mehrere Dampfturbinen für Parabolrinnen-Anlagen, wie z. B. ANDASOL 3, sowie direktverdampfende Systeme realisiert. In verschiedenen Forschungsprojekten engagiert sich MAN Diesel & Turbo seit Jahren innovativ auf dem Gebiet der Solarforschung. Zudem ist MAN Technologieführer in der flüssigsalzbasierten Verfahrenstechnik und verfügt zudem über Jahrzehnte lange Erfahrung im Kraftwerksbau und technischen Betrieb, sowohl als Equipment Lieferant, als auch als Generalunternehmer (EPC).
MAN hatte die Leitung der folgenden Arbeitspakete:

- AP 3.2: Betriebskonzept
- AP 3.3.3: Receiver
- AP 3.3.4: Wärmeträgerkreislauf

AP 3.3.6: Speicher
AP 3.3.7: Turbine / Kreislauf
AP 3.3.8: BOP

sbp sonne GmbH (SBP)
schlaich bergermann partner (sbp) ist seit über 30 Jahren im Bereich der solarthermischen Kraftwerke aktiv, insbesondere in den Bereichen Parabolrinnen und Turm-Solarkraftwerke. Seit 2007 sind die Solaraktivitäten in der sbp sonne GmbH gebündelt. Zu den Entwicklungen des Büros sbp gehören EuroTrough, HelioTrough, UltimateTrough und der Stellio Heliostat. sbp sonne hatte die Leitung des folgenden Arbeitspakets.
AP 3.2.2: Heliostatenfeld

Steinmüller Engineering GmbH
Bereits in den 1980er Jahren forschte und entwickelte LCS an volumetrischen Receivern für Solarturmkraftwerke (Projekt PHOEBUS). Dieses Wissen wurde nach 2003 durch ehemalige LCS Mitarbeiter bei SE im Rahmen von weiteren Forschungsprojekten gemeinsam mit dem damaligen Mutterkonzern Siemens weiter ausgebaut.
Des Weiteren wurde von SE ein Zwangsdurchlaufdampferzeuger für das HPS2 Forschungsprojekt in Evora, Portugal ausgelegt und geliefert. Neu an diesem Projekt ist die Verwendung von Flüssigsalz sowohl als Speichermedium als auch als Wärmetransportmedium in Parabolrinnenkraftwerken. Durch die höheren Temperaturen (~560 °C) verglichen mit Thermalölen können so höhere Wirkungsgrade erzielt werden. Der von SE entwickelte Zwangsdurchlaufdampferzeuger weist gegenüber den üblicherweise in solarthermischen Kraftwerken verwendeten Naturumlauf-Dampferzeugern verschiedene Vorteile auf. So sind beispielsweise höhere Dampfparameter und flexiblere Lastwechsel mit dem Zwangsdurchlaufkonzept möglich.
Steinmüller hatte die Leitung des folgenden Arbeitspakets.
AP 3.3.5: Dampferzeuger und Hybridisierung

Tractebel Engineering GmbH
Tractebel Engineering (ehemals Lahmeyer International) bietet als unabhängiges Ingenieurunternehmen ein breites Spektrum an Planungs- und Beratungsleistungen. Schwerpunkt der Tätigkeiten sind komplexe Infrastrukturprojekte in den Bereichen Energie, Wasser und Wasserkraft sowie Bau und Verkehr. Tractebel Engineering ist eines der führenden, international operierenden Ingenieurunternehmen mit Projekterfahrung in 165 Ländern der Welt.
Tractebel Engineering seit drei Jahrzehnten im Bereich der Erneuerbaren Energien. In CSP ist Tractebel Engineering seit 1996 aktiv, insgesamt hat Tractebel Engineering an über 30 solarthermischen Kraftwerksprojekten mitgearbeitet.

Tractebel Engineering hatte die Leitung der folgenden Arbeitspakete:

- AP 2: Bedarfsanalyse
- AP 3.3.1: Baugewerke
- AP 3.3.8: BoP
- AP 5: Risikoanalyse und Bankability
- AP 6: Roadmap

Zum Zeitpunkt der Antragstellung und auch noch zum Zeitpunkt der Bewilligung war Innogy SE als assoziierter Partner im Projekt vorgesehen und wäre für die Leitung von AP 2 (Bedarfsanalyse) und AP 3.3.1 „Bauarbeiten“ zuständig gewesen. Im Mai 2019 musste Innogy SE allerdings die Beteiligung am Projekt absagen, da interne Umstrukturierungen und eine Neuausrichtung es nicht erlaubten. Die Aufgaben, die für Innogy SE im Projekt vorgesehen waren, wurden auf die verbliebenen Partner aufgeteilt.

4. Planung und Ablauf des Vorhabens

Die Projektpartner haben ihre Bewilligungsbescheide im Februar 2019 erhalten und der formale Projektbeginn war laut Bescheid am 1.3.2019.
Das Kickoff-Meeting fand am 16.5.2019 in Köln statt. Im Juni 2020 wurde eine kostenneutrale Verlängerung der Laufzeit bis zum 31.12.2020 beantragt, die vom Projektträger bewilligt wurde.
Die Gründe für die Verlängerung waren:

- Der Projektstart erfolgte mit Verzögerung, unter anderem auch weil die Mitwirkung des assoziierten Partners Innogy unklar war.
- Die für die Bearbeitung notwendigen Mitarbeiter waren bei einigen Partnern nur eingeschränkt verfügbar. Die Gründe dafür waren vielfältig und meist nicht vorhersehbar (andere parallellaufende Projekte, Mitarbeiterwechsel, Elternzeit, etc.)
- Die Bearbeitung der Unter-Arbeitspakete 3.3.x dauerte länger, als ursprünglich geplant.
- Schließlich hat die „Corona-Krise“ ab März 2020 ein Aufholen der Verzögerungen erschwert.

Abbildung 1 und Abbildung 2 zeigen den Projektplan in der ursprünglichen Fassung bzw. in der aktualisierten Fassung vom Juni 2020.

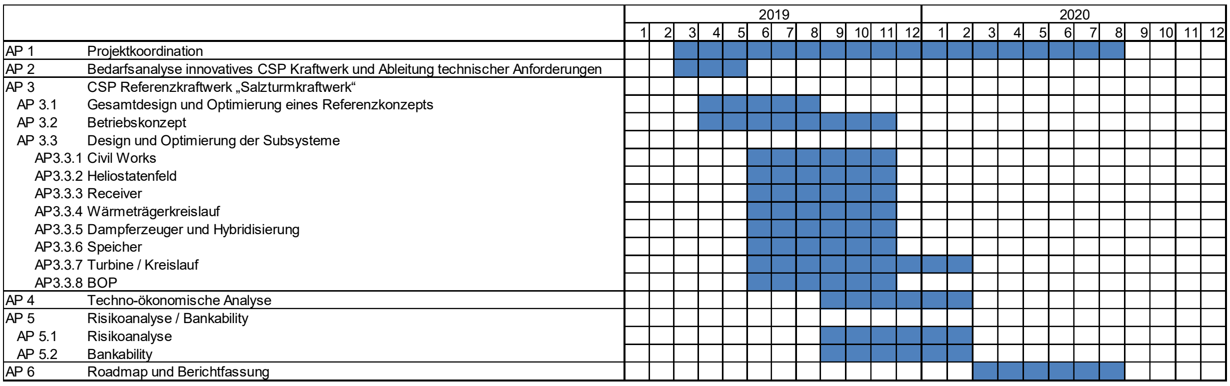

Abbildung 1: Zeit- und Arbeitsplan zum Zeitpunkt der Bewilligung

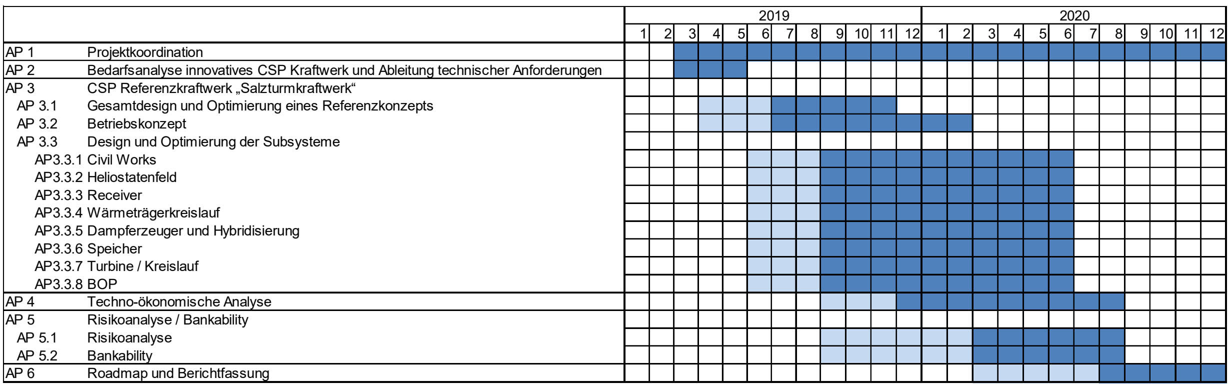

Abbildung 2: Angepasster Zeit- und Arbeitsplan nach Verlängerung der Laufzeit

5. Wissenschaftlicher Stand, an den angeknüpft wurde

Obwohl die Mehrzahl der bis heute realisierten solarthermischen Kraftwerke die Parabolrinnentechnologie einsetzen, steht die Solarturm-Technologie mit Flüssigsalz als Wärmeträger- und Speichermedium kurz vor der breiten Markteinführung. Diese Systeme bieten durch das integrierte Speicherkonzept eine äußerst attraktive Wirtschaftlichkeit. Zudem wird durch die thermischen Speicher mit hoher Kapazität erreicht, dass die Anlagen bedarfsgerecht Strom erzeugen können und diese hohe Solaranteile selbst bei Grundlastbetrieb erreichen können. Somit tragen diese Systeme einen entscheidenden Beitrag zum Aspekt der Versorgungssicherheit und der Ressourcenschonung (geringe CO_2-Emissionen) bei.

Wie alle solarthermischen Kraftwerke nutzen Salztürme konzentrierte Solarstrahlung, um Wärme bei hohen Temperaturen zu erzeugen und konventionelle Wärmekraftwerke, um diese Wärme in Strom zu wandeln. In Abbildung 3 ist der schematische Aufbau eines Salzturmkraftwerkes mit seinen wichtigsten Komponenten dargestellt. Hierzu gehören Heliostatenfeld, Turm mit Receiver, Wärmeträgerkreislauf, thermischer Speicher und der konventionelle Power Block. Jedes dieser Komponenten trägt durch seinen Teilwirkungsgrad entscheidend zum Gesamtwirkungsgrad und somit zur Wirtschaftlichkeit des Kraftwerkes bei. Während beim konventionellen Teil (Dampferzeuger und Dampfturbine) nur noch eine moderate Wirkungsgradsteigerung möglich ist, beinhaltet das System Heliostatfeld-Receiver-solarer Hochtemperaturkreislauf bei einer gesamtheitlichen Optimierung noch ein enormes Verbesserungspotential. Wie aus Abbildung 3 ersichtlich, trennt das Speichersystem den hochdynamischen solaren Teil vom konventionellen Teil durch das Speichersystem. Durch die direkte Speicherung der heißen Salzschmelze ist es hierdurch möglich die Systeme entkoppelt zu optimieren.

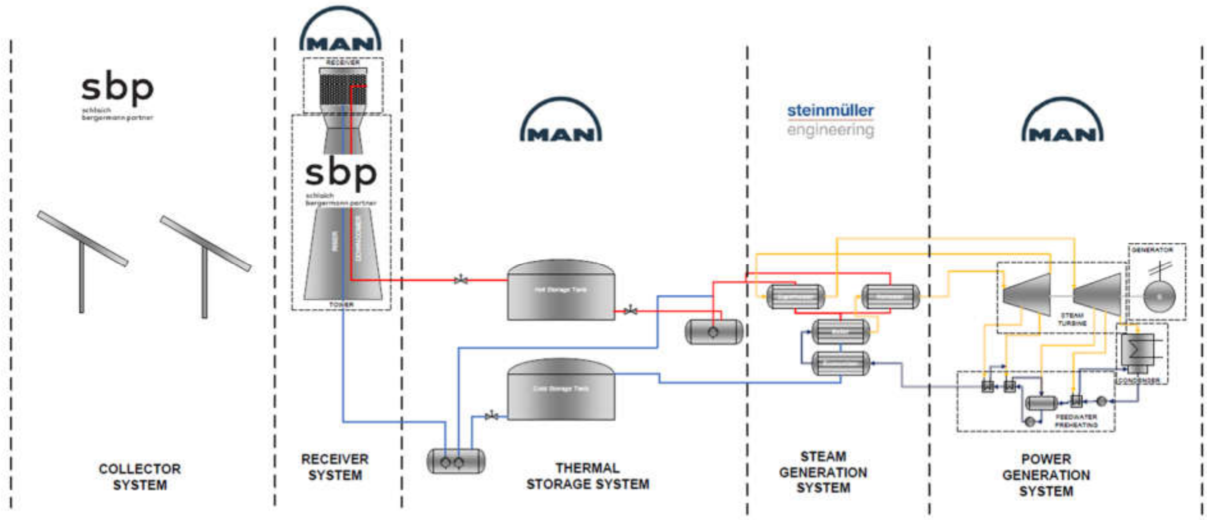

Abbildung 3: Schematischer Aufbau eines Salzturmkraftwerkes und Zuständigkeit der einzelnen Projektpartner

Im Bereich der Salztürme wurden bereits 3 Demonstrationsanlagen errichtet:

- *MSEE* (Molten Salt Electric Experiment) am CRTF (Central Receiver Test Facility) mit 750 kW_{el} elektrischer Leistung in Albuquerque, USA, Inbetriebnahme 1983
- *THEMIS* mit 2 MW_{el} elektrischer Leistung in Targasonne, Frankreich, Inbetriebnahme 1984
- *Solar Two* mit 10 MW_{el} elektrischer Leistung in Barstow, USA, Inbetriebnahme 1996

Die Entwicklungen, der Bau und der Betrieb dieser Anlagen haben den Weg für die kommerzielle Nutzung dieser Technologie bereitet. Die erste kommerziell genutzte Anlage ging im April 2011 in Spanien ans Netz (Solar Tres bzw. jetzt: Gemasolar mit ca. 20 MW_{el}). In China wurde 2016 die 10 MW Anlage von Supcon in Betrieb genommen, gefolgt von einer 50 MW Anlage in unmittelbarer Nachbarschaft, die seit Ende 2019 am Netz ist.
Das erste große kommerzielle Salzturmkraftwerk (Crescent Dunes von Solar Reserve mit 120 MW_{el}) wurde nach einer langen Inbetriebnahmephase mittlerweile wieder von Netz genommen, weil es wegen technischer Probleme, vor allem mit den Salztanks, die Ertragserwartungen nicht erfüllen konnte.
Die Anlage Cerro Dominador in Chile (110 MW), mit deren Bau bereits in 2014 begonnen wurde, wird aktuell fertig gestellt, nachdem der Bau von 2016 bis 2018 pausierte.
Die aktuelle Technologie erreicht Salztemperaturen bis 565°C. Oberhalb dieser Temperatur setzen Degradationseffekte der Salzmischung ein. Auf der Agenda zur Weiterentwicklung dieser Technologie steht auch eine Temperaturerhöhung, was zur Erhöhung der Effizienz und somit ggfs. der Wirtschaftlichkeit dient. Die schrittweise Anhebung der Dampfparameter war bereits in der Vergangenheit bei den konventionellen, fossil betriebenen Kraftwerken zu beobachten, um die Effizienz und die Wirtschaftlichkeit zu erhöhen. Derzeit arbeiten die modernsten überkritischen Dampfprozesse mit einer Frischdampftemperatur von ca. 620°C. Um diese Kraftwerksprozesse für solarthermische Kraftwerke zu nutzen, müssten die Salztemperaturen auf ca. 650°C angehoben werden. Bei diesen Temperaturen müssen die Eignung und die Degradation der Salzmischungen, die Materialfragen für z.B. solare Receiver und thermische Speicher sowie grundsätzliche systemanalytische Fragestellungen bearbeitet werden. Abgesehen von der Fragestellung, ob bei diesen Temperaturen ein geeignetes Wärmeträgermedium zur Verfügung steht, ist zurzeit nicht abschließend geklärt, ob diese Temperaturanhebung auch wirtschaftlich sinnvoll ist. In diesem Projekt wurde die Frage der Temperaturanhebung über 565°C nicht näher untersucht, weil sich die Projektpartner auf eine Anlage konzentrieren wollten, die kurzfristig Chancen auf eine komerzielle Realisierung hat. Das erscheint bei den vielen offenen Fragen im Zusammenhang mit Salztemperaturen oberhalb von 600°C nicht wahrscheinlich.

6. Zusammenarbeit mit anderen Stellen

Die Deutsche Industrieverband Concentrated Solar Power (DCSP) wurde zweimal im Projektverlauf konsultiert. Am 25.11.2019 wurde das Projekt und die grundsätzliche Anlagenkonfiguration bei der DCSP Jahrestagung in Hamburg vorgestellt und am 21.09.2020 wurde ein Online-Workshop durchgeführt, bei dem die wesentlichen Ergebnisse des Projekts den DCSP-Mitgliedern vorgestellt und mit ihnen diskutiert wurden.

7. Durchgeführte Arbeiten

7.1. Bedarfsanalyse und Randbedingungen

Aufgrund der Kostendegression, die bei PV-Kraftwerken in den letzten 10 Jahren stattgefunden hat, stellen diese zurzeit die günstigeste Option zur Erzeugung von solarer elektrischer Energie dar. Das gilt zunächst für die unmittelbare Nutzung, ohne Speicher. Aufgrund der kostengünstigen großen thermischen Speicher werden solarthermische Kraftwerke daher in Zukunft eher für die Stromerzeugung in den Abend- und Nachtstunden eingesetzt werden, um einen möglichst hohen Anteil an solaren Deckungsgrad in Kombination mit einer planbaren Erzeugung zu gewährleisten.
Daher wurden für das Referenzkraftwerk zwei grundsätzliche Betriebsszenarien angenommen:

1. Die Stromproduktion startet etwa zum Sonnenuntergang und die Anlage läuft etwa mit Nennleistung bis zu Sonnenaufgang am nächsten Tag, soweit der Speicherinhalt dafür ausreicht (**Nachtbetrieb**)
2. Die Stromproduktion startet etwa zum Sonnenuntergang und die Anlage läuft bis Mitternacht, wenn der Speicherinhalt dafür ausreicht (**Peaker-Betrieb**)

Viele weitere Variationen dieser Szenarien sind denkbar aber um die Zahl der zu untersuchenden Szenarien zu begrenzen, wurden sie auf diese beiden grundsätzlichen Betriebsweisen beschränkt.
Als Beispielstandort für das Referenzkraftwerk wurde Ouarzazate im Marokko ausgewählt, da sowohl der Breitengrad, als auch die Jahressumme der Direktstrahlung als typisch angesehen werden können.

7.2. Auslegung der Gesamtanlage und der Untersysteme

7.2.1. Auslegung der Gesamtanlage und grundsätzliche Vorgehensweise

Die Analyse der neueren CSP-Projekte hat ergeben, dass eine typische Anlagengröße etwa zwischen 100 und 200 MW elektrischer Nennleistung liegt. Sbp sonne GmbH hat im Rahmen einer Voruntersuchung festgestellt, dass ein Heliostatfeld von etwa 1.5 km² Apertur Fläche an guten Standorten (bzgl. Direktstrahlung und atmosphärischen Bedingungen) zu minimalen spezifischen Kosten führt. Zu einem solchen Solarfeld passt ein Salzreceiver mit einer thermischen Nennleistung von 700 MW.
In ähnlicher Weise hat der Projektpartner MAN herausgefunden, dass eine Turbine von 200 MW elektrischer Nennleistung gegenüber kleineren Maschinen die niedrigeren spezifischen Kosten aufweist. Diese Nennleistung stellt gleichzeitig die größte Nennleistung dar, die MAN Turbinen liefern können, wenn diese Maschinen für ein tägliches An- und Abfahren geeignet sein müssen (eine essentielle Forderung an Turbinen für CSP-Kraftwerke).
Einige erste Jahresrechnungen für den ausgewählten Standort haben daraufhin ergeben, dass die Grundkonfiguration zusammen mit einem Speicher für etwa 12 Volllaststunden

geeignet für den Nachtbetrieb wäre und bei Verwendung von 2×200 MW Kraftwerksblöcken für den Peaker Betrieb.
Daher wurden diese Grundkonfigurationen festgelegt und die Untersysteme zusammen weiter optimiert, um die endgültige Auslegung zu erhalten. Die techno-ökonomische Analyse wurde dann schließlich eingesetzt, um die Speichergröße festzulegen, die zu den niedrigsten Stromgestehungskosten für den jeweiligen Betriebsmodus führt.

7.2.2. Heliostatfeld

7.2.2.1. Schnittstellen

Die Heliostaten beziehungsweise das Heliostatenfeld haben die folgenden wichtigen Schnittstellen zu den Nachbarsystemen und der Umgebung.

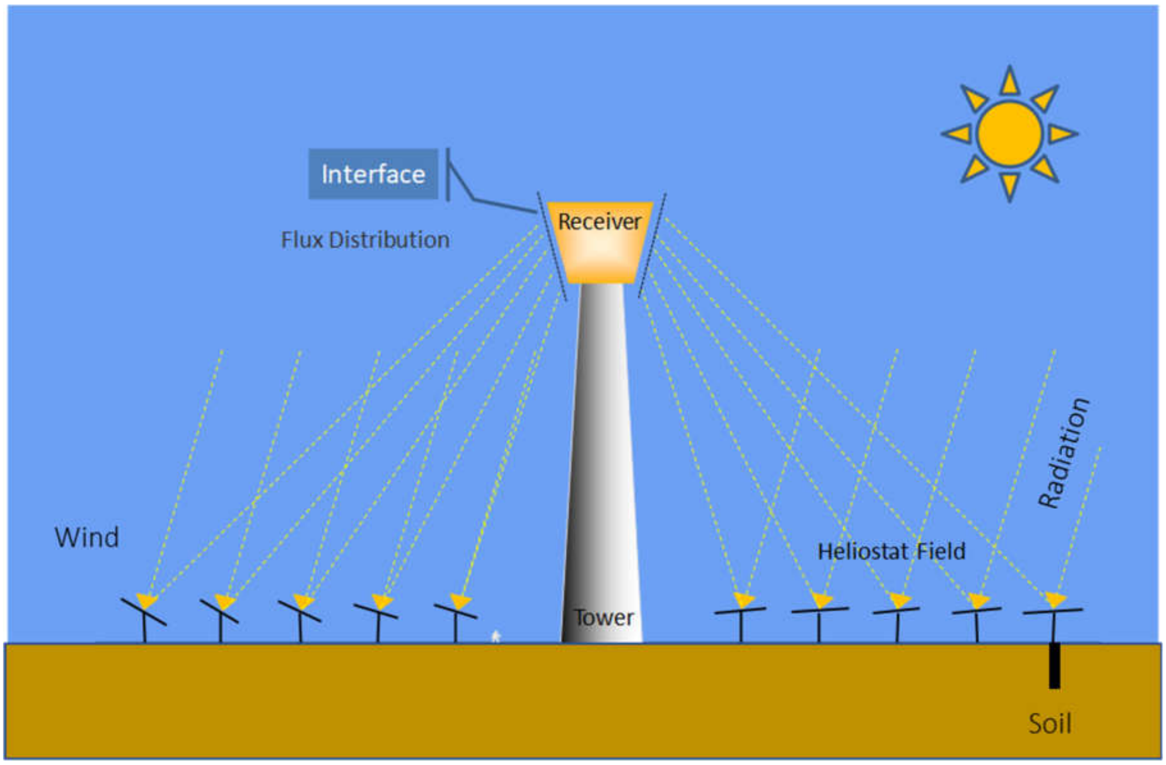

Abbildung 4: Schnittstellen des Heliostatenfeldes

Die Schnittstellen zur Umgebung sind Boden, Atmosphäre, Wind und Strahlung. Für die Auslegung des Heliostaten selbst sind diese Randbedingungen vor Ort ausschlaggebend. Für die Auslegung und Optimierung des Heliostatenfeldes und des Betriebs sind die wichtigsten Schnittstellen die physikalischen Oberflächen des Receivers (+ Hitzeschild + Turmstruktur) sowie die Anbindung an das Leitsystem.

7.2.2.2. Mindestanforderungen an den Heliostaten:

Folgende Mindestanforderungen wurden definiert für das Referenzkraftwerk:

- Refelktivität > 0,93
- Optische Fehler kleiner als:

3-s-Boe (m/s @ h = 10 m)	**Tracking error (1D, RMS, mrad)**	**Slope error (1D, RMS, mrad)**
0	0.5	1.07
4	0.5	1.28
12	1.4	1.5

- Go to Stow < 10 Minuten
- Verfügbarkeit > 0,99

Für das CSP-Referenzkraftwerk wurde ein dem Stand der Technik entsprechender Stellio-Heliostat für die Auslegung verwendet. Der Stellio-Heliostat wurde von sbp und Partnern im Stellio-Konsortium entwickelt (Keck, et al., 2020).
Die oben genannten Anforderungen, die für diesen Bericht verwendet werden, basieren auf der Verwendung des Stellio Heliostat.

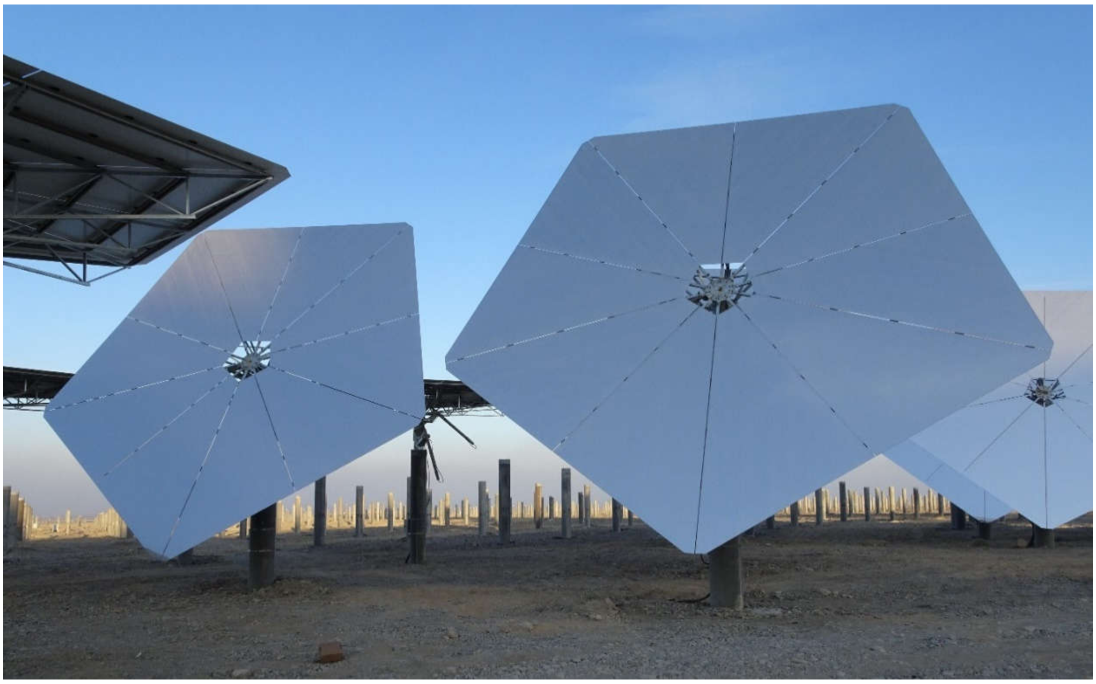

Abbildung 5: Referenzheliostat Stellio (Kraftwerk Hami, China)

7.2.2.3. Heliostatenfeldoptimierung

Heliostaten-verschiedener Anbieter unterscheiden sich in Parametern wie Größe, Achsenorientierung, Leistungsbedarf, optische Leistung, Eigenschaften der Zielstrategie und mehr. Auch die Receiver verschiedener Anbieter unterscheiden sich stark in Leistung und

Geometrie. Daher ist es ratsam, eine Optimierung der Solarfeld-/ Receiver-Konfiguration durchzuführen, um die spezifizierte Leistung mit möglichst geringen Kosten zu erreichen.

Zunächst muss das Optimierungsziel festgelegt werden. Typische Ziele sind minimale Stromgestehungskosten (Levelized Cost of Electricity, LCoE) oder maximaler Wert des Stroms unter Berücksichtigung der Stromlieferzeiten.

Die folgenden Anlagenparameter müssen in Bezug auf das Heliostatenfeld optimiert werden:

- Feldfläche (-> Grundstückskosten, Turmhöhe, Visibility)
- Heliostatengeometrie, Design und optische Qualität (Stellio wurde für große Kraftwerke optimiert)
- Höhe und Durchmesser des Receivers
- Zulässige Strahlungsflussdichte auf dem Receiver sind abhängig von Receiver-Panels, Lastfaktor und Wind.
- Ausmaß des Dumpings (high und low entsprechend der minimalen und maximalen thermischen Receiverbelastung)

Beispielhaft werden in Abbildung 6 die jährlichen Energieerträge von Konfigurationen mit unterschiedlichen Turmhöhen und Receivergrößen beziehungweise zulässiger maximaler Strahlungsdichten gezeigt. Anhand derartiger Untersuchungen wurde die Konfiguration für das Referenzkraftwerk abgeleitet.

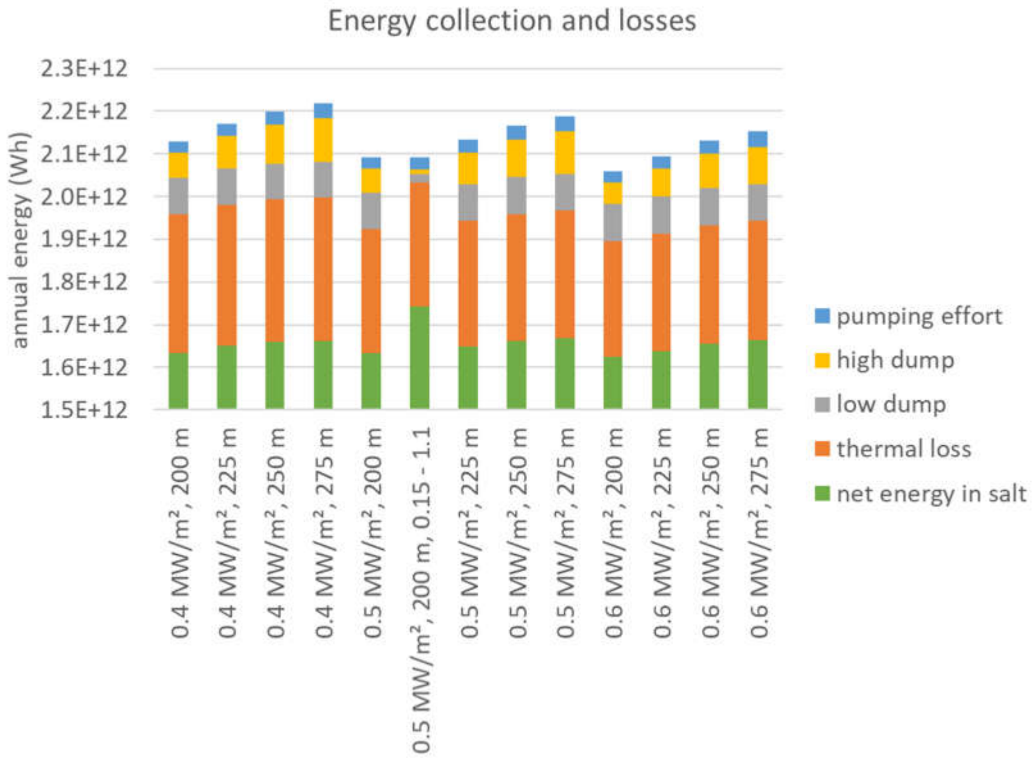

Abbildung 6: Optimierung von Turmhöhe und Receivergrößen (erlaubte maximale Strahlungsflussdichte)

7.2.2.4. Heliostatenfeldspezifikationen für das Referenzkraftwerk

Die vollständigen Design Spezifikationen sind in der englischen Fassung des Berichtes zu finden

No.	Spezifikations	Unit	Value	Remark
	Heliostat			
1.	Heliostat Type	[-]	2-axes trackingachsiger multi facet glass-metal Heliostat, mounted on pylon	Stellio
2.	Apertur width	[m]	~ 9 m	
3.	Apertur height	[m]	~ 9 m	
4.	Number of mirrors per heliostat	[-]	10 + 1	horizontal x vertical
5.	Reflektive area of single mirror	[m²]		
6.	Optical height (Pylon)	[m]	~4.5	Center of heliostat
7.	Total reflektive area per heliostat	[m²]	48.5017	
8.	Reflectivity HFLCAL (annual mean)	[%]	89.34	HFLCAL input as product of reflectivity, cleanliness, availability: 0,94*0,96*0,99
9.	Beam quality	[mrad]	3.664	HFLCAL input as sum of slope error, tracking error, sun shape error
10.	Canting	[-]	On-axis	
11.	Electricity consumption tracking	[kW]	~0.02	Demand of single heliostat
12.	Slope error	[mrad]	1.06	1 dim, v_wind < 4 m/s
13.	Tracking error	[mrad]	0.6	V_wind < 4 m/s
14.	Root mean square deviation of sun-shape	[mrad]	2.23	

			V1.1	
No.	**Spezification**	**Unit**	**Value**	**Remark**
	Solar field			
	Solar Multiple (SM)	[-]	1.5	
1.	Shape	[-]	360°	Sur.: 360°; N / S: North- / Southfield
2.	Number of Heliostats	[-]	30'927	1.5 km² net mirror area
3.	Optical efficiency @DP	[%]	66.9	
4.	Electricity consumption tracking	[kW_{el}/m^2]		
5.	Distance tower – first row	[m]	100	Abstand vom Mittelpunkt zu erster Reihe (RTURM)
6.	Land usage	[km²]	7.36	

Abbildung 7: Heliostatenfeldspezifikationen für das Referenzkraftwerk

7.2.3. Receiver

Wichtige Designgrößen für die Receiverauslegung sind: Die zulässige Flussdichte, Materialauswahl, Teillast-Zustände, Investitions- und Betriebskosten, Fertigungs- und Montagekonzept sowie eine einfache Wartung. Der 700 MW Receiver wird in einem Salztemperaturbereich von 290 °C bis 565 °C betrieben.
Eine Design-Studie ist mit neun verschiedenen thermo-hydraulischen Konzepten durchgeführt worden. Dabei wurde der thermische Wirkungsgrad den Fertigungskosten gegenübergestellt und letztendlich ein finales Receiverkonzept ausgewählt. Dieses Konzept ist bzgl. verschiedenster techne-ökonomischer Parameter, wie Druckverlust, Konstruktionsaufwand, Haltbarkeit, Lebensdauer und Transport zur Baustelle optimiert. Reale Wetterdaten vom Standort Ouarzazate in Marokko bilden die Basis für die Bestimmung der zulässigen Flussdichte (vgl. Abbildung 8).

Der Receiver setzt sich aus zwei Strömungswegen mit je vier seriell durchströmten Panels zusammen. Die Panels bestehen aus 23 m langen Absorberrohren und weisen eine Breite von 7,2 m auf. Diese Panels werden mit einer mittleren Flussdichte von 536 kW/m² bestrahlt und auf der Salzseite mit 3,4 m/s durchströmt.
Der analytische Ansatz zur Bestimmung der zulässigen Flussdichte ist durch eine Kriech-Ermüdungs-Bewertung nach ASME BPVC Section III (Nuklear Code) validiert worden. Dazu ist ein 2 m langes Rohrsegment mit der entsprechenden Flussdichte beaufschlagt und die sich einstellenden Temperaturen berechnet worden.

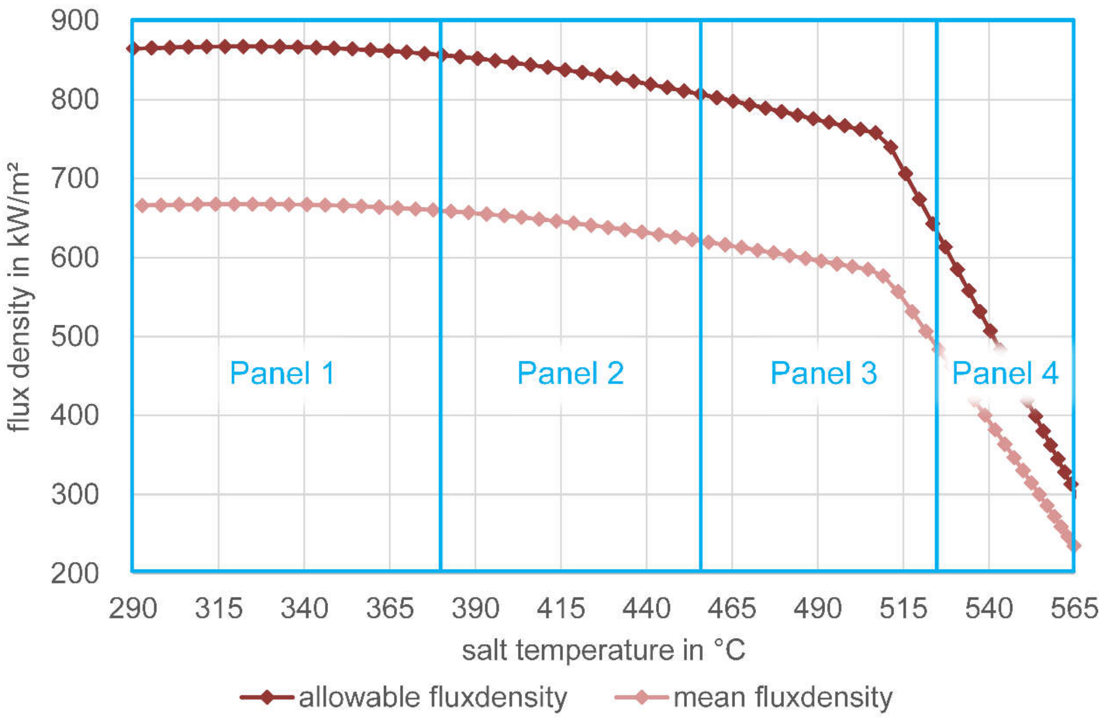

Abbildung 8: Zulässige und mittlere Flussdichte entlang des Strömungspfades

Um Ermüdungs- und Kriecheffekte hinreichend genau bewerten zu können, sind drei verschiedene Salzeinlasstemperaturen (290 °C, 506 °C und 518 °C) betrachtet worden. Aus den numerisch bestimmten Temperaturen, Dehnungen und Spannungen ist dann über den Ansatz der linearen Schadensakkumulation die Schädigung durch Ermüdung, Kriechen und Kriech-Ermüdungs-Interaktion bewertet worden. Die Konservativität des Berechnungsansatzes nach dem ASME Nuklear Code ist dabei reduziert worden, da das Schädigungspotential von solaren Anlagen deutlich geringer bewertet wird, als von nuklearen Anwendungen. Aus der numerischen Analyse wird deutlich, dass der Kriechanteil nicht zu vernachlässigen ist und ebenfalls zur Bauteilschädigung beiträgt. Weitere Untersuchungen mit einer detaillierter aufgelösten Receivergeometrie und einem verfeinerten Berechnungsansatz werden hierzu für einen sicheren Betrieb und die finale Festlegung der Wartungsintervalle der Anlage noch durchgeführt.

7.2.3.1. Betriebszustände und Übergänge

In dem unten dargestellten Petri-Diagramm sind die einzelnen Betriebszustände und die Schrittketten abgebildet. Das Hochfahren der Anlage erfolgt in folgenden Schritten: Mit den Begleitheizungen werden die Leitungen und Behälter auf 290 °C vorgeheizt. Anschließend werden 2 von 6 Kaltsalzpumpen angefahren und das Steigrohr gleichzeitig mit dem Fallrohr geflutet, bis im Einlasstank der vorgegebene Füllstand erreicht wird. Dann werden die Ventile so umgestellt, dass sich die Strömungsrichtung im Fallrohr umkehrt. Kaltes Salz wird durch den Salzkreis inkl. Receiver-Bypass zurück in den Kaltspeichertank gefördert. Die

Receiveröfen (Begleitheizungen der Header) werden aktiviert, sodass die Header auf 290 °C vorgewärmt werden. Die Heliostaten werden aus der Ruheposition in die Standby-Stellung gefahren. Anschließend werden einzelne Heliostaten fokussiert, sodass die Absorberrohre gleichmäßig und schrittweise auf 350 °C vorgeheizt werden. Danach wird zunächst der Druck im Einlasstank erhöht (niedriger als Betriebsdruck) und anschließend die Receiverventile geöffnet, sodass die Receiver-Panels mit Salz geflutet werden. Die Drainageventile werden geschlossen, sodass sich ein Serpentinenstrom einstellt. Zuletzt wird der Druck im Einlasstank auf Betriebsdruck erhöht. Das Salz fließt weiterhin zurück in den Kaltspeichertank. Ab diesem Zeitpunkt darf die Flussdichte erhöht werden, indem mehr Heliostaten auf den Receiver fokussiert werden. Es wird auf eine Auslasstemperatur von 565 °C geregelt. Ab einer Temperatur von 470 °C im Auslasstank wird das Salz in den Heißspeichertank gefördert. Die Anlage wird durch Verringerung der Flussdichte und Einleiten der Drainage in den Anfangszustand abgefahren.

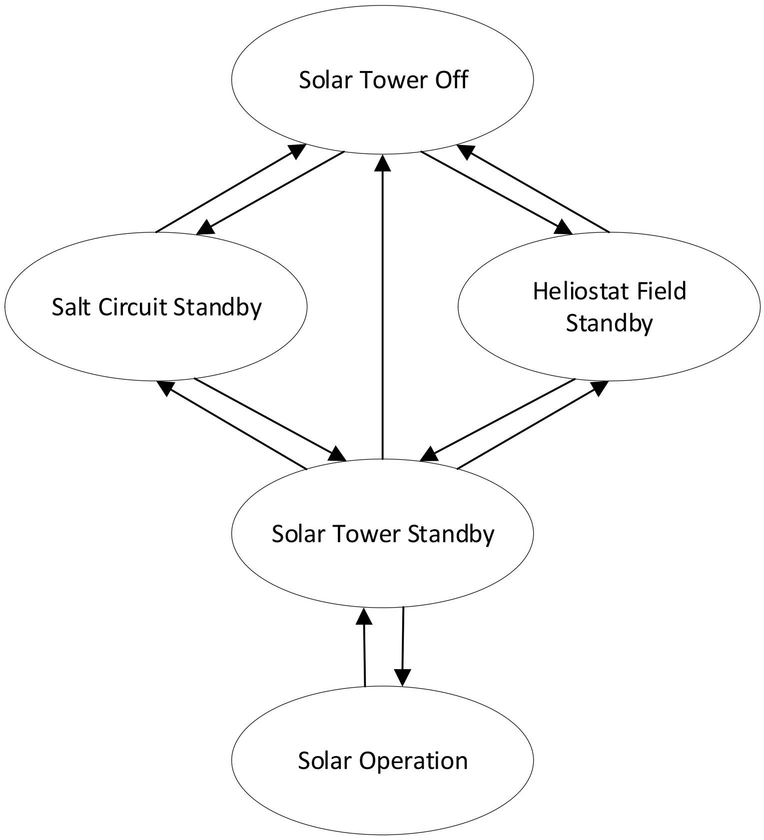

Abbildung 9: Betriebszustände Receiver

7.2.4. Speicher

Das 2-Tank-Speichersystem umfasst einen Kalttank, der Salz bei 300 °C aus dem Dampferzeuger speichert und den Solarturm-Receiver versorgt. Die Auslegungstemperatur des Tanks beträgt 400 °C. Um ein gutes Teillastverhalten des Solarreceivers zu erreichen, ist es notwendig, den Kalttank mit fünf Salzpumpen auszustatten. Der Heißtank, der für Temperaturen bis zu 593 °C ausgelegt ist, speichert heißes Salz aus dem Receiver und liefert

heißes Salz an das Dampferzeugersystem. Jeder Heißtank ist mit drei Pumpen ausgestattet, die jeweils 25 % des nominalen Salzmassenstroms fördern können.
Aufgrund der Korrosivität von geschmolzenem Salz ist die Materialauswahl für Tanks und Rohrleitungen sehr wichtig. Geschmolzene Nitratsalze beginnen sich bei Temperaturen über 370 °C zu zersetzen. Bis zu Temperaturen von 450 °C wird Kohlenstoffstahl verwendet. Oberhalb von 450 °C muss auf Edelstahl umgestellt werden, um die Korrosionsraten zu reduzieren. Neben der thermischen Zersetzung des Solar Salzes hat auch der Chloridgehalt des Salzes selbst einen Einfluss auf die Korrosionsrate. Danach sollte der Chloridgehalt unter 100 ppm liegen.
Verschiedene Werkstoffe wurden in der Vergangenheit hinsichtlich des Korrosionsverhaltens in isothermen Versuchen bis zu Temperaturen von 565 °C untersucht. Oberhalb von 450 °C müssen austenitische Stähle verwendet werden, um die Korrosionsraten zu reduzieren. Werkstoffe wie 316Ti, 321H, 347 zeigen eine gute Korrosionsbeständigkeit unter statischen Bedingungen. Für Temperaturen unter 450 °C ist die Korrosionsrate sehr langsam, so dass ferritische Stähle verwendet werden können. Hier ist der SA 204 Grade B eine sehr gute Wahl. Die folgende Tabelle zeigt die Abmessungen der Tanks:

Tabelle 1: Salztankabmessungen

	Kalttank	**Heißtank**
Anzahl	1	2
Außendurchmesser	59.6 m	44.3 m
Mantelhöhe	12.5 m	12.5 m
Max. Füllhöhe	11 m	11 m
Min. Füllhöhe	1 m	1 m

7.2.4.1. Hauptkomponenten

Die Salztanks sind mit elektrischen Einsteckheizern ausgestattet, die sich unterhalb des Mindestsalzspiegels befinden. Die Heizer sind innerhalb der Ummantelungen 0,4 m über dem Tankboden angebracht. Die Ummantelungen erstrecken sich radial in das Innere der Tanks und sind ordnungsgemäß am Tank befestigt. Alle notwendigen Elemente zur Sicherung der Ummantelungen sind vorhanden. Im Betrieb kann die Temperatur im Inneren der Ummantelung 400 ºC überschreiten.
Die Salzpumpen sind vertikale Kreiselpumpen mit langer Welle (ca. 15 m Länge), die von oben in den Salztank eingebracht sind. Die Kaltsalzpumpen werden verwendet, um das 290 ºC heiße Salz in den Einlasstank des Recievers zu fördern.
Es sind sechs Kaltsalzpumpen (6 mal 20 %) und je nach Betriebsart vier oder sechs Heißsalzpumpen auf einer abgestützten, vom Tank unabhängigen Plattform installiert, die sich in einer Höhe von etwa 16 m befindet.

Jede der Kaltsalzpumpen entspricht 20 % der erforderlichen Kapazität und liefert einen maximalen Massenstrom von 334 kg/s bei einer maximalen Förderhöhe von 305 m. Fünf der Pumpen werden in Betrieb sein, während die sechste in Reserve gehalten wird.
Jede der sechs/vier Heißsalzpumpen liefert 25 / 50 % (je nach Anlagengröße) der erforderlichen Leistung und fördert einen maximalen Massenstrom von 542 kg/s bei einer maximalen Förderhöhe von 40 m. Vier/zwei der Pumpen werden in Betrieb sein, während die restlichen in Reserve gehalten werden. Die Pumpen werden durch einen Elektromotor angetrieben und mittels Frequenzumrichter auf eine Salzautrittstemperatur nach Receiver von 565°C geregelt. Der Durchfluss der Heißsalzpumpen ist abhängig von der Nachfrage des Dampferzeugersystems.
Damit die Salzwärmeübertrager und Leitungen zu entleert werden können ist ein Drainagetank vorgesehen. Der Drainagetank ist einige Zentimeter über dem Boden angeordnet. Die salzführenden Leitungen haben ein Gefälle von min. 1 %, so dass ein drainieren sichergestellt ist. Der Tank ist durch Mineralwolle thermisch isoliert und mit einer redundanten elektrischen Begleitheizung mit gleichzeitiger Anschlussmöglichkeit ausgestattet.

7.2.4.2. Investitionskosten

Es wurden unterschiedliche Speichergrößen von diversen Herstellern angefragt. Die spezifischen Kosten liegen zwischen 2,5 und 4,2 €/kWhth. Die Speicher werden mit Steinwollmatten isoliert. Es wird zwischen der Isolierung des heißen und des kalten Tanks unterschieden. Der heiße Tank wird mit einer Dämmstärke von ca. 500 mm isoliert, während die Dämmstärke des kalten Tanks auf 350 mm reduziert wird. Die spezifischen Kosten der Isolierung liegen bei ca. 1100 €/m³ für den Warmtank und 1000 €/m³ für den Kalttank. Insgesamt liegen die spezifischen Kosten bei etwa 0,7 €/kWhth. Einen typische Aufbau des Fundaments ist in der folgenden Tabelle dargestellt. Je nach Bodenbeschaffenheit können Variationen notwendig werden. Das Fundament enthält auch die Dämmung zum Erdreich. Die Kosten für das Fundament belaufen sich auf ca. 1,6 €/kWhth Grundfläche.
Generell unterscheidet sich die Hydraulik der Pumpen in Abhängigkeit von der Schachtlänge, da die Konstruktion und die Lagerung mit zunehmender Schachtlänge komplexer wird. Es können Wellenlängen bis zu 22 m gefertigt werden, jedoch ist zu beachten, dass bei längeren Wellen Änderungen in der Befestigung notwendig sind, um Vibrationen und Schwingungen zu vermeiden. Eine Reduzierung der Wellenlänge auf 15 m reduziert die Kosten um ca. 8 %. Damit liegen die spezifischen Kosten für die Pumpen in einem Bereich zwischen 1 und 1,5 €/kWhth. Die Kosten für das Wärmeträgersalz belaufen sich auf ca. 850 €/to. Hinzu kommen die Kosten für das Aufschmelzen des Salzes. Die spezifischen Kosten für das Schmelzen belaufen sich auf ca. 150 €/to. Nimmt man alle Kosten inklusive elektrischer Heizungen, Anlagenbilanz und Aufschlägen zusammen, liegen die spezifischen Kosten für das Speichersystem in einem Bereich zwischen 20 und 22 €/kWhth.

Tabelle 2: Aufbau des Fundaments

	Heißtank	**Kalttank**
Ziegel	250 mm	0 mm
Foamglas	400 mm	500 mm
Beton	50 mm	50 mm
Verdichteter Schotter	150 mm	150 mm
Sand	300 mm	300 mm

Tabelle 3: Kosten für Salzpumpen

Heißsalzpumpe 6 x 25 %	**Kaltsalzpumpe 6 x 20 %**
650.000 USD/Pump	500.000 USD/Pump

7.2.5. Salzkreislauf

Der Salzkreislauf verbindet den Receiver über die Speichertanks mit dem Dampferzeuger und der Turbine. Auf Basis der Turbinenauslegung ergibt sich eine untere Salztemperatur von 290 °C. Die obere Salztemperatur wird mit 560 °C festgelegt. Aus thermodynamischer Sicht ist eine höhere Salz und damit Dampftemperatur zwar sinnvoll, allerdings verringert sich aufgrund erhöhter Korrosionsraten die Lebensdauer, weshalb man aus wirtschaftlichen Gesichtspunkten auf eine weitere Erhöhung der Salztemperatur verzichtet.
Die Anzahl der Pumpen ergibt sich aus der Anzahl der Speichertanks, der vorgehaltenen Redundanz sowie der zu erfüllenden Teillastfälle. Der Receiver soll zwischen 15 % und 110 % betrieben werden. Somit werden 6 Kaltsalzpumpen vorgesehen. Die Förderhöhe bestimmt sich aus der Turmhöhe und dem Druck im Einlasstank. Aus den Druckverlusten auf der Salzseite des Dampferzeugers sowie aus dessen Positionierung ergibt sich die Förderhöhe der Heißsalzpumpen. Die Auslastung der Turbine beträgt zwischen 25 % und 100 %, sodass im Nachtmodus 4 Heißsalzpumpen und im Peaker-Modus 6 Heißsalzpumpen vorgesehen werden.
Die Hauptkomponenten wurden spezifiziert auf Basis einer verfahrenstechnischen Auslegung. Für die Behälter wurde die Festigkeit berechnet. Eine Übersicht der Rohrleitungen inkl. Armaturen und Messstellen wurde erstellt.

7.2.6. Dampferzeuger

7.2.6.1. Aufgabedefinition

Das Arbeitspaket 3.3.5 hat als Ziel, für den Dampferzeuger sowie den Back-up Erhitzer eines 200 MWe CSP-Kraftwerks, eine passende Auslegung zu konzipieren.
Die entsprechende Kostenschätzung ist ebenfalls ein Teil des Arbeitspaketes.

7.2.6.2. Designparameter vom Dampferzeuger

Da Salzschmelzen über eine relativ hohe, zulässige Arbeitstemperatur verfügen, wird deren Gebrauch als Wärmeträgermedium in CSP-Anwendungen positiv bewertet.
Die Dampfproduktion und die Abkühlung der Salzschmelze werden durch den Dampferzeuger ermöglicht. Die maximal erlaubten Arbeitstemperaturen, variieren je nach Komposition der Salzschmelze. Für das Design wurde die sogenannte „Solar Salt", eine binäre Salzschmelze aus 40% Kaliumnitrat und 60% Natriumnitrat, betrachtet. Diese Salzschmelze hat eine maximal zulässige Arbeitstemperatur von etwa 565°C. Die minimal erlaubte Temperatur liegt bei etwa 240°C, welche mit dem Schmelzpunkt des Salzes korreliert.
Ähnlich wie bei konventionell befeuerten Dampferzeuger, werden folgende Ziele bei einem Salzschmelze Dampferzeuger angestrebt:

- Hohe Dampftemperatur
- Hohe Dampfdruck
- Geringe Salzschmelze Austrittstemperatur

In der vorliegenden Studie, ist die am Eintritt in den Dampferzeuger maximale Temperatur 560°C. Um ein Erstarren der Salzschmelze zu vermeiden, wurde die Austrittstemperatur der Salzschmelze auf 290°C festgelegt. Für die Frischdampftemperatur und die Zwischenüberhitzer-Austrittstemperatur wurden jeweils 550°C festgelegt.
Das Fließen der Salzschmelze durch den Dampferzeuger ist in Abbildung 10 dargestellt.
Die Salzschmelze aus dem heißen Salztank wird in den Überhitzer und in den Zwischenüberhitzer gepumpt. Die Mischung der abgekühlten Salzschmelze hinter diesen Heizflächen, speist den Verdampfer. Danach wird die Salzschmelze im Vorwärmer weiter abgekühlt. Am Ende wird die abgekühlte Salzschmelze zum kalten Salztank befördert.

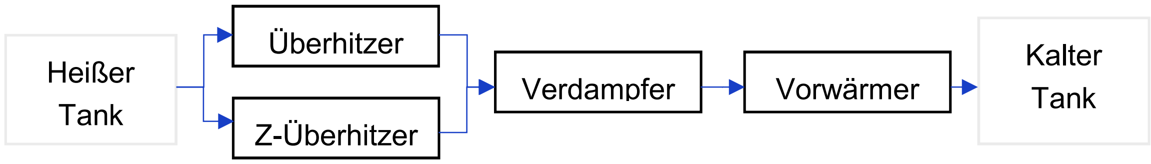

Abbildung 10: Schema des Fließens von der Salzschmelze durch den Dampferzeuger

Eine Analyse verschiedener Parameterkombinationen (siehe Tabelle 4) ergab die folgenden Ergebnisse:

- Hohe Dampfdrücke führen zu Salzaustrittstemperaturen oberhalb des Zielwertes (290°C)
- Hohe Speisewassertemperaturen führen zu Salzaustrittstemperaturen oberhalb des Zielwertes

- Die hohen Druckverluste in der Salzschmelze, führen zu kleineren Heizflächen, welche wiederum Salzaustrittstemperaturen oberhalb des Zielwertes zur Folge hat
- Kleine „Pinch-point“ Werte führen zu geringen Salz-Austrittstemperaturen, aber auch zu großen Heizflächen

Tabelle 4: Untersuchte Designfälle

Parameter				Designfall											
				A	B	C	D	E	F	G	H	I	J	K	L
				5K pinch	0K pinch	5K pinch	5K pinch	10K pinch	5K pinch	10K pinch	10K pinch	5K pinch	5K pinch	5K pinch	5K pinch
Salz-schmelze	Massenstrom	Eintritt/Austritt	kg/s	546,81	545,76	563,28	556,64	558,19	555,15	564,28	598,11	581,61	582,28	568,88	574,08
	Temperatur	Eintritt	°C	565,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0
		Austritt	°C	297,8	289,5	301,4	295,7	296,5	293,1	297,4	318,2	311,2	309,1	295,7	298,1
	Druckverlust	Gesamt	mbar	2497	1554	2578	693	656	614	510	612	855	735	708	2578
Wasserdampf HD	Massenstrom	Frischdampf	kg/s	77,60	77,60	77,60	77,60	77,60	77,60	77,60	82,98	82,98	82,98	80,88	80,88
	Druck	Frischdampf	bar	157,00	131,00	165,00	140,00	140,00	120,00	120,00	165,00	165,00	140,00	140,00	140,00
		Eco-Eintritt	bar	180,00	154,00	189,00	158,00	159,00	140,00	139,00	181,00	184,00	159,00	159,00	174,00
	Temperatur	Eco-Eintritt	°C	245,0	245,0	245,0	245,0	245,0	245,0	245,0	275,0	275,0	275,0	245,0	245,0
		Eco-Austritt	°C	352,1	340,8	358,2	345,4	345,5	334,2	335,0	352,2	340,6	345,9	344,2	350,7
		Verdampfer-Aus	°C	366,9	361,4	372,6	353,8	344,8	343,9	337,9	394,1	386,3	349,6	358,4	358,7
		Frischdampf	°C	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0
	Druckverlust	Eco	bar	2,8	4,1	3,0	1,6	1,7	1,1	0,9	1,1	1,0	1,6	1,5	2,8
		Verdampfer	bar	6,0	6,0	5,2	3,6	3,1	4,4	3,7	3,8	5,5	4,0	4,1	6,6
		Überhitzer	bar	13,7	12,9	16,2	12,3	12,7	13,9	13,7	11,2	12,2	13,2	13,4	24,3
		Gesamt	bar	22,4	23,1	24,4	17,4	17,5	19,4	18,3	16,1	18,7	18,8	19,0	33,7
Wasserdampf MD	Massenstrom	ZÜ-Austritt	kg/s	69,16	69,16	69,16	69,16	69,16	69,16	69,16	70,21	70,21	70,21	73,06	73,06
	Druck	ZÜ-Eintritt	bar	37,80	37,80	37,80	37,80	37,80	37,80	37,80	42,00	42,00	42,00	37,80	37,80
		ZÜ-Austritt	bar	35,80	35,80	35,60	35,80	35,80	35,80	35,80	40,00	40,00	40,00	35,70	35,70
	Temperatur	ZÜ-Eintritt	°C	329,2	329,2	329,2	329,2	329,2	329,2	329,2	347,2	347,2	347,2	356,1	356,1
		ZÜ-Austritt	°C	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0
	Druckverlust	ZÜ	bar	2,2	1,9	2,2	1,9	1,9	1,9	1,9	1,8	1,8	2,0	2,1	2,1
Geometr. Angaben	Heizfläche	Eco	m²	1.786	5.725	1.864	2.163	2.226	1.590	1.272	1.272	1.272	1.972	1.908	1.669
		Verdampfer	m²	1.359	3.180	1.165	1.431	1.113	1.590	1.209	1.431	2.862	1.431	1.590	1.262
		Überhitzer	m²	738	1.209	932	1.272	1.336	1.209	1.209	1.145	1.272	1.209	1.272	1.126
		ZÜ	m²	1.563	1.340	1.563	1.340	1.340	1.340	1.340	1.388	1.388	1.570	1.340	1.340
		Gesamt	m²	5.445	11.454	5.523	6.206	6.015	5.729	5.029	5.236	6.794	6.181	6.110	5.397
System	Nutzwärmeleistung		MWth	220,5	222,7	219,8	221,9	221,9	223,6	223,6	218,5	218,5	220,6	226,9	226,9

Mit der Berücksichtigung der oben genannten Punkte, wurde der Fall K, aus Tabelle 4, als Basis für das Design angenommen; das bedeutet:

- Speisewassertemperatur 245°C
- Frischdampfdruck 140 bar
- Zwischenüberhitzer-Austrittstemperatur 550°C
- Salzschmelze-Eintrittstemperatur 560°C
- Salzschmelze-Austrittstemperatur 296°C

7.2.6.3. Werkstoffauswahl

Es gibt zahlreiche Studien über Werkstoffe und deren Beständigkeit beim Kontakt mit Salzschmelzen. Da die Randbedingungen der Studien (Temperatur, Expositionsdauer, Strömungsart, usw.) keiner Norm oder Einheitlichkeit unterliegen, ist ein Vergleich der Ergebnisse nicht leicht.
Für die betrachtete binäre Salzschmelze, sollte mit den folgenden Werkstoffen eine ausreichende Korrosionsbeständigkeit, gewährleistet sein:

- Unlegierter Stahl wie z.B. 1.5415 für Temperaturen unterhalb 450°C
- Edelstahl wie z.B. 1.4571 für Temperaturen oberhalb 450°C

7.2.6.4. Dampferzeugertyp

7.2.6.4.1. Naturumlauf-Dampferzeuger

Der Naturumlauf-Dampferzeuger, nutzt den Dichteunterschied (zwischen Wasser und Wasserdampfgemisch) als treibendes Mittel für den Wasserumlauf.
Der Vorwärmer erhitzt das Speisewasser zu einer Temperatur unterhalb des Sättigungspunkts. Das Speisewasser tritt in die Trommel ein. Der Trommel speist den Verdampfer mit gesättigtem Wasser. Das Wasserdampfgemisch vom Verdampfer kehrt in die Trommel zurück. Die Trennung von Wasser und Dampf aus dem Dampfgemisch findet in der Trommel statt. Der Sattdampf aus der Trommel fließt in den Überhitzer, wo die erforderlichen Dampfparameter (von der Turbine) erreicht werden. Abbildung 11 zeigt ein Schema mit den Hauptkomponenten eines Naturumlauf-Dampferzeugers.

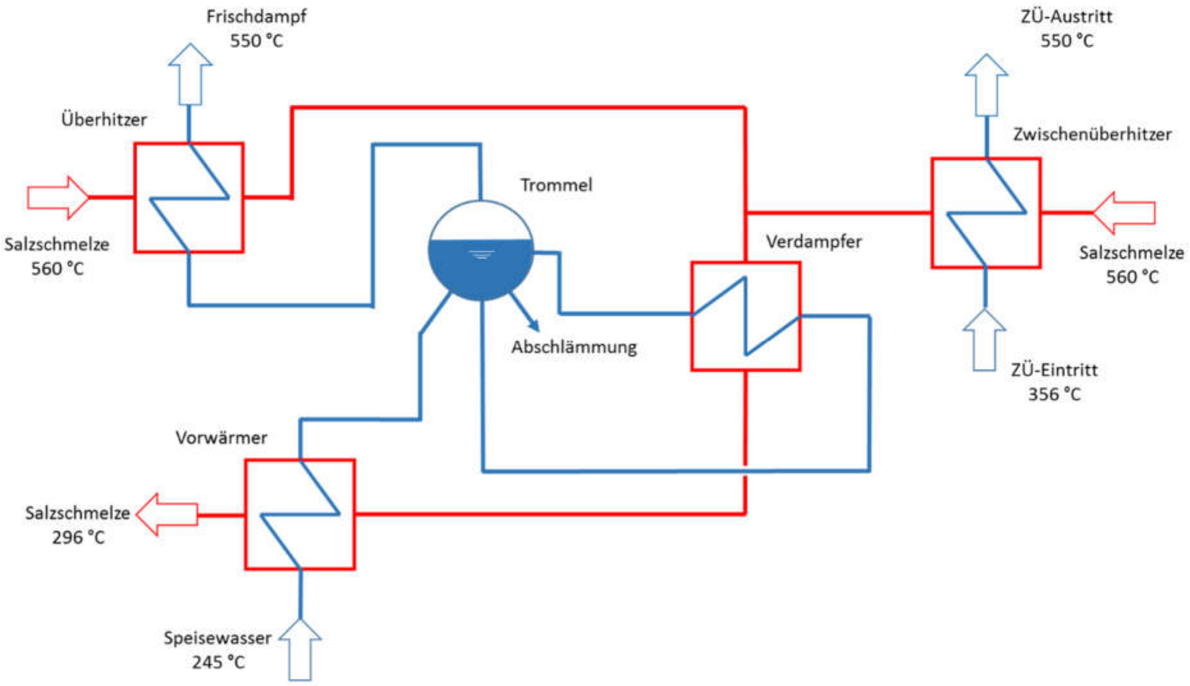

Abbildung 11: Schema eines Naturumlauf-Dampferzeugers

7.2.6.4.2. Zwangsdurchlauf-Dampferzeuger

Das Strömen von Wasser durch die Rohre eines Zwangsdurchlauf-Dampferzeugers wird mit der Hilfe einer Pumpe bewerkstelligt. Vorwärmung, Verdampfung und Überhitzung finden in einem zusammengebildeten Rohr statt. Um den Anfahrvorgang effizienter zu gestalten, werden die Heizflächen des Verdampfers und Überhitzers getrennt. Ein Trenngefäß wird in den Trennungspunkt positioniert.
Während der Anfahrt, ermöglicht das Trenngefäß die Trennung des Wassers aus dem Wasserdampfgemisch vom Verdampfer. Das Wasser wird mittels einer Umwälzpumpe in den Vorwärmer zurückgeführt. Abbildung 11 zeigt ein Schema mit den Hauptkomponenten eines Zwangsdurchlauf-Dampferzeugers.

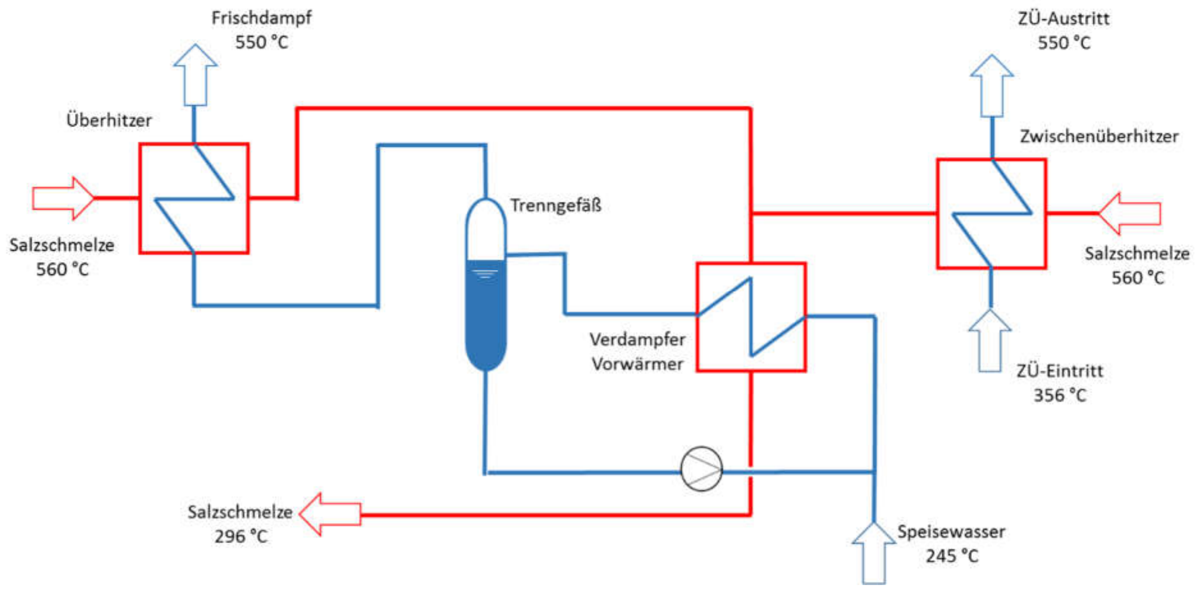

Abbildung 12: Schema eines Zwangsdurchlauf-Dampferzeugers

7.2.6.5. Ausgewählter Dampferzeuger

Das Trenngefäß eines Zwangsdurchlauf-Dampferzeugers ist viel kompakter und dünnwandiger als die Trommel eines Naturumlauf-Dampferzeugers. Dies bildet den bedeutsamsten Vorteil des Zwangsdurchlauf-Dampferzeugers gegenüber dem Naturumlauf-Dampferzeuger. Dank dieses Merkmals, sind höhere Gradienten möglich, was eine schnelle Anfahrt Vorgänge und schnelle Laständerungen zulässt.
Da das Kraftwerk der vorliegenden Studie eher bei einer konstanten Volllast arbeiten soll, bleiben die Vorteile des Zwangsdurchlauf-Dampferzeugers ausstehend.
Außerdem, die Randbedingungen der Studie erfordern, dass die Umwälzpumpe über einen breiten Lastbereich aktiv bleibt.
Der Naturumlauf-Dampferzeuger wurde daher als passender für die vorliegende Studie angesehen. Für jede Heizfläche wurden unterschiedliche Design-Varianten untersucht.
Das ausgewählte Design entstand aus der Kombination der geeignetsten Varianten.
Es wurde angenommen, dass durch den relativ kleinen und einfach gestalteten Wärmetauscher des ausgewähltes Designs, Reparatur- und Umtauschmaßnahmen (falls erforderlich) erleichtert werden.

7.2.6.5.1. Gesamtanordnung

Der ausgewählte 100 MWe Naturumlauf-Dampferzeuger besteht aus den folgenden Hauptkomponenten:

- 1 Dampftrommel
- 3 Vorwärmer-Behälter
- 1 Verdampfer-Behälter
- 2 Überhitzer-Behälter
- 2 Zwichenüberhitzer-Behälter

- 1 Anfahrt-Vorwärmer
- 1 Umwälzpumpe

Das 200 MWe Kraftwerk würde zwei solcher Dampferzeuger-Einheiten besitzen.
Die Komponenten sind innerhalb einer drei stöckigen Struktur, wie in Abbildung 13 dargestellt, angeordnet. Der Vorwärmer (dritter Behälter), der Verdampfer, der Überhitzer (zweite Behälter) und der Zwischenüberhitzer (zweite Behälter) sind auf der untersten Ebene der Struktur platziert. Der Vorwärmer (zweite Behälter), der Anfahrt-Vorwärmer, der Überhitzer (erste Behälter) und der Zwischenüberhitzer (erste Behälter) sind auf der mittleren Ebene der Struktur platziert. Der Vorwärmer (erste Behälter) und die Dampftrommel sind auf der obersten Ebene der Struktur platziert.
Ein ausreichender vertikaler Abstand zwischen Trommel und Verdampfer ermöglicht, dass eine adäquate Umwälzung im Verdampfer gewährleistet wird. Die Positionierung der Behälter wurde unter Berücksichtigung einfacher Verläufe von Befüllung und Drainage realisiert. Elemente mit direktem Kontakt zur Salzschmelze (Mantelseite der Wärmetauscher, Verbindungsleitungen, Ventile, usw.) haben eine Begleitheizung, um das Einfrieren des Salzes zu verhindern. Die Umwälzpumpe und der Anfahrt-Vorwärmer sind nur für die erste Vorwärmung vorgesehen (siehe 7.2.6.5.2.1).

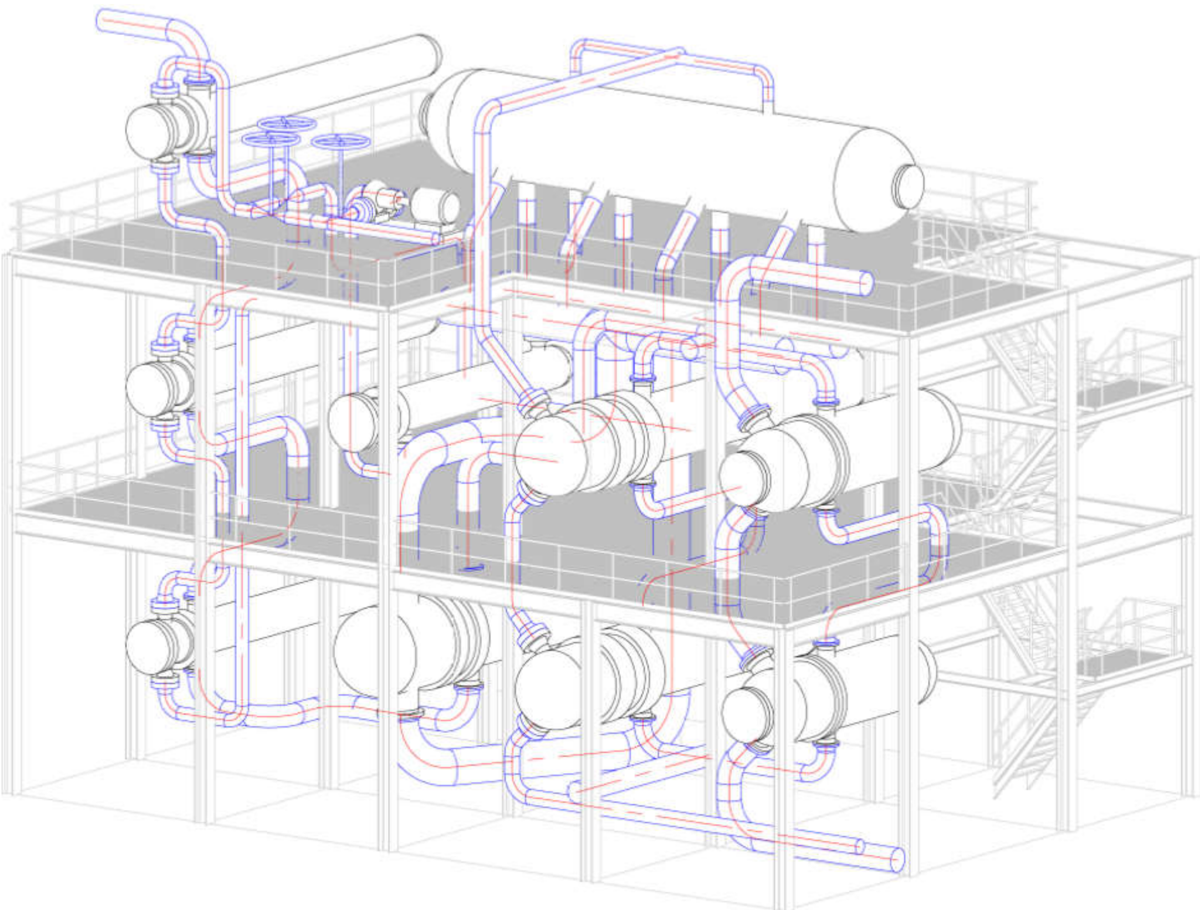

Abbildung 13: Gesamtanordnung des ausgewählten Naturumlauf-Dampferzeugers

7.2.6.5.2. Betriebskonzept

Nach dem all die regulären Aktivitäten (Druckprobe, Reinigung, Trocknung, usw.) abgeschlossen sind, kann die Inbetriebnahme stattfinden.

7.2.6.5.2.1. Erste Vorwärmung

Die erste Vorwärmung hat das Ziel, dass alle Teile, welche im Kontakt mit Salzschmelze stehen, eine Temperatur zwischen 240°C und 270°C haben. Die Mantelseite der Wärmetauscher und die Verbindungsleitungen können mit der Begleitheizung vorgewärmt werden. Das ist jedoch für die innere Teile des Wärmetauschers (wie die Heizflächen) nicht realisierbar. Für die Wärmeübertragung (ausschließlich aus Strahlung) müsste die Temperatur an der Mantelseite wesentlich höher sein. Dementsprechend ist es sinnvoller die Wasser Vorwärmung mit der ersten Vorwärmung des Dampferzeugers zu kombinieren.
Die Wasser Vorwärmung kann mit Fremddampf realisiert werden. In Abwesenheit einer Fremddampfquelle, wurde ein Anfahrt-Vorwärmer eingeplant. Dieser Komponente befindet sich zwischen dem Vorwärmer und dem Verdampfer, hinter der Umwälzpumpe (siehe Abbildung 14).

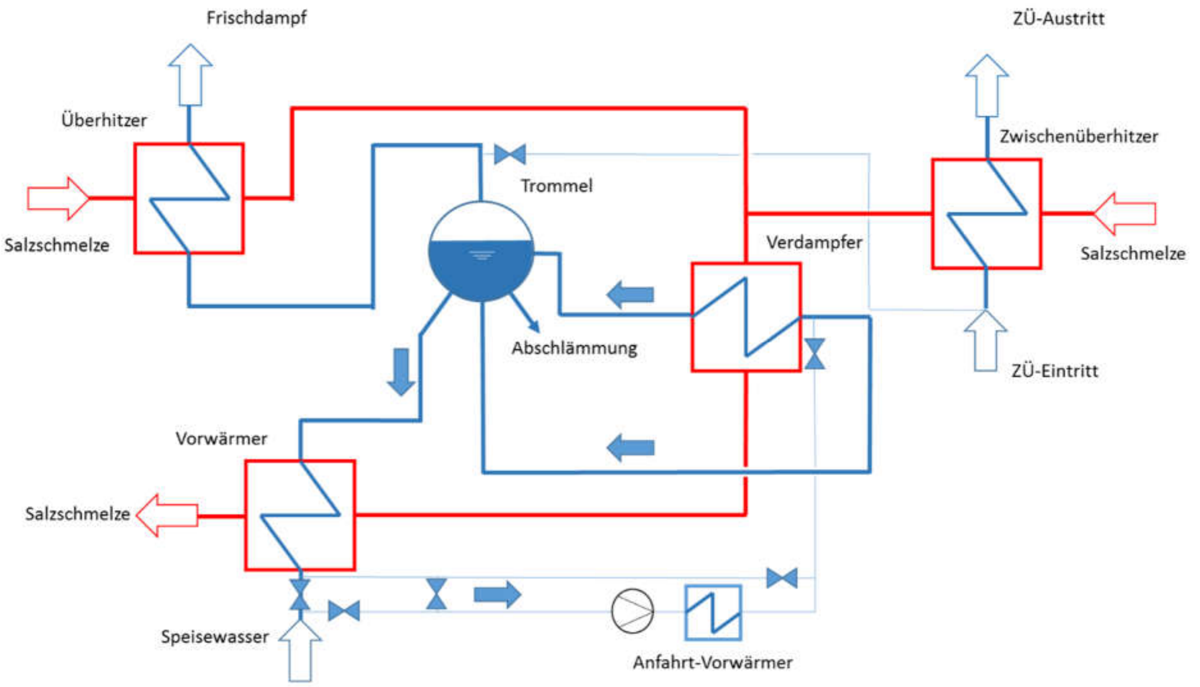

Abbildung 14: Schema zur ersten Vorwärmung

Als erstens, müssen die Trommel, der Anfahrt-Vorwärmer und die Wasserdampfseite vom Vorwärmer und Verdampfer mit Wasser gefüllt werden. Danach wird die Umwälzpumpe das Wasser durch die erwähnte Komponenten zirkulieren lassen. Die durch den Vorwärmer etablierte Strömung ist umgekehrt zu der normalen Richtung (während des normalen Betriebs).
Mit der Wärmezufuhr des Anfahrt-Vorwärmers, wird die Temperatur des Wassers steigen. Mit der Verdampfung bei Umgebungsdruck, wird der erste Dampf produziert und dem Überhitzer

und Zwischenüberhitzer zugeführt. Die Leitung zum Zwischenüberhitzer ist nur während Anfahrt Vorgänge aktiv.
Der produzierte Dampf wird den Druck im System steigen lassen. Mit dem steigendem Druck, wird die Sättigungstemperatur angehoben und die Vorwärmung der Heizflächen findet statt. Mit einem 700 kW elektrischen Anfahrt-Vorwärmer, wird die erste Vorwärmung etwa 25 Stunden in Anspruch nehmen.

7.2.6.5.2.2. Befüllung

Nachdem durch die erste Vorwärmung, die Komponenten des Dampferzeugers eine Temperatur oberhalb des Gefrierpunkts des Salzes erreicht haben, findet die Befüllung der Wärmetauscher mit der Salzschmelze statt.
Die Salzschmelze aus dem kalten Tank (bei etwa 290°C) wird durch den Überhitzer und Zwischenüberhitzer gepumpt. Danach findet die konsekutive Befüllung von Verdampfer und Vorwärmer statt.
Es gibt Leitungen, welche zur Entlüftung der Salzseite dienen. Diese Leitungen sind nur während der Befüllung aktiv. Die Luft wird durch die Salzschmelze geschoben und durch die Entlüftungsleitungen Richtung kalten Tank evakuiert.
Nach ein paar Minuten tritt die Salzschmelze vom Vorwärmer zum kalten Tank hin aus. Anschließend können die Entlüftungsventile geschlossen werden. Danach ist den Anfahrt vom Dampferzeuger möglich.

7.2.6.5.2.3. Anfahrt

Nachdem alle Wärmetauscher befüllt sind, strömt eine konstante, minimale Salzmenge durch den Dampferzeuger.
Danach wird eine konstante, minimale Wassermenge in den Vorwärmer gepumpt. Eine Mindesttemperatur von 245°C beim Speisewasser wird durch den HD-Vorwärmer des Kraftwerks gewährleistet.
Die Temperatur der Salzschmelze wird kontinuierlich angehoben. Gradienten von 5 K/min sind zulässig; dies bedeutet, dass in etwa einer Stunde die Temperatur des Salzes vor dem Überhitzer von 290°C zu 560°C angehoben werden kann.
Der produzierte Dampf wird den Druck und die Temperatur im System erhöhen. Der Anfahrprozess wird als beendet eingestuft, wenn der Frischdampf 550°C und 65 bar erreicht hat. Somit wird die Synchronisierung mit der Turbine ermöglicht (etwa 25% Last).

7.2.6.5.2.4. Normal Betrieb

Nachdem die Anfahrt abgeschlossen ist, sind Laständerungen von 5 bar/min realisierbar. Dies bedeutet, dass eine Laständerung von 25% zu 100% Last etwa 15 Minuten in Anspruch nimmt.
Die Steuerung der Frischdampftemperatur wird durch einen Einspritzkühler hinter dem Überhitzer realisiert. Die Steuerung der Zwischenüberhitzer-Austrittstemperatur erfolgt über ein Regelventil, welches die Salzmenge durch den Zwischenüberhitzer regelt.

Der Dampferzeuger arbeitet bei Festdruck bis zum 25% Last und bei Gleitdruck zwischen 25% und 100% Last. Mit einer Salztemperatur von 560°C vor dem Überhitzer, sind Temperaturen zwischen 271°C und 300°C am Austritt des Dampferzeugers zu erwarten. Tabelle 5 zeigt eine Zusammenfassung der Parametern vom Dampferzeuger bei unterschiedlichen Lastfällen während des normalen Betriebs.

Tabelle 5: Dampferzeuger Lastfälle

Parameter				Lastfall			
				100%	75%	50%	25%
Salz-schmelze	Massenstrom	Eintritt/Austritt	kg/s	608,52	445,20	298,31	158,89
	Temperatur	Eintritt	°C	560,0	560,0	560,0	560,0
		Austritt	°C	300,8	289,4	272,0	271,2
	Druckverlust	Gesamt	mbar	1781	1064	549	146
Wasserdampf HD	Massenstrom	Frischdampf	kg/s	82,92	66,24	46,65	24,40
		Einspritzung	kg/s	0,00	0,32	0,30	0,19
	Druck	Frischdampf	bar	140,00	105,00	66,00	65,00
		Eco-Eintritt	bar	146,00	110,00	70,00	67,00
	Temperatur	Eco-Eintritt	°C	245,0	250,6	251,2	255,0
		Eco-Austritt	°C	334,8	316,2	285,0	282,0
		Verdampfer-Aus	°C	338,9	316,7	284,9	281,9
		ÜH-Austritt	°C	550,2	554,7	556,8	558,1
		Frischdampf	°C	550,0	550,0	550,0	550,0
	Pressure drop	Eco	bar	1,5	0,9	0,5	0,1
		Verdampfer	bar	0,3	0,2	0,1	0,0
		Überhitzer	bar	3,2	2,9	2,4	0,7
Wasserdampf MD	Massenstrom	ZÜ-Austritt	kg/s	74,87	58,15	40,26	19,98
	Druck	ZÜ-Eintritt	bar	40,50	30,77	21,47	10,65
		ZÜ-Austritt	bar	37,40	27,74	19,30	9,66
	Temperatur	ZÜ-Eintritt	°C	328,9	378,9	392,3	329,3
		ZÜ-Austritt	°C	550,0	550,0	550,0	550,0
	Druckverlust	ZÜ	bar	2,9	2,4	1,7	0,9
System	Nutzwärmeleistung		MWth	239,1	182,4	129,9	69,2

7.2.6.5.2.5. Stand by

Der Dampferzeuger kann im Wartebetrieb stehen. Dies bedeutet, dass die Dampfproduktion temporär eingestellt wird und ein neuer Start zeitnah realisiert werden kann.
Zuerst müssen der Salz- und Speisewassermassenstrom reduziert werden (bis etwa 25% Last). Dabei soll die 5 bar/min Änderung eingehalten werden.
Danach wird die Salztemperatur reduziert (5 K/min) bis die Salzschmelze ausschließlich aus dem kalten Tank kommt.
Der Druck auf der Wasserdampfseite wird bei dem zu der Salztemperatur entsprechenden Saturationspunkt gehalten. Dies bedeutet, dass bei einer Salztemperatur von 290°C (aus dem kalten Tank), der Druck auf der Wasserdampfseite75 bar beträgt.
Als nächstes wird der Speisewassermassenstrom zum Vorwärmer wird unterbrochen. Das Wasser im Vorwärmer und Verdampfer kann ggf. vollständig verdampfen (abhängig von der Dauer im Stand by). Die Wärmeverluste werden durch die Begleitheizung ausgeglichen, um das Einfrieren des Salzes zu vermeiden.

Alternativ, kann die Salzschmelze vom Dampferzeuger bei einem Druck von 75 bar auf die Wasserdampfseite evakuiert werden. Der Speisewassermassenstrom zum Vorwärmer wird ebenfalls unterbrochen. Der Druck auf der Wasserdampfseite wird im Laufe der Zeit sinken.

Es wird erwartet, dass das Wasser im Dampferzeuger etwa 8 Stunden oberhalb des Erstarrungspunkt des Salzes bleiben kann.

7.2.6.5.2.6. Abfahren

Für längere Stillstände kann ein zum Stand by ähnliches Verfahren angewendet werden. Der Unterschied hierbei ist, dass nachdem die eintretende Salzschmelze eine Temperatur von 290°C erreicht hat, diese evakuiert wird und der Druck auf die Wasserdampfseite abgebaut wird.
Die Entleerung auf die Salzseite wird durch die statische Höhe des Salzes in den Wärmetauschern verursacht. Alle Entleerungsleitungen verfügen über Ventile, welche während des normalen Betriebs geschlossen bleiben.
Nach vollständiger Entleerung der Salzseite, wird die Begleitheizung ausgeschaltet. Der Dampferzeuger . Nach einige Zeit erfolgt ein Druckabbau auf der Wasserdampfseite durch die Ventile zum Entspanner. Das Restwasser wird zum Kondensat System fließen.

7.2.6.5.3. Kostenabschätzung

Mit der Berücksichtigung der in Kapitel 7.2.6.5.1 erwähnten Komponenten, Verbindungsrohrleitungen, Isolierung, Ventilen, Instrumentierung und Stahlstruktur, die spezifischen Kosten des Dampferzeugers liegen bei 110 €/kWe.

7.2.6.6. Back-up Erhitzer

Um die Verfügbarkeit der Lieferung des Kraftwerks an das Netz zu sichern, kann einen Back-up Erhitzer implementiert werden.
Es gibt zwei Möglichkeiten für die Implementierung des Back-up Erhitzers: parallel zum Receiver oder parallel zum Dampferzeuger.
Ein Back-up Erhitzer, parallel zum Receiver, erhitzt die Salzschmelze zwischen den kalten und den heißen Tank. Somit können Probleme im Solarfeld oder im Receiver überbrückt werden. Der Back-up kann in diesem Fall elektrisch oder mittels fossiler Feuerung angetrieben sein.
Ein Back-up Erhitzer, parallel zum Dampferzeuger, wird bei Problemen mit dem Dampferzeuger genutzt. In Anbetracht der Dampfparameter in der vorliegenden Studie, soll der Back-up Erhitzer mittels fossiler Feuerung fungieren. Diese Option ist nicht allzu angemessen, denn ohne aktive Salzschmelze-Komponenten, würde das Kraftwerk rein konventionell sein. Das Risiko eines kompletten Ausfalls der Dampfproduktion, ist mit den zwei 100 MWe Dampferzeuger verringert.
Ein Back-up Erhitzer scheint die geeignetere Option zu sein. Die Implementierung ist eng verbunden mit dem Standort des Kraftwerks. Da die Randbedingungen, wie die Verfügbarkeit von einem spezifischen Brennstoff, Zuschüsse, usw. eine Rolle spielen, wurde entschieden diese Komponenten bei der Betrachtung des Referenzkraftwerks nicht mit einzubeziehen.

7.2.7. Kraftwerksblock

Die vom Solarturm aufgenommene und in den Salztanks gespeicherte Energie wird vom Kraftwerksblock zur Stromerzeugung genutzt. Daher wird die Wärme aus dem Salzsystem an den Wasser-Dampf-Kreislauf im Dampferzeuger übertragen, wie im vorherigen Kapitel beschrieben.

Der Wasser-Dampf-Kreislauf (WDK) beschreibt im Wesentlichen den „Clausius-Rankine-Cycle". Ein für CSP-Anwendungen konzipierter WDK nach aktuellem Stand der Technik ist in Abbildung 15 dargestellt. Dieser WDK besteht aus den folgenden Hauptkomponenten:

- Dampferzeuger
- Hochdruck-Dampfturbine
- Niederdruck-Dampfturbine
- Luftgekühlter Kondensator (ACC)
- Niederdruck-Vorwärmer (LP-PH 1-3)
- Speisewasserbehälter
- Hochdruck-Vorwärmer (HP-PH 1-2)

Die Randbedingungen des Dampferzeugers wie Druckverlust und minimale Eintrittstemperatur basieren auf der Auslegung von Steinmüller.
Der Frischdampf aus dem Dampferzeuger tritt im Design-Betrieb mit 140 bar und 550°C in die HD-Dampfturbine ein. Die HD-Dampfturbine verfügt über eine Anzapfung, aus der ein kleiner Teil des Dampfes zum Speisewasservorwärmer HD-PH2 geleitet werden kann, um die Mindest-Eintrittstemperatur des Dampferzeugers zu gewährleisten.
Die minimale Kessel-Eintrittstemperatur in Kombination mit einer minimalen Temperaturdifferenz innerhalb des Speisewasservorwärmers definieren die Sättigungstemperatur und den Eintrittsdruck des Dampfes, der für den Vorwärmer HP-PH2 benötigt wird. Der WDK ist so ausgelegt, dass der Eintrittsdruck der Zwischenüberhitzung dem erforderlichen Sättigungsdruck des Vorwärmers HP-PH2 entspricht. Somit ist im Auslegungsbetrieb die Anzapfung der HD-Turbine nicht aktiv, da der Gegendruck der HD-Turbine hoch genug ist, um den HD-PH2 mit Dampf zu versorgen. Im Teillastbetrieb, in dem der Frischdampfdruck sinkt, kann jedoch Dampf aus der HD-Turbinenanzapfung oder aus dem Frischdampf verwendet werden, um die minimale Kessel-Eintrittstemperatur in allen Betriebsbereichen sicherzustellen.

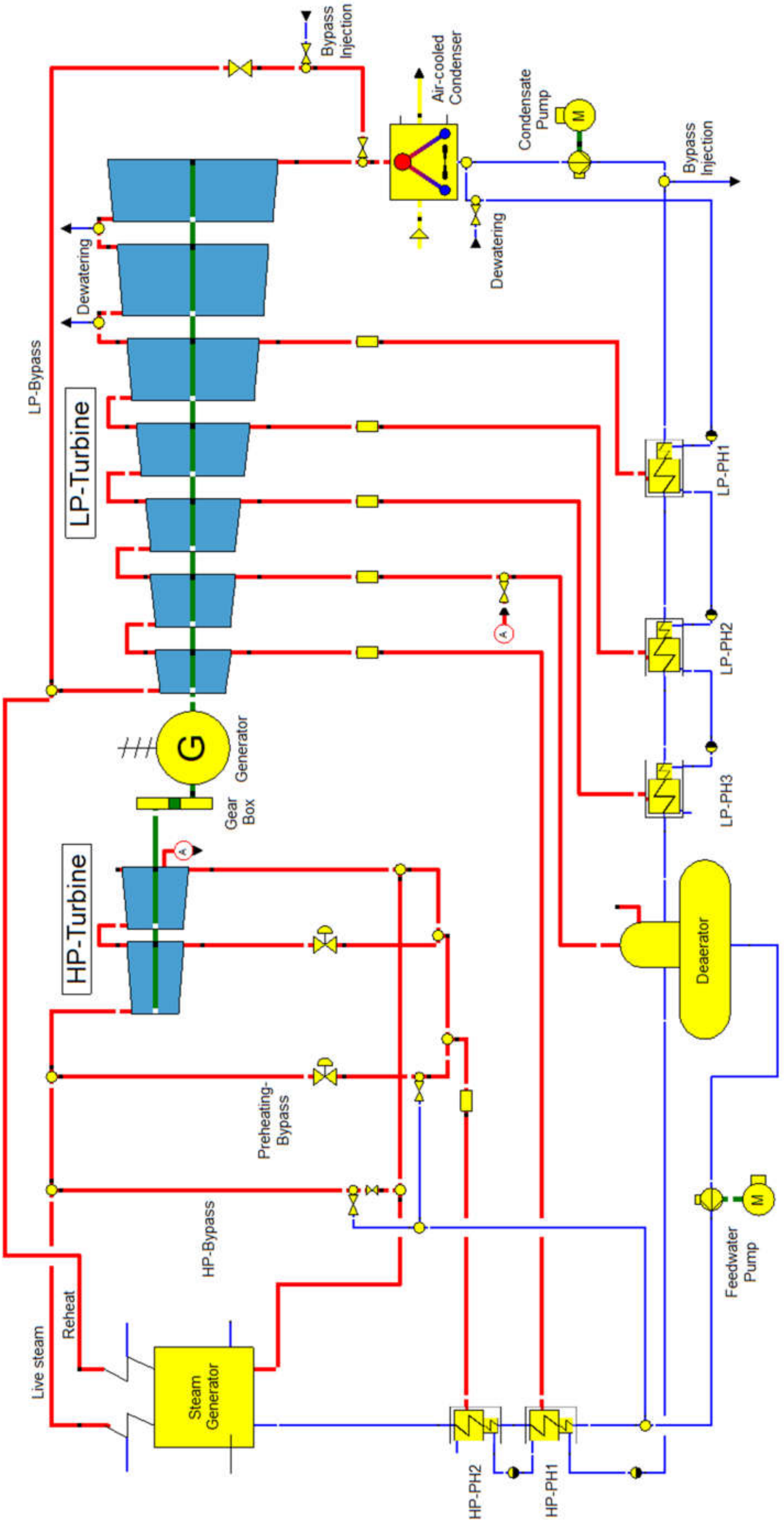

Abbildung 15: Wasser-Dampf-Kreislauf

Die Austrittstemperatur aus der Zwischenüberhitzung entspricht der Frischdampftemperatur. Der wiedererhitzte Dampf tritt in die ND-Dampfturbine ein, durch die dieser auf den Kondensatordruck entspannt wird. Die ND-Turbine besitzt in Summe 5 Anzapfungen zur Speisewasservorwärmung. Der Kondensatordruck wird durch den luftgekühlten Kondensator und damit auch durch die Umgebungsbedingungen bestimmt.

Das Vorwärmsystem ist so ausgelegt, dass die Exergieverluste beim Aufheizen des Kondensats auf Dampferzeugereintrittsbedingungen minimiert werden. Um dies zu erreichen, wird die Wärme des Dampfes in mehreren Stufen auf das Kondensat/Speisewasser übertragen, um die Temperaturdifferenz zwischen wärmeabgebendem und wärmeaufnehmendem Medium zu verringern. Damit wird der Clausius-Rankine-Kreislauf soweit möglich an einen Carnot-Prozess angeglichen, wodurch der Kreislaufwirkungsgrad erhöht wird. Allerdings nimmt der Wirkungsgradzuwachs mit der Anzahl der Vorwärmer ab und nähert sich einem Grenzwert. Daher ist die gewählte Anzahl der Vorwärmer das Ergebnis einer techno-ökonomischen Analyse.

Der Nettowirkungsgrad des Kraftwerksblocks ist ein wichtiges Maß zur Bewertung des Kraftwerksbetriebs. Im Allgemeinen wird der Nettowirkungsgrad des Kraftwerksblocks durch die Betriebsart des Dampferzeugers (Gleitdruck-/Festdruckbetrieb), den Wirkungsgrad der Dampfturbine, den Kondensationsdruck und die interne Leistungsaufnahme von ACC, Pumpen etc. beeinflusst.

Der Nettowirkungsgrad des Kraftwerksblocks in Abhängigkeit von der Last ist in Abbildung 16 dargestellt. Im Auslegungsbetrieb bei 100 % Last beträgt der Nettowirkungsgrad 41,5 %. In einem Lastbereich zwischen 100 % und 75 % Last sinkt der Nettowirkungsgrad nur geringfügig. Bei 50 % Last ist der Nettowirkungsgrad mit ca. 40 % immer noch recht hoch. Unterhalb von 50 % Last sinkt der Nettowirkungsgrad jedoch stärker ab, bis auf 36,7 % bei einer Mindestlast von 25 %.

Der Betrieb des Kraftwerksblocks wird durch den Dampferzeuger in einem weiten Betriebsbereich zwischen 100 % und 50 % im Gleitdruckbetrieb geregelt. In diesem Betriebsbereich wird der Abdampfdruck des luftgekühlten Kondensators über die Lüfterdrehzahl geregelt, wodurch der Energieverbrauch des Kondensators sinkt und ein Wirkungsgradabfall in diesem Teillastbereich teilweise kompensiert werden kann. Im Teillastbetrieb zwischen 90 % und 70 % Last kann der HD-Vorwärmer 2 (HD-PH2) effizient mit Dampf aus der HD-Turbinen-Anzapfleitung betrieben werden, wie in Abbildung 15 dargestellt. Ab ca. 50 % Last und darunter wechselt die Betriebsart aufgrund einer definierten Mindestdruckgrenze von 75 bar am Dampferzeugeraustritt auf Festdruck-Regelung. Um den Frischdampfdruck konstant zu halten werden Regelventile am Eintritt der HD-Turbine eingesetzt, was zu Drosselverlusten führt. Zudem sinkt der Wirkungsgrad der Dampfturbine im niedrigen Teillastbetrieb. Zusätzlich muss die Vorwärmer HD-PH2 mit Frischdampf versorgt werden und der Kondensatdruck wird konstant bei 100mbar gehalten, was zu keinen weiteren Kompensationseffekten durch einen reduzierten Abgasdruck führt. Alle diese Effekte führen dazu, dass der Nettowirkungsgrad unterhalb von 50% Last vergleichsweise stark abnimmt.

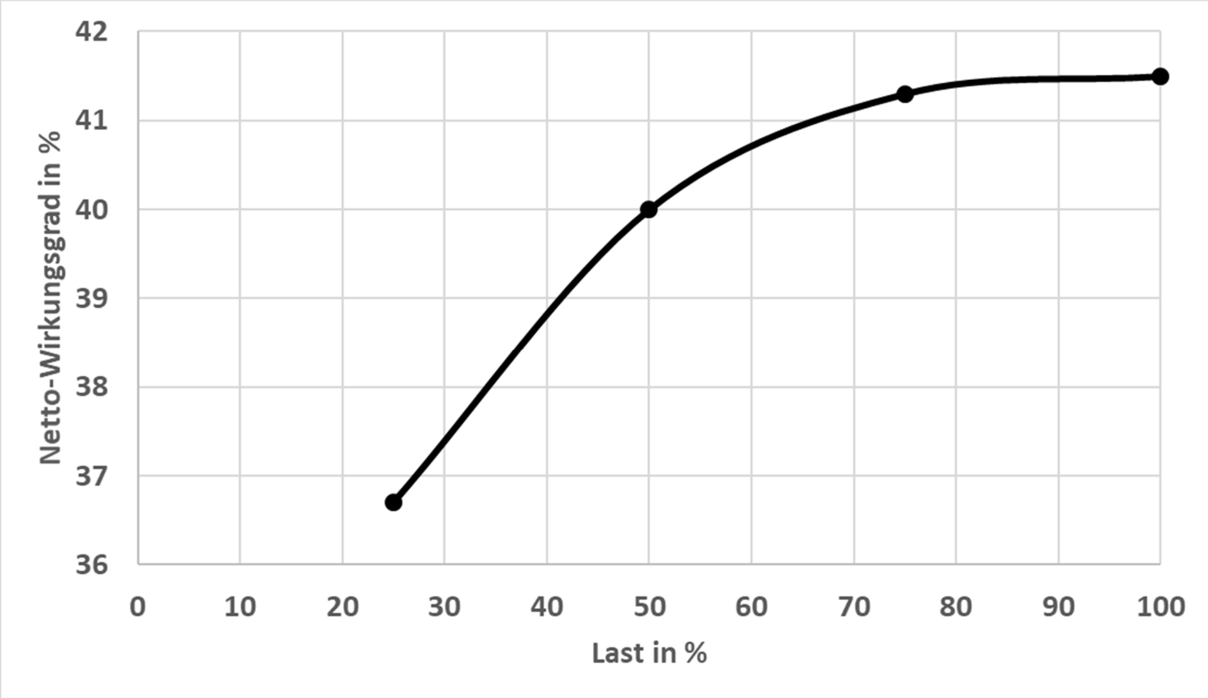

Abbildung 16: Netto-Wirkungsgrad in Abhängigkeit der Last

Die Gesamtkosten des Kraftwerksblocks werden auf 850 €/kWh veranschlagt, einschließlich der folgenden Teilsysteme:

- Dampferzeugungssystem
- Dampfturbinen-Generator
- Abschlämmsystem
- Kühlungssysteme
- Kondensat-System
- Speisewasser-System
- Hilfskühlwassersystem
- Dampfverrohrung, Isolierung, Ventile und Armaturen
- Wasseraufbereitungssystem
- Stromverteilungssysteme
- Notstromsysteme
- Instrumente und Steuerungen
- Feuerschutz-System
- Fundamente & Tragwerke
- Gebäude
- Mechanische Systeme
- Elektrische Systeme

7.2.8. Nebensysteme

Ein Kraftwerk besteht nicht nur aus Wärmetauscher, Dampferzeuger und Dampfturbine allein, sondern benötigt ein ganze Reihe von gut abgestimmten Nebensystemen. Diese müssen auch für dieses Projekt zumindestens grob eingegrenzt und bepreist werden. In diesem Kapitel werden die folgenden zusätzlichen Systeme benannt und grundsätzliche Annahmen getroffen, die dann unter anderem in die Kostenschätzung mit eingeflossen sind. Mehr Details finden sich in der Englischen Ausgabe des Berichts für:

- Neben- und Hilfskühlsystem mit Wärmetauscheren und Nasskühlturm für z.B. Generator, ST-Ölsysteme, Luft-Kompressoren, Probenkollektor, Kondensat- und Vacuumpumpen, etc.,
- Prozessleitsystem
- Druckluft / Instrumentenluft
- Probennahme- und Dosierungssystem
- Wasseraufbereitungssystem für Trinkwassersystem, Löschwasser, Brauchwassersystem, Kühlwasser, Reinigungswassersystem und demineralisiertem Wasser
- Abwassersammlung und -aufbereitung
- Brandmelde- und Feuerlöschsystem
- Heizung, Klima, Lüftung für Gebäude, Container, Cabinets, etc.
- Kran und Hebezeuge: z.B. Turm / Maschinenhaus
- Lagergebäude mit Werkstatt
- Labore
- Generatoranschluß
- Maschinen-Trafo, Eigenbedarfs-Trafo, Stromverteilungssysteme MV, LV, MCC inkl. Verteilerboxen und Verkabelung
- Erdungs- und Blitzschutzanlagen (für z.B. Turm (und Solar Field))
- DC und UPS System, Umrichter
- Notstromaggregat (-diesel)
- Kraftwerks- und Straßen-/Wegebeleuchtung
- Flughindernisbefeuerung
- Schaltanlage

7.2.9. Baugewerke

Ein Kraftwerk erfordert umfangreiche Baugewerke. Diese müssen auch für dieses Projekt zumindestens grob eingegrenzt und bepreist werden. In diesem Kapitel werden die folgenden zusätzlichen Gewerke benannt und grundsätzliche Annahmen getroffen, die dann unter anderem in die Kostenschätzung mit eingeflossen sind. Mehr Details finden sich in der Englischen Ausgabe des Berichts für:

- Auslegungsgrundlagen
- Dampfturbinenhalle

- Wärmetauscherfundamente
- Steuerwarte
- Wasseraufbereitungsgebäude
- Pumpenhaus
- Kühlerfundamente
- Solarturm
- Heliostatfundamente
- Salztankfundamente
- Gebäude
- Erdverschiebungen
- Verdunstungsbecken
- Erosions- und Staubkontrolle
- Flutwassermanagement
- Landschaftsgestaltung
- Überlaufauffangsstrukturen

7.3. Techno-ökonomische Analyse

Für die techno-ökonomische Analyse wurde die Levelized Cost of Electricity (LCOE) für die beiden Ausführungen des Referenzkraftwerks auf Basis einer Ertragssimulation für ein typisches Jahrs ermittelt. Dazu wurde die DLR Software greenius eingesetzt (DLR, 2020). Die Projektpartner haben dazu die spezifischen Kosten der Baugruppen geliefert, für die sie zuständig waren, bzw. die in ihren Lieferumfang fallen.
Die optimale Speichergröße wurde so gewählt, dass für die jeweilige Kraftwerkskonfiguration minimale LCOE erreicht werden. Abbildung 17 zeigt den typischen Verlauf der LCOE in Abhängigkeit von der Speicherkapazität am Beispiel der Anlage für den Nachtbetrieb.

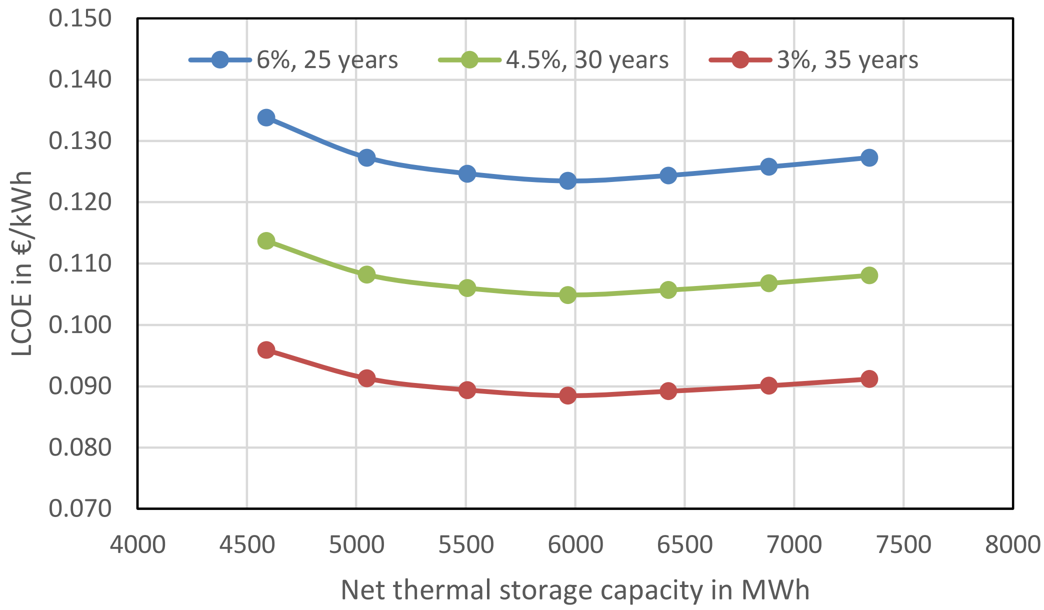

Abbildung 17: LCOE für unterschiedliche Speicherkapazitäten und finanzielle Parameter (Zinssatz und Lebensdauer) für das Referenzkraftwerk für Nachtbetrieb.

Aus den Berechnungen hat sich, unter den angenommen Betriebsmodus „Nachtbetrieb“ (elektrische Nennleistung 200 MW) eine optimale thermische Speicherkapazität von 5967 MWh, entsprechend 13 Volllaststunden für den Kraftwerksblock ergeben. Für die Anlage für den „Peaker-Betrieb“ (elektrische Nennleistung 2×200 MW) würde eine Speichergröße entsprechend 6 Volllaststunden die niedrigsten LCOE ergeben.

7.4. Risikoanalyse und Bankability

Das technisch schönste Projekt ist wertlos falls es mit unüberwindbaren Risiken verbunden ist oder bei der Finanzierung durch Banken durchfällt. Dieses Kapitel versucht die in dieser Studie verwendeten Komponenten fair zu beleuchten und Hinweise zu geben, wo eine unabhängige und tiefschürfende Risikoanalyse nachfassen sollte.

Risiken sind vor allem mit neuen, innovativen Technologien oder maßgeschneiderten Lösungen verbunden. Im Falle eines Solarturmkraftwerks sind dies natürlich die Komponenten im optischem Pfad wie Heliostaten und Receiver, aber auch selten realisierte wesentliche System wie die Salzwärmespeicher. Die Studie hat bewusst auf Komponenten zurückgegriffen, die im Markt bereits Einsatz gefunden haben und von erfahrenen Systemlieferanten bereitgestellt werden können. Das sind nicht unbedingt die in der Anschaffung preiswertesten Komponenten, aber der Vorteil in der Risikominimierung sollte sich auszahlen.
Eine etwas detaillierte Diskussion befindet sich in der englischen Version der Studie.
Die Einschätzung durch Banken ist entscheidend für die Realisierung eines Solarturmkraftwerks. Ein Kraftwerk auf der Basis dieses Konzepts sollte gute Chancen bei der Bewertung durch Finanzierungsinstitute bekommen. Die Detaillierung ist noch nicht ausreichend für eine tiefschürfende Bewertung, deswegen sind in diesem Kapitel hauptsächlich die wichtigsten Finanzierungsmodelle dargestellt, mit denen in der Vergangenheit vergleichbare Projekte realisiert werden konnten. Diese sollen weitere Aspekte bei der Auslegung und Realisierung eines technischen Infrastrukturprojektes aufzeigen.

Die Bankfähigkeit eines CSP-Projekts hängt von der technischen Reife der Technologie, dem Business Case für das Projekt und der allgemeinen Finanzierungslandschaft in dem Land des Projekts ab.
Es gibt fast 100 CSP-Projekte, die in 25 Ländern auf der ganzen Welt umgesetzt wurden. Innerhalb der letzten fünf Jahre haben sechs dieser Projekte, die auf einem Turm mit Speichertechnologie basieren, den Financial Close erreicht. Diese Anzahl von Projekten, die den finanziellen Abschluss erreichen, beweist dass die CSP-Technologie technisch verstanden und als bankfähige Technologie akzeptiert wird.

Der Vorteil der CSP-Technologie gegenüber anderen variablen Erneuerbare Energien -Technologien (vRE) besteht darin, dass sie aufgrund ihrer hohen Dispatchability und Flexibilität Strom für Spitzenzeiten und/oder in der Nacht unter Verwendung von thermischen Energiespeichern erzeugen kann. Viele CSP-Anlagen nutzen die Vorteile zeitabhängiger Preisgestaltung, d. h. Time-of-Delivery (TOD)-Schemata, die Anreize für Zeiträume (z. B. Off-Peak, On-Peak) schaffen, in denen der Stromversand den höchsten Wert haben könnte. Der Einsatz von thermischen Energiespeichern optimiert den solaren Kapazitätsfaktor.
Diese "Dispatchability" in Kombination mit den sinkenden LCOE führt dazu, dass CSP zu einer finanziell machbaren Option für Systeme wird, bei denen der Zeitpunkt der Lieferung eine wichtige finanzielle Überlegung ist. Wie in der Abbildung unten dargestellt, ist der LCOE-Trend für CSP-Projekte zwischen 2008 und 2020 von 0,29 USD/kWh auf 0,13 USD/kWh gesunken und wird wahrscheinlich weiter sinken.

Die Finanzierungslandschaft für CSP bleibt komplex. Die meisten IPP-Projekte werden als Build-Own-Operate (BOO), Build-Operate-Transfer (BOT) oder Build-Own-Operate-Transfer (BOOT) ausgeschrieben, wobei eine Projektfinanzierungsstruktur (Special Purpose Vehicle) verwendet wird, die den Einsatz von Fremdkapital aus dem privaten Sektor von

Geschäftsbanken oder eine Mischung aus privatem und öffentlichem Fremdkapital, unterstützt durch eine konzessionäre Finanzierung von Entwicklungsbanken oder Entwicklungsfinanzierungsinstituten (DFI), ermöglicht.
Rein kommerzielle Finanzierungen für CSP-Projekte, ohne konzessionäre Finanzierung, bleiben aufgrund der hohen CAPEX-Kosten im Vergleich zu anderen erneuerbaren Energietechnologien schwierig.

Die meisten Entwicklungsbanken bieten verschiedene Arten von Finanzierungsprodukten an, die von Zuschüssen über Konzessionsdarlehen (zinsgünstige Darlehen) bis hin zu quasi-kommerziellen Darlehen und Darlehen an den privaten Sektor zu kommerziellen Bedingungen reichen. Um die Wahrscheinlichkeit zu erhöhen, einen Finanzierungsabschluss zu erreichen, bilden Finanzinstitute, sowohl Entwicklungs- als auch kommerzielle, oft Konsortien, um das individuelle Risiko zu reduzieren und den politischen Einfluss zu erhöhen, genauso wie Projektentwickler, Zulieferer und Eigenkapitalinvestoren Partnerschaften bilden, um Erfahrung und Know-how zu nutzen und ihr Risiko zu streuen.

Zu diesen Herausforderungen beim Erreichen des Financial Close kommen noch der Genehmigungsprozess und das regulatorische Umfeld in den Projektländern hinzu. Der Genehmigungsprozess kann intransparent sein, was zu Risiken und zusätzliche Kosten aufgrund von Verzögerungen führt. Ein solides und stabiles regulatorisches Umfeld vor Ort ist für eine Projektfinanzierung unerlässlich. Das Navigieren im regulatorischen Umfeld, das besonders in neuen Märkten wichtig ist, in denen es oft unzureichende regulatorische Regelungen oder unzureichende Stabilität der Regelungen gibt, kann eine besondere Herausforderung darstellen. Dies ist ein Aspekt, bei dem die politische Stärke einer Entwicklungsfinanzierungsinstitution von Vorteil sein kann, um ein erfolgreiches Ergebnis zu erzielen.

7.5. Roadmap

Diese Studie ist nur ein kleiner Baustein in der Entwicklung und Realisierung eines Solarkraftwerks.
Angerissen werden typische notwendige Schritte in einem langfristigem Prozess, um ein Kraftwerksprojekt dieser Größe zum Erfolg zu bringen. Dabei gilt es zu beachten, dass das technische Konzept wie in dieser Studie dargelegt durch zahlreiche weitere Untersuchungen und Abschätzungen ergänzt werden muss, um Unterstützung, Genehmigung und eine erfolgreiche Finanzierung zu erzielen. Dazu gehören unter anderem auch eine Abschätzung der einzelnen Realisierungsschritte in einem typischen Zeitplan, der dem englischsprachigem Bericht beigefügt ist und für das entsprechende Projekt angepasst werden muss.

8. Nutzen und Verwertbarkeit der Ergebnisse

Deutsches Zentrum für Luft und Raumfahrt e.V. (DLR)	Das DLR baut mit dem Projekt seine international führende Position im Bereich der solarthermischen Solarkraftwerke weiter aus. Durch die im Projekt geplanten Arbeiten erweitert das DLR neben den theoretischen Untersuchungen das praktische Know-how im Anlagenbau. Im Projekt entwickelt das DLR ein neues Simulationsmodell für Solarturmsysteme mit Salzschmelze als Wärmeträgermedium und erweitert das Know-how im Bereich der Salzschmelzen und des Speichers. Die gewonnenen Erkenntnisse dienen als Basis für zukünftige wissenschaftliche Arbeiten. Die Roadmap gibt wichtige Vorgaben für die Schwerpunktsetzung in der F&E Strategie (CSP) des DLR. Die Ergebnisse werden in Veröffentlichungen, Dissertationen, Konferenzbeiträgen etc. wissenschaftlich verwertet.
Steinmüller Engineering GmbH	Steinmüller Engineering kann durch das Projekt seine Kenntnisse im Bereich der Dampferzeuger für solarthermische Kraftwerk weiter ausbauen. Hierdurch soll neben der konventionellen Kraftwerkstechnik der Produktbereich regenerative Energietechnik weiterentwickelt und ausgebaut werden. Neben der Verwendung in solarthermischen Kraftwerken könnte die Technik auch in angrenzenden Marktsegmenten, wie z.B. Flüssigsalzspeicher für die Industrie, verwendet werden. Durch Veröffentlichung der Projektergebnisse erhofft sich SE weitere Bekanntheit als Lieferant für solarthermische Dampferzeuger zu erlangen.
Tractebel Engineering GmbH	Die Ergebnisse des Projekts bieten Tractebel eine hervorragende Basis zur Beratung seiner Kunden. Das erstellten Referenzkraftwerk kann dem Kunden als gut untersuchtes Konzept vorgeschlagen und Projekt- und Kundenspezifisch angepasst werden. Den beteiligten Partnern können auf diese Weise neue Märkte erschlossen werden.
MAN Energy Solutions SE (MAN)	Mit den zu entwickelnden Hochtemperatur-Solar-Dampfturbinen können neu entstehende Märkte bedient werden. Nach Vertriebszuführung der neu erworbenen Technologien erhofft sich MAN Diesel & Turbo SE gute Absatzchancen auf dem wachsenden Solarthermie Markt. Im Bereich der Solarenergie sind insbesondere in Südafrika und den USA diverse Projekte bekannt, welche in dieser Dekade umgesetzt werden sollen. Langfristige Projekte sind auch in

	anderen Regionen rund um den Sonnengürtel zu erwarten, so zum Beispiel im Mittleren Osten und in Afrika.
schlaich bergermann partner, sbp sonne GmbH (SBP)	SBP hat in den vergangenen Jahren Heliostaten entwickelt. Gemeinsam mit Partnern wurden kürzlich verbindliche Angebote für ein 100 MW und ein 50 MW Heliostatenfeld abgegeben. Die Ergebnisse des Projekts werden helfen, auf dem Markt für Heliostatenfelder erfolgreich agieren zu können.

9. Während der Durchführung bekannt gewordener Fortschritt bei anderen Stellen

Aktuell bieten große PV-Anlagen die kostengünstigste Möglichkeit in sonnenreichen Regionen tagsüber Solarstrom zu erzeugen. Wenn es aber um eine Versorgung auch in den Abendstunden oder während der ganzen Nacht geht, bieten solarthermische Kraftwerke durch ihren kostengünstigen thermischen Speicher Vorteile. Daher werden zurzeit sogenannte hybride PV-CSP-Kraftwerke diskutiert, die beide Technologien kombinieren und so rund um die Uhr eine solare Stromerzeugung bieten können. Eine erste solche hybride Anlage, bei der beide Technologien nicht lediglich in dasselbe Netz einspeisen, sondern tatsächlich integriert gebaut und betrieben werden sollen ist für Marokko am Standort Midelt geplant (https://www.solarpaces.org/morocco-pioneers-pv-to-thermal-storage-at-800-mw-midelt-csp-project/).
Diese Hybridisierung wurde im vorliegenden Projekt nicht explizit untersucht, allerdings ist das Referenzkraftwerk für den Betrieb nach Sonnenuntergang konzipiert und kann so komplementär zu PV-Kraftwerken Solarstrom liefern. Eine optionale Versorgung des CSP-Kraftwerks tagsüber (Deckung des Eigenbedarfs zum Betrieb von Solarfeld und Receiver) durch ein kleines PV-Feld wurde im Rahmen von AP 4 kurz untersucht.
Durch die ausgesuchten Betriebsweisen des Referenzkraftwerks sind die Ergebnisse auf den CSP-Teil von hybriden CSP-PV-Kraftwerken übertragbar, falls die Energiebereitstellung weitgehend getrennt erfolgt.
Im Juni 2020 wurde von NREL die „Concentrating Solar Power Best Practices Study“ (Mehos, 2020) veröffentlicht, die wertvolle Hinweise auf viele Aspekte zur Planung, Durchführung und Betrieb von CSP Kraftwerken gibt. Sie enthält allerdings keine beispielhafte Auslegung und Ertragsabschätzung für eine konkrete Anlage.

10. Veröffentlichungen

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CSP-Reference Power Plant “Made in Germany”.
Vortrag: SolarPACES 2020 International Conference, 28. Sep. - 02. Oct. 2020, Albuquerque.
Zu diesem Vortrag wurde auch eine Veröffentlichung als AIP Conference Proceedings eingereicht, die im Laufe des Jahres 2021 erscheinen wird.

Am 28. Oktober 2020 wurde ein Webinar durchgeführt. Organsiert wurde es von ata Insights, entsprechend einem Auftrag der Projektpartner. In diesem Webinar wurde das Projekt und die zu diesem Zeitpunkt vorliegenden Ergebnisse vorgestellt. Als Sprecher traten Alexander Stryk (Tractebel Engineering GmbH), Christian Schuhbauer (MAN Energy Systems SE) und Fabian Gross (spb sonne GmbH) auf. Die Organsiation durch ata Insights wurde gewählt, da dieser kommerzielle Veranstalter eine hohe Sichtbarkeit hat und viele potenzielle Teilnehmer ansprechen konnte.
Laut der nachträglichen Auswertung von ata Insights gab es mehr als 400 Anmeldungen aus 58 Ländern. Die Teilnahmerquote lag bei 32%, wobei alle angemeldeten Personen im Nachgang die Möglichkeit hatten, sich die Aufzeichnung anzusehen.

Der vollständige Abschlussbericht in englischer Sprache ist diesem Bericht beigefügt. Er wird darüber hinaus über die Internetseiten der Projektpartner zum freien Download zur Verfügung gestellt.
https://elib.dlr.de/141315/

11. Literaturverzeichnis

Bradshaw, R., & Goods, S. (2001). *Corrosion Resistance of Stainless Steels During Thermal.* Sandia Report SAND2001-8518.

DLR. (15. 3 2020). *greenius*. Von http://freegreenius.dlr.de abgerufen

Keck, T., Gracia, J., Eizaguirre, I., Sun, D., Balz, M., & Iriondo, J. (2020). *Solar Field Experiences from Hami Solar Tower Project.* SolarPaces Conference.

Keck, T., Schönfelder, V., Zwingmann, B., Gross, F., Balz, M., Siros, F., & Flamant, G. (2020). *High-Performance Stellio Heliostat for High Temperature Application.* SolarPaces Conference.

Mehos, M. P. (2020). *NREL Concentrating Solar Power Best Practices Study, NREL/TP-5500-75763*. Retrieved from https://www.nrel.gov/docs/fy20osti/75763.pdf

Blueprint for Molten Salt CSP Power Plant

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https://blog-tractebel.lahmeyer.de/publications/

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1. Executive Summary

This report shows the results of the German national research project “CSP-Reference Power Plant”. The major goal of the project consortium from German industry supplemented by DLR is the development and optimization a solar tower plant with 2-tank molten salt thermal storage and the publication of a blueprint. This report and blueprint shall be used as starting point for future Concentrating Solar Power (CSP) power plants and can help to save costs and time for future plants.

Solar photovoltaic power plants may deliver cheap electricity during daylight hours. Therefore, a complementary renewable electricity production is needed to increase the overall renewable power generation and satisfy the demand. Here CSP may step in by harvesting the solar energy during daylight hours, storing heat in cost effective thermal storage units and providing electricity on demand after sunset and during the whole night if required.

To suit these requirements in the best way, the consortium develops the reference CSP plant with one common approach but considers two typical operation strategies:

1. The power block starts around sunset and operates at full load until sunrise of the next day, if the storage content is sufficient (called **Night-time Operation**).
2. The power block starts around sunset and operates at full load until midnight, or until the storage is empty (called **Peaker Operation**).

These two scenarios are indicative for more specific ones which may be tailored for a certain site.

The overall design idea is that the most economic plant consists of the most economic subsystems considering their integration and the load demand. The solar or heliostat field is one of the essential subsystems and accounts for about 20 % of the overall costs. sbp sonne gmbh finds that a solar field of about 1.5 km² leads to the lowest specific costs. At sites suitable for solar tower systems, this field size is sufficient to provide heat for a 700 MW_{th} solar receiver and the matching storage capacity is in the range of 5 to 7 GWh_{th} if the solar field shall be able to fill it during good days. Similarly, a power block of 200 MW_e shows the lowest specific costs among MANs turbine portfolio capable for daily start-up and shutdown. This conceptual overall design serves as starting configuration to further detail and optimize the subsystems.

An annual performance simulation is done to find the storage capacity leading to the lowest LCOE and to calculate the possible LCOE of the optimized plant under different financing conditions. Table 1 shows the final design parameters and makes the modular design obvious: The plants optimized for the two different operating scenarios are using identical subsystems. The only difference between them is that the peaker plant has two 200 MW power blocks instead of one.

Calculated LCOE are between 0.089 and 0.124 €/kWh for the night-time operation plant and between 0.130 and 0.182 €/kWh for the peaker plant, depending on financing conditions and life time assumptions. Higher LCOE for the peaker plant are caused by the fact that investment and O&M costs are increased since this plant needs 2 power blocks with reduced operating hours compared to the plant designed for night-time operation.

Table 1: Final design parameters of the reference CSP plant

Part	Plant for night time operation	Plant designed as peaker	Unit
Power block nominal output	200	2×200	MW_e
Solar multiple	1.6	0.8	-
Solar field aperture area	1.5		km²
Tower height	200		m
Receiver design power	700		MW_{th}
Thermal storage capacity	5967		MWh_{th}

Chapter 4 of this report provides details of the subsystems optimized by the industrial partners MAN, Steinmüller and sbp sonne. This is completed by an overview about all parts that are additionally required for the such a plant.

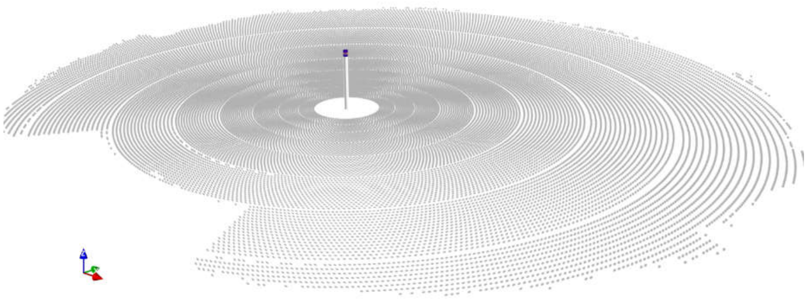


Figure 1: Exemplary sketch of the CSP reference plant

The formation of the consortium of these experienced partners ensures well-coordinated and well described interfaces between the subsystems. This advantage is also reflected positively in the detailed analysis on risk and bankability of the reference CSP plant done by Tractebel and described in chapter 6. Exemplarily roadmap and time schedule complete this report. The authors hope that this document will help future owners to plan, predesign and prepare tender documents for their CSP plants. Furthermore, it provides insights into the expertise of the involved companies.

2. Introduction

Up till now, CSP plants are tailor-made installations requiring a lot of engineering work for optimization and site adaption. This is particularly true for solar tower plants with less operational units compared to parabolic trough plants. Additionally, solar tower plants are less modular than parabolic trough plants since they often consist of one central receiver surrounded by a heliostat field, which is individually designed for each plant. Parabolic trough plants are rather made of a large number of identical loops containing four or more single troughs.

This report shows the results of the German national research project “CSP-Reference Power Plant”. The major goal of the project consortium from German industry supplemented by DLR is the development and optimization a solar tower plant with 2-tank molten salt thermal storage and the publication of a blueprint, which can be used as starting point for future CSP power plants. The report can help to save costs and time for future plants.

Figure 1 shows the overall system as well as the major components and the responsible companies for these components. As further partners Tractebel Engie and DLR are involved with more general tasks and therefore not shown in Fig. 1.

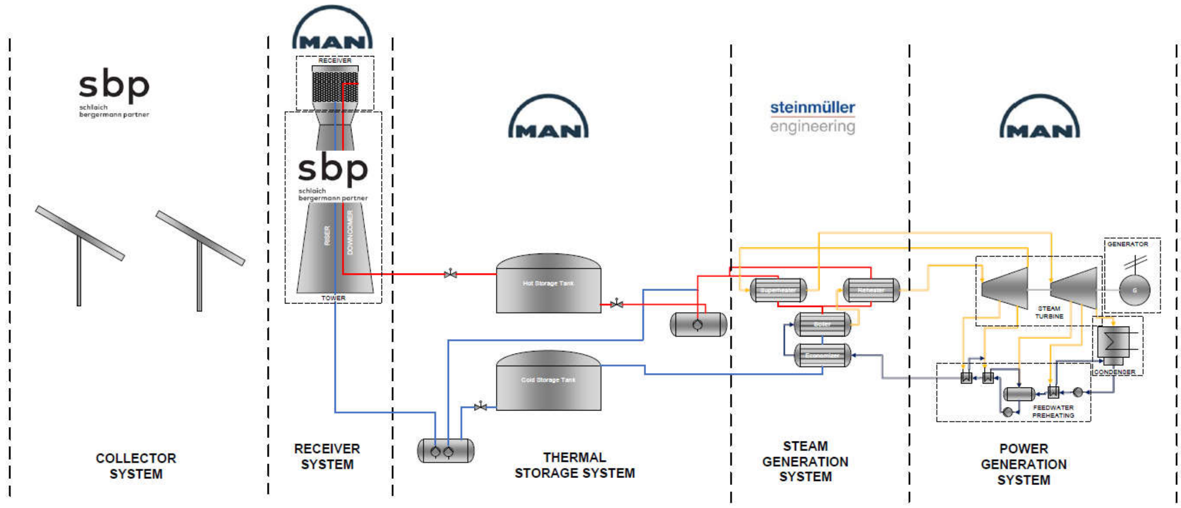


Figure 2: Subsystems of a molten salt solar tower plant and responsibility of the involved companies

The project has been conducted from May 2019 to December 2020 and started with an analysis of existing planned CSP plants worldwide and the definition of probable operation scenarios for future plants. From this starting point an overall concept was defined using a preliminary design which was based on component groups offering the lowest specific costs. Further harmonization and fine-tuning led to the final system layout which is documented in this report.

3. Requirement Analysis and Boundary Conditions

3.1. CSP plants under construction and under development

The first step of the analysis was a compilation of information about all ongoing CSP projects. One valuable source of information is the SolarPACES list of CSP projects around the world (SolarPACES, CSP projects around the world, 2020).
The detailed list is maintained by NREL (NREL, 2020b) and allows for searching for projects using several criteria like status, country, technology, and project name.

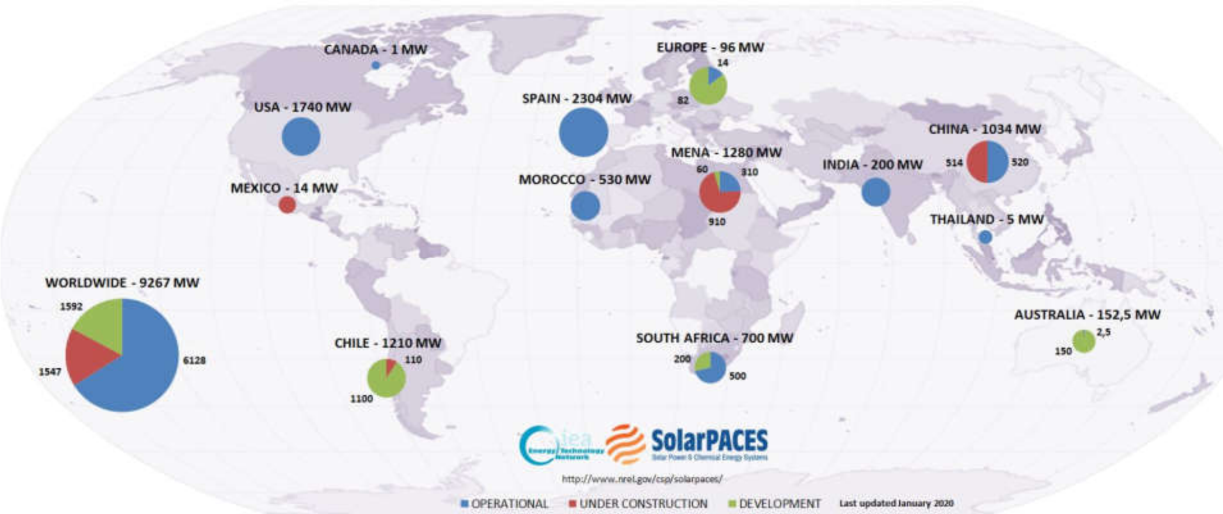


Figure 3: Worldwide status of CSP according to (SolarPACES, CSP projects around the world, 2020)

Nevertheless, some information given on the NREL website is not up-to-date and therefore the authors of the current report tried to complement it with more recent information.

Table 2 lists four CSP plants located in India. These plants have been part of the so-called Jawaharlal Nehru National Solar Mission Phase I published by the end of 2011 and with seven CSP projects (470 MW in total). All projects approved for this mission were expected to be operational by the end of 2013 and actually only three plants are operating by June 2019 (Godawari 50 MW parabolic trough plant, Dhursar 125 MW Linear Fresnel plant, Megha 50 MW parabolic trough plant). Since the remaining plants of this solar mission are marked as "under construction" for 6 years or more, it is very unlikely that they will be completed and they are not considered for the statistics given below. Small plants under 20 MW and ISCC plants are also not shown.

Table 2: CSP plants under construction (November 2020)

Name	Size in MW	Tech-nology	Country	Comment
Abhijeet Solar Project	50	PT oil	India	unlikely to be completed
Atacama-1	110	ST salt	Chile	
DEWA CSP Tower Project	100	ST salt	Dubai	
DEWA CSP Trough Project	600	PT oil	Dubai	
Diwakar	100	PT oil	India	unlikely to be completed
Gansu Akesai 50MW Molten Salt Trough project	50	PT salt	China	
Golmud	200	PT salt	China	
Gujarat Solar One	28	PT oil	India	unlikely to be completed
Hami 50 MW CSP Project	50	ST salt	China	
KVK Energy Solar Project	100	PT oil	India	unlikely to be completed
Rayspower Yumen 50MW Thermal Oil Trough project	50	PT oil	China	
Yumen 50MW Molten Salt Tower CSP project	50	ST salt beam down	China	
Sum	**1488**			
Sum without Indian projects	**1210**			
Sum MS towers	**310**			

Table 3 gives a survey about the CSP plants under development. The status of the Aurora Solar Energy Project in Australia is undetermined because Solar Reserve has failed to secure financing (HelioCSP, 2019). Furthermore, the large solar tower projects developed by Solar Reserve in Chile are listed since several years without any substantial progress and obviously Solar Reserve is no longer active since the beginning of 2020. Therefore, the future of these plants is uncertain.

Table 3: CSP plants under development (November 2020)

Name	Size in MW	Technology	Country
Aurora Solar Energy Project	150	ST salt	Australia
Chabei 64MW Molten Salt Parabolic Trough project	64	PT salt	China
Copiapó	260	ST salt	Chile
Golden Tower 100MW Molten Salt project	100	ST salt	China
Gulang 100MW Thermal Oil Parabolic Trough project	100	PT oil	China
Likana Solar Energy Project	390	ST salt	Chile
MINOS	52	ST salt	Greece
Kahlushi	200	PT	Zambia
Redstone Solar Thermal Power Plant	100	ST salt	South Africa
Shangyi 50MW DSG Tower CSP project	50	ST steam	China
Tamarugal Solar Energy Project	450	ST salt	Chile
Yumen 50MW Thermal Oil Trough CSP project	50	PT oil	China
Zhangjiakou 50MW CSG Fresnel project	50	LFR Steam	China
Midelt	400		Morocco
sum	**2416**		
sum MS towers	**1566**		

These tables show that solar towers have taken a certain market share in the last years but the technology is still less mature than parabolic troughs. On the other hand, molten salt towers, due to their higher temperature level, offer the option for higher power block efficiencies and smaller thermal storage tanks.
Technical problems of the Crescent Dunes solar tower plant in Nevada also may cause questions about the reliability of molten salt towers. According to (reve, 2020) and (Mehos, Price, Cable, & Kearney, 2020) this example is an isolated case and other molten salt towers like Gemasolar (Spain), NOOR III Ouarzazate (Morocco) and Supcon Solar Delingha 50 MW plant (China) are obviously operating as expected or even better (HelioCSP, 2020). Furthermore, the CSP industry is working on these problems to avoid them in future plants.
Molten salt solar tower power plants can offer advantages compared to other CSP technologies, particularly when thermal storage is essential and for sites with clear atmosphere. Due to their significantly higher upper temperature at receiver outlet, they reach higher power block efficiencies and better storage utilization. Furthermore, they have lower requirements for land preparation.

3.2. Operating Scenarios for future CSP-Plants

Current CSP projects like the 4th phase of Mohammed Bin Rashid Al Maktoum Solar Park in Dubai and Noor Midelt in Morocco use a combination of CSP and PV power plants to combine the advantages of both solar technologies. PV power plants underwent an impressive cost reduction during the last ten years and today provide the most cost-effective solar electricity generation during sunshine hours. CSP plants in contrast offer the option of cheap thermal storage and can provide electricity generation on demand particularly during periods when the sun is not shining.

The combination of both technologies therefore can lead to solar power plants with low cost and dispatchable solar electricity production. There are several options of combining these plants, from having two separate plants, which are just connected by the grid to fully integrated plants. The scope of this project is not to define a hybrid PV-CSP-plant but it is focused on the CSP plant. Nevertheless, the hybrid option is considered in the operating schemes of the CSP plant.

At sites with high solar resources, a proper designed PV power plant will be able to provide sufficient electricity during daytime and the CSP plant will rather charge its thermal storage during daytime and start electricity production around sunset. Depending on the local requirements in the specific country, electricity production of the CSP-plant will be required for the whole night or for some hours after sunset (often 5 – 7 hours). This is because in most countries electricity demand typically decreases in the late evening hours and reaches a minimum in early morning hours. If there are sufficient other power plants available in the local grid to provide the low night demand, the CSP plant has to deliver only during the evening hours. If not, it will eventually be operating the whole night until the PV plant starts again.

From these considerations, two basic operating scenarios have been drafted for CSP plants:

1. The power block starts around sunset and operates at full load until sunrise of the next day, if the storage content is sufficient (called **Night-time Operation**).
2. The power block starts around sunset and operates at full load until midnight, or until the storage is empty (called **Peaker Operation**).

Several variations of these scenarios are possible, e.g. operation at lower load to extend electricity production for the whole period, particularly in winter months, or operation from sunset to 10 pm for scenario 2, etc. However, these are only slight modifications and in order to limit the number of scenarios, we have decided to stay with the two basic ones.

4. Overall design and Subsystems

4.1. Overall Design and Methodology

In chapter 3 recent CSP projects have been analyzed to find typical requirements which may be important for future plants. Nominal electrical output is typically between 100 and 200 MW_e, with some smaller units in regions where the technology is being introduced for the first time (e.g. China). In principle, there is a large number of degrees of freedom for the design of a solar tower power plant and a full enumeration and optimizing process could be very time consuming. Therefore, the approach is different: starting from the idea that each industrial partner knows very well the specific costs of his individual subsystem, a preliminary design of the plant is made by using these least cost subsystems. This is particularly valid for the heliostat field and the power block unit.

Acccording to sbp sonne GmbH, a heliostat field made of its Stellio units (Balz, 2015) of about 1.5 km² of aperture area would lead to minimal specific costs for good DNI and clear atmosphere conditions. For smaller solar fields the fixed cost components like engineering, assembly hall, optical quality control system etc. and for larger fields the decreasing efficiency of the outmost heliostats are raising the specific costs for heat reflected onto the receiver. Similar MAN Energy Solutions SE knows that their largest turbine units capable for fast daily start/stop operation will show lowest specific investment costs. These turbines have a gross electricity output of about 200 MW_e. Some simplified first simulation runs show that the matching receiver thermal power would be 700 MW_{th} and the storage size should be in the range of 12 full load hours (~ 6 GWh_{th}) to operate the turbine at night between sunset and sunrise.

For the molten salt thermal storage, specific costs are decreasing with increasing storage capacity. Technical limits for single tanks require the step from 2 tanks to 4, 6, etc. if a certain size is exceeded with a step up in specific costs. This step is not so big that it would limit the storage capacity of our plant (Figure 4). The same solar field and receiver configuration is foreseen for the plant designed for peaker operation. This implies the same amount for heat collected during daylight times combined with approximately halved number of power block operating hours. Therefore, the power block nominal output should be doubled and this can be done by using two identical power blocks of 200 MW_e nominal output. This is a modular approach, which will help in reducing overall system costs.

This starting configuration has been fixed and afterwards the subsystems solar field, receiver, storage, steam generator and power block were optimized separately, of course considering the interfaces to other subsystems and their inter-dependency where applicable. The involved companies with their special expertise in different areas ensure the market availability of the subsystems. Combined design optimization is particularly necessary between heliostat field and receiver due to the flux constraints on the receiver surface as well as between steam generator and power block cycle. An annual yield calculation is finally used for fine-tuning and to find the storage capacity leading to the lowest Levelized Cost of Electricity (LCOE).

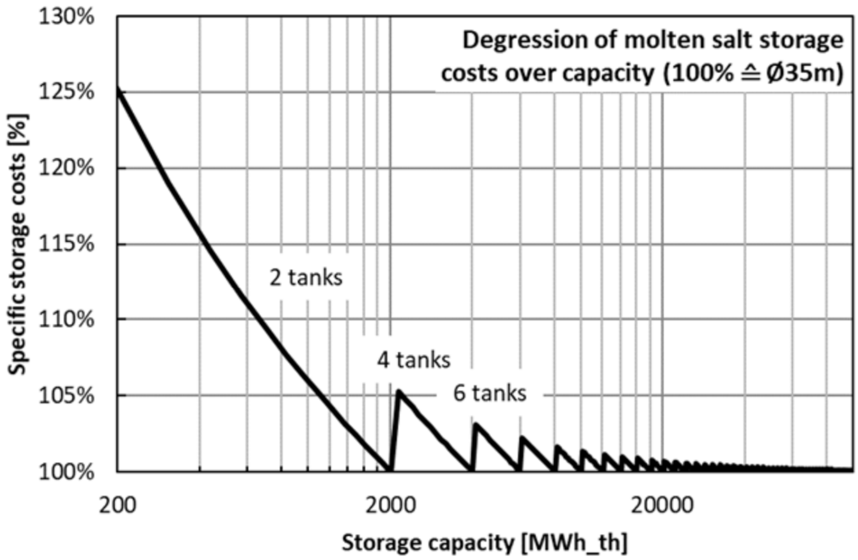


Figure 4: Preliminary cost estimation for 2-tank molten salt storage systems. Calculated based on internal cost database for solar salt (290-560°C), foundation, insulation and tanks. Pumps are not included. Base year 2020.

4.1. Site and boundary conditions

Although the findings of this report shall be applicable for many sites, the design of some parts (particularly the heliostat field) as well as the annual performance simulations need specific site information and some other boundary conditions. Ouarzazate in Morocco is chosen as exemplarily site since is located at a latitude which may be considered as typical for CSP plants and it has good but not extreme solar resources.

Location of site

Particularly, the solar field design needs general geographical data of the site to correlate the site with areas defined in national codes (e.g. wind load areas) or to define loads to structural system of the heliostats (e.g. temperature loads).

Figure 5: Definition of geographical location

- Ouarzazate 31°3'N; 006°52'W (WGS84)

Service lifetime

For all components a service lifetime of 25 years is assumed.

- Service lifetime ≥ 25 years

Longer lifetimes can be defined and may allow more economic financing conditions.

4.2. Heliostat Field

4.2.1. Heliostat field design parameter definition

The subsystem heliostat field of the Reference Power Plant contains:
Mirrors, drives, support system/pylons, solar field earthworks and foundations, control system and strategy, power and control cabling, meteorological stations, cleaning system or vehicles.

Term	Definition	Further reading
Intercept	Amount of irradiation intercepted by the receiver divided by the irradiation reflected by the heliostat field and attenuated by the passage through the air	

Reflectance, reflectivity	Specular reflectance of solar radiation such that light can be directed to the receiver	SolarPACES guideline for Heliostat Performance Testing
Incident flux density	Radiative power per area incident on the receiver surface, gross = before losses; it determines the heating of the receiver and needs to be controlled by an aim point strategy	
Net power	Thermal power absorbed by the heat transfer fluid (molten salt) after thermal losses	
Slope error (1 dimensional)	Root mean square (RMS) of deviations of the normal vector of the reflector material due to mirror shape (mrad)	SolarPACES guideline for Heliostat Performance Testing
Tracking error (1 dimensional)	Root mean square (RMS) of deviation of heliostat normal vector form desired orientation (mrad)	SolarPACES guideline for Heliostat Performance Testing
Gross mirror area	Heliostat aperture area including gaps between facets	
Net mirror area	Aperture area which is filled with mirror	

4.2.2. Interfaces

The heliostats and the heliostat field have the following key interfaces to the neighbouring systems. The interfaces are treated as boundary conditions in section 4.2.3.1 .
The interface to the environment is soil, atmosphere and radiation.

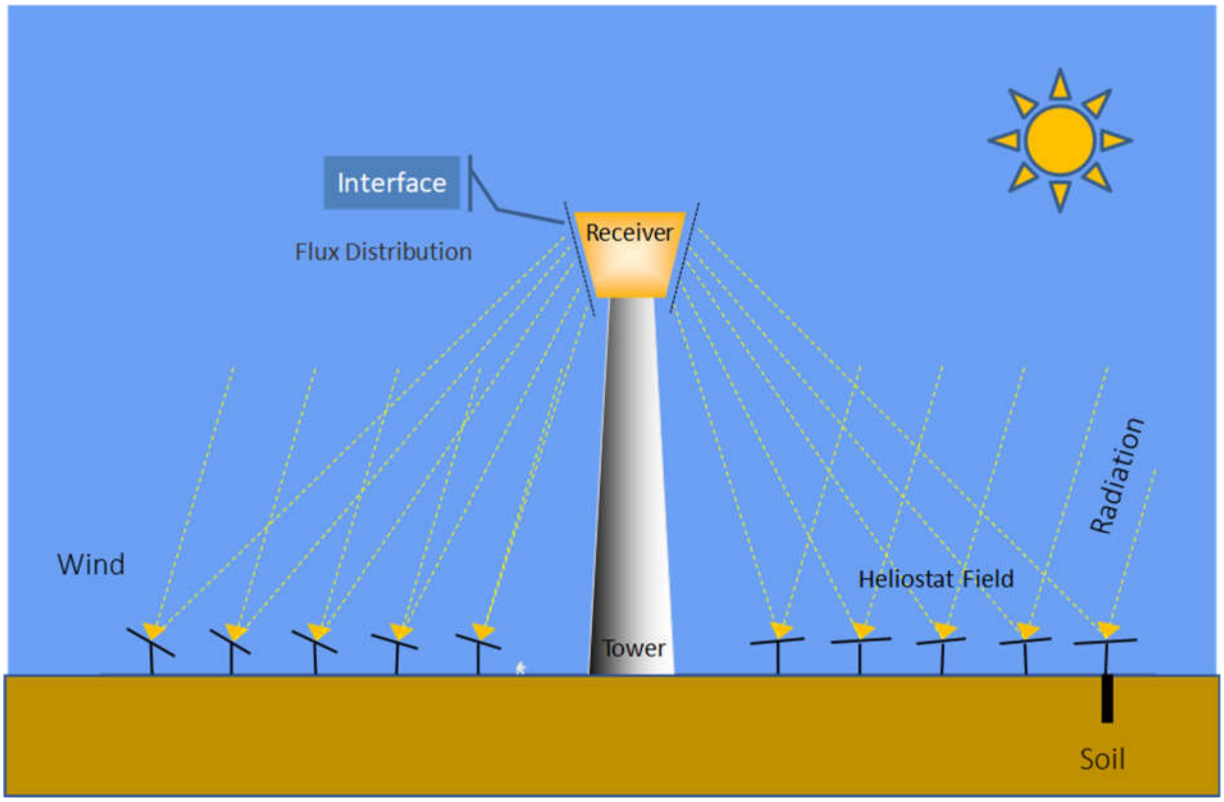


Figure 6: Interfaces of the heliostat field

For operation, the key interfaces are the physical surfaces of the receiver (+ heat shield + tower structure) as well as the link to the control system.
In O&M, cleaning and repair define an interface.

4.2.3. Heliostat field design

The key design parameters and design processes of the subsystem are described in the subchapters below. A summary table is given in the Data Book in the appendix 9.3.

4.2.3.1. Boundary conditions

Sourcing of boundary conditions

Boundary conditions of the specific site for the heliostat design are defined by the project developer or owner in a tender document or a request for proposal. It is necessary that the boundary conditions are fixed as precisely as possible to allow

- technology providers of the heliostat field to offer safe and cost optimized designs,
- competitive designs to be compared on the same base, and
- to have confidence in achieving the performance predicted by the performance model.

Many boundary conditions can be extracted from the relevant national codes. For sound and economic design, it is required to support the definition of boundary conditions with relevant expert investigations and reports. These are the following:

- Digital elevation model or topographical map of site including tower location, heliostat exclusion zones, roads etc.
- Expert report on solar resource (with additional characteristic meteorological data) from ground stations and satellite-based measurement (TMY, including atmospheric attenuation)
- Expert report on geotechnical characteristic of site.
- Expert report on extreme wind analysis for design wind load assessment
- If applicable: Expert report on soiling and corrosive environment

Boundary conditions for single heliostat design

For the CSP reference plant, typical boundary site conditions have been chosen. Mostly they refer directly to the reference site close to Ouarzazate, Morocco. The data given here is to be used only for general reference and cannot be used/compared to a real detailed design for a selected site. This would have been beyond the scope of this study and report.
In the following chapters, the definition of boundary conditions related to the heliostat design are given. They enable every heliostat technology provider to optimize a design. To adapt the CSP reference plant to other sites, the respective lists have to be modified.

Wind loads on heliostats

Usually wind loads are the governing load for the design of the heliostat structure including for example support structure, foundation, drives and performance.

Survival wind load (per code / per expert report)

The maximum design wind speed is important for safe and economic design. If it is taken on the very save side, the design will result in a heavy and uneconomic design. If it is taken on the unsafe side, the probability of damages to heliostats or underperformance is high.
Usually, the value of the basic wind speed (3-second-gust speed at 10 m height above ground) with a 50 year recurrence period is taken as base of the load definition. The value can be taken from the local wind load code (usually conservative / see also paragraph “Extreme wind analysis” below).

- Basic wind speed (3 second gust speed at 10 m above ground): 35 m/s

To calculate the survival wind load from this value, the effects of the local topography, vegetation and buildings on the wind profile need to be included.

For the reference power plant:
- Complete flat terrain without vegetation and buildings

As the load calculation is based on wind pressure, also site altitude, normal atmospheric pressure and turbulence intensity are important to have.

- Altitude: ~1280 m,
- Atmospheric pressure: ~850 mbar

Aerodynamic coefficient to be used in the design of the heliostats shall be according to the Code or determined in a boundary layer wind tunnel test by an experienced well-established wind expert like CPP, RWDI or Wacker Engineers. CFD analysis shall not be allowed.

- Expert report on aerodynamic coefficients of the heliostat and the heliostat field

Extreme wind analysis (definition of survival wind load)

The design code usually allows also the survival wind load to be determined for the local site by a wind expert (usually more realistic and economic). This approach is therefore generally recommended. This approach is based on measured weather data in the region and conclusion on a characteristic wind load for the site based on a code supported procedure that also accounts for the local topography and terrain roughness. As weather data include also atmospheric pressure, temperature etc., the effects of e.g. altitude of the site and temperature on wind pressure are included.

Wind in operation

Local instantaneous wind speed measurements or prediction are also important to determine performance of heliostats depending on:

- Performance losses from wind loads in operation
- Down time from heliostats being in wind protection mode at higher wind speeds
- Implementation of a smart stow regime (wind protection mode depending on wind direction, heliostat position in the field and actual concentrator orientation of individual heliostats)

To perform this evaluation and detailed design, a statistical representative evaluation of wind data with high time resolution (< 3 sec) is desirable. The following wind data is required therefore:

- Expert report/measurement on local wind characteristic in operation
  - Wind speed (t),
  - Wind direction (t)

The above-mentioned data in 10 min resolution is also usually part of the Meteorological report on solar resource and the TMY data set (DNI, visibility, wind characteristics). Wind data is usually seen as to be of secondary importance in the assessment of the meteorological data, therefore the quality of the wind data within the TMY must be verified.

- Meteorological report on solar resource (DNI, visibility) and wind characteristics

A minimum requirement is a representative or reference wind speed for operation, although this simplification is a significant restriction to the heliostat design and performance optimization.

- Reference wind speed (at 10 m height): 4 m/s

Usually, the minimum requirements of heliostat performance have to be fulfilled/guaranteed below the reference wind speed. Between reference wind speed and Go-to-Stow wind speed reduced performance is acceptable. The reduced performance can be given with the reduced tracking accuracy (RMS value in mrad / see also chapter 4.2.3.3

Go-to-Stow Wind speed/load (wind alarm)

Heliostats have to move to their wind protection position above a certain wind speed/load level (go-to-stow wind speed). A wind alarm is released therefore based on local wind measurement at representative locations at the heliostat field.

- Go-to-Stow Wind speed: 15 m/s

If the wind measurement indicates a wind speed beyond this level, the heliostats have to move to their wind protection position.

Smart Stow strategy

An alternative smart stow strategy is more economic compared to a single and constant Go-to-Stow Wind speed. With this strategy the wind alarm is released at different levels of windspeed and for different parts of the field, depending on the real wind load on the heliostat and depending on the time the heliostat requires to reach the wind protection position.
The smart stow strategy allows longer operation with more heliostats and is used for optimized performance.

Temperature load

All temperature induced effects on material properties and thermal stress in structures have to be considered.

- Min/Max extreme ambient temperatures ~ -10,0 / 50,0 °C

Soil and seismic characteristic

Base of the design of foundation is a detailed expert investigation in the solar field area. Usually, the expert can recommend the most economic type of foundation according to the soil characteristic. The density of tests in the solar field must be high enough to optimize the foundation throughout the solar field.

The heliostats have also to be designed to resist seismic events. Seismic events shall be detected during operation and heliostats shall be shut down upon seismic events to be checked for damages. Heliostats shall be operational within 24 hours after the occurrence of a seismic event. The Geotechnical report shall also include an assessment and classification of the seismic characteristics of the site.

- Geotechnical report (soil characteristic, recommended foundation types and seismic classification)

Applicable codes and standards for heliostat field

The structural design of all components and the application of the loads is be done according to international standards. The compliance with national standards has to be checked additionally. International standard is for example the EC code. In particular:

- EN 1990: Basis of structural design
- EN 1991: Actions on structures
- EN 1992-1-1: Design of concrete structures – Part 1-1: General rules and rules for buildings
- EN 1994-1-1: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings
- EN 1993-1-1: Design of steel structures – Part 1-1: General rules and rules for buildings
- EN 1993-1-8: Design of steel structures – Part 1-8: Design of joints
- EN 1997-1: Geotechnical Design

Further applicable guidelines, codes and standards

- SolarPACES Reflectance Guideline: Parameters and method to evaluate the solar reflectance properties of reflector materials for concentrating solar power technology. (Available online: http://www.solarpaces.org/tasks/task-iii-solar-technology-and-advanced-applications/reflectance-measurement-guideline).

- SolarPACES Guideline: Guideline for accelerated aging for silvered-glass mirrors and silvered-polymer films (preparation in task III group)

- SolarPACES Guideline: Guideline for accelerated sand erosion testing of reflectors for concentrating solar power technology (preparation in task III group)

- SolarPACES Guideline: Guideline for measurement and assessment of mirror shape for concentrating solar collectors (preparation in task III group)
- SolarPACES Guideline: Best practices for Heliostat Field Performance Testing (task force being launched in task III group)
- ISO 9806:2013 Solar energy - Solar thermal collectors - Test methods (Hailstone Test)
- AENOR Standard: Reflector Panels for Concentrating Solar Technologies (in preparation)
- IEC TC 117: Solar Thermal Electrical Plants – Part 1-1 Terminology: 117/75/DTS (in preparation)

Water drainage

The water drainage system in the field needs to be designed according to maximum expected precipitation to avoid flooding and washing out of the solar field. See also chapter 4.9.15.

- Average yearly/max daily precipitation [mm] ~ 132 / 28

Corrosive environment

To design the materials and equipment to be used outdoors, a characterization of the corrosive environment on site is requested in accordance with EN ISO12944 (Corrosion protection of steel structures by protective paint systems). In case of doubt on corrosive problems (industry, corrosive elements in the soil, humidity etc.) a local expert survey is required.

- Corrosion category according to EN ISO12944 ~ 3 (medium)
- Expert report on local corrosive environment
- Avg/Min relative humidity [%] ~ 29 / 0

Guaranteed performance

The guaranteed performance values should be based on the following operating conditions of the solar field:

- Data from the Typical Meteorological Year file (TMY)
    - Direct Normal Irradiation (DNI)
    - Wind speed (m/s)
    - Relative Humidity (%)
    - Ambient Temperature (°C)
    - Attenuation in the atmosphere
    - Soiling on the mirrors

It must clearly be stated which availability is assumed and/or guaranteed.

Minimum requirements for heliostats

High requirements for heliostat quality with low optical and tracking errors allowing a fine-tuned supply of irradiance to the receiver shall be defined. This enables safe and efficient operation with detailed aim point strategy (see Section 0).

- reflectivity > 0.93
- optical errors

3-s-gust (m/s @ h = 10 m)	Tracking error (1D, RMS, mrad)	Slope error (1D, RMS, mrad)
0	0.5	1.07
4	0.5	1.28
12	1.4	1.5

- go to stow < 10 minutes
- availability > 0.99

Reference heliostat: Stellio

For the CSP reference plant, a reference state of the art Stellio heliostat has been used for the design.
The Stellio high performance heliostat has been developed by sbp and partners in the Stellio Consortium. It is arguably one of the world's most cost-efficient heliostats and received awards from SolarPACES, CSP Plaza and CSP Today (von Reeken et al. 2015; Monterreal, Fernández, and Enrique 2015; Balz et al. 2015; Iriondo et al. 2015; Monterreal and Enrique 2015; Arbes, Weinrebe, and Wöhrbach 2015), (Hankin et al. 2018). For reference, papers of the SolarPACES Conference 2020 can be used (Keck, et al., 2020) (Keck, et al., 2020).
The above-mentioned requirements used for this report are based on using the Stellio Heliostat.

Figure 7: Reference heliostat Stellio (power plant Hami, China), see https://www.sbp.de/en/project/kumul-dongfang-tower-stellio/)

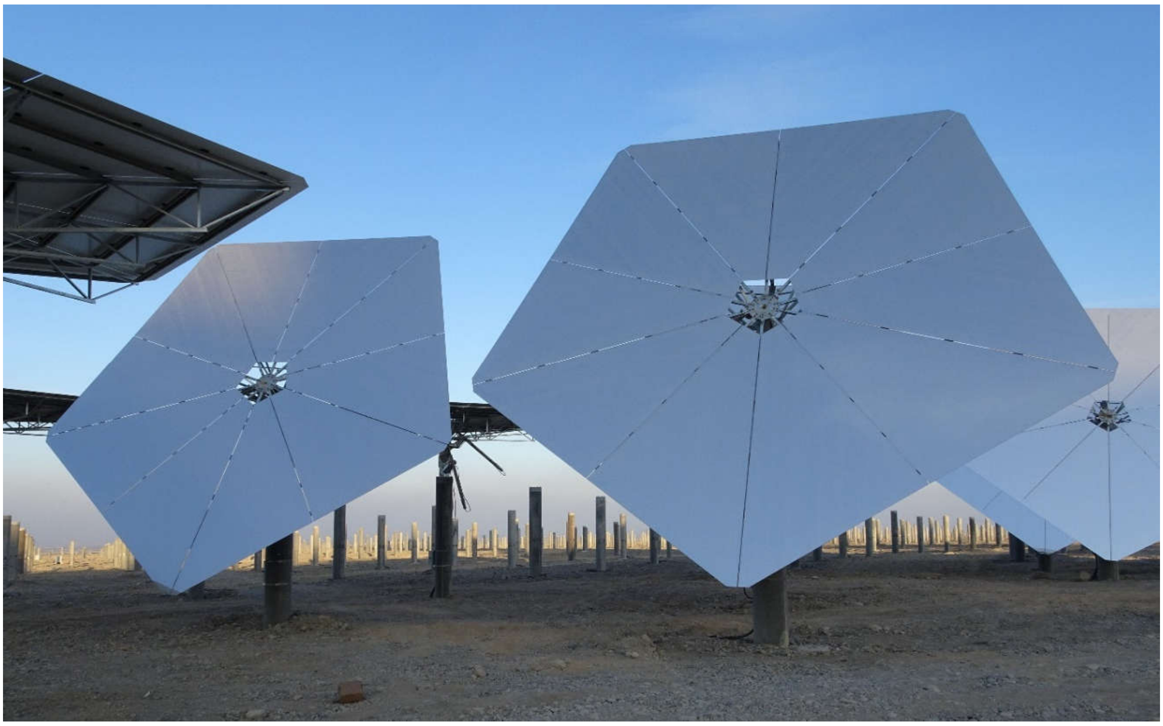


Figure 8: Reference heliostat Stellio (Hami power plant, China)

Boundary conditions for heliostat field design

This section lists all necessary inputs to perform a comprehensive field layout as described in Section 4.2.3.2.

- Load profile (time of delivery-value),
- min/max power of receiver,
- receiver flux limits depending on load, wind;
- receiver efficiency as function f(load, wind)
- restrictions in transient conditions (preheating, clouds, …)
- TMY (DNI, wind speed, wind direction, at least hourly), P50, P90

Receiver limits and operation

The receiver typically has a window of power it can accept for stable operation (min/max power). For each receiver state and during the state-to-state transitions, the receiver has maximum allowable flux density limits that the irradiation supply by the heliostat field may not surpass. It is the critical task of the aim point strategy to provide as much power to the receiver as is safely doable.

The TMY allows to simulate the joint heliostat field / receiver operation and adjust their respective power capacity.

The transient situations may require quite delicate flux distributions with good control about heliostats with low tracking and slope error. The higher the temporal resolution (< 1 h, preferably <=10 min), the better the transient analysis. Cloud and shadow patterns are decisive here.

Once safety of operation is ensured, thermal efficiency is a function of load and is important for an optimized net power capture into the heat transfer medium. Especially the part load behaviour is critical and may motivate to shift heliostats between positions in the field for morning/evening or noon productivity.

Solar resource

The solar resource is typically described by typical meteorological years (P50, P90) based on ground and satellite measurements. The visibility or attenuation affects the absorption of light whilst travelling from the heliostats to the receiver.

The site and the TMY describing it is attractive for a concentrating solar plant when the annual sum of (direct normal) irradiation is high (say > 2 MWh/m²) and the intra-day and intra-year variability is low. This allows a steady operation with a high capacity factor.

Weather patterns like regular clouds at certain times of the day will change the field layout to adapt it to the productive hours of the day.

A high atmospheric attenuation would prohibit heliostats to stand far away from the receiver and would drive receiver height and cost up and field efficiency down.

Topography

Heliostat fields are usually not strongly affected by the topography as long as the ground is fairly flat in general. For implementation and layout of the heliostat field a topographical survey

is required anyway. It is mandatory to exactly define the systems of reference with its relation to WGS84 (being the reference for the sun position algorithm), e.g. by an “epsg” code as well as scale (Gross & Balz, Potentially Confusing Coordinate Systems for Solar Tower Plants, 2019)
The slope should be lower than 10°, no bigger boulders impede access to the sites of the heliostat installations, dirt roads are enough for typical machinery to access the field. Steeper slopes can be accommodated with suitable road layout.
The field layout should consider the topography to optimize shading, blocking and ground coverage.

- Expert report on topographic survey of site (dwg, point cloud) in epsg-coordinate reference system

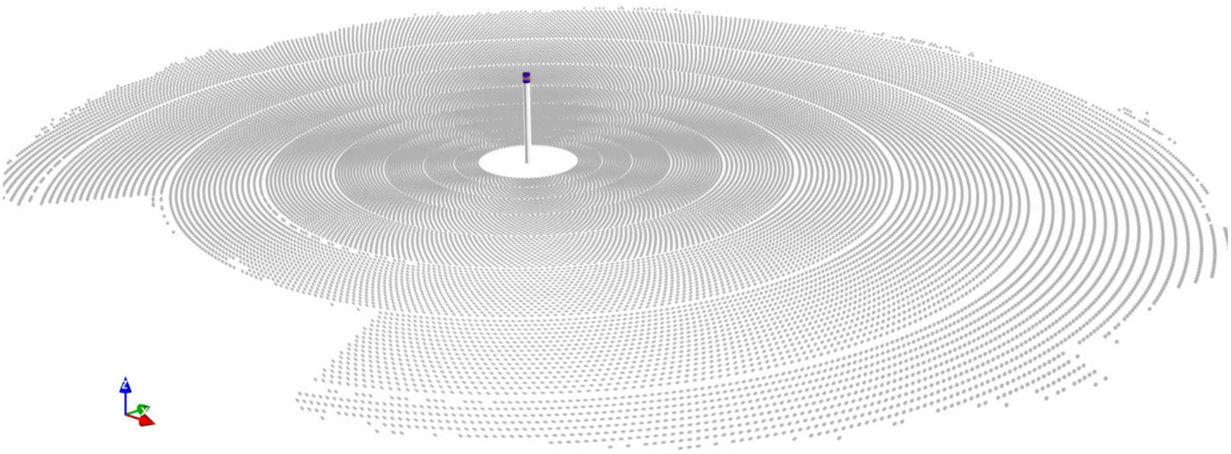


Figure 9: Exemplary sketch of a CSP reference plant with 30927 Stellio heliostats.

Assembly concept

The design concept of the reference heliostat Stellio consists of a combination of subcomponents (steel components, mirrors etc) that can be manufactured in optimal cost localizations in order to be transported to the site. On site they are assembled in a workshop using an industrialized assembly process in an assembly line, to be installed and commissioned in the field. The assembly workshop is a temporary building.
The component supply rate can be adapted to suit the required or most economic overall assembly schedule. Also, the assembly time in the workshop can be adapted to the schedule requirements by installing additional assembly lines to work in parallel.
For the reference plant an assembly time of approx. 7 months using two assembly lines in one temporary workshop was assumed.

Boundary conditions for fabrication, assembly and commissioning schedule

A critical factor to economics of all CSP plants is the relatively long fabrication, installation and commissioning time. Due to complexity of the system and different subsystems, the number of interfaces and dependencies is high.

This requires a fully integrated project schedule and controlling. To integrate all dependencies, all suppliers of subsystems need to deliver the best/shortest lead time or if not equivalent, the most economic lead time of the most critical project phases to the EPC.

The integration in the overall schedule adapts the different lead times to allow for just-in-time delivery. Obviously, too long lead times lead to negative economic impact, but also too short lead times can be costly.

It is assumed that a preliminary and basic engineering of heliostat design and solar field design is already done during tender or project development stage. The following exemplary milestone and time schedule for heliostat field starts with the Notice to proceed (NTP) to the Heliostat Field subcontractor/EPC.

An exemplary time schedule including these milestones is shown in Figure 10 below. A consistent timeline covering the whole development and realization time of the complete CSP tower plant is given in chapter 7.1.

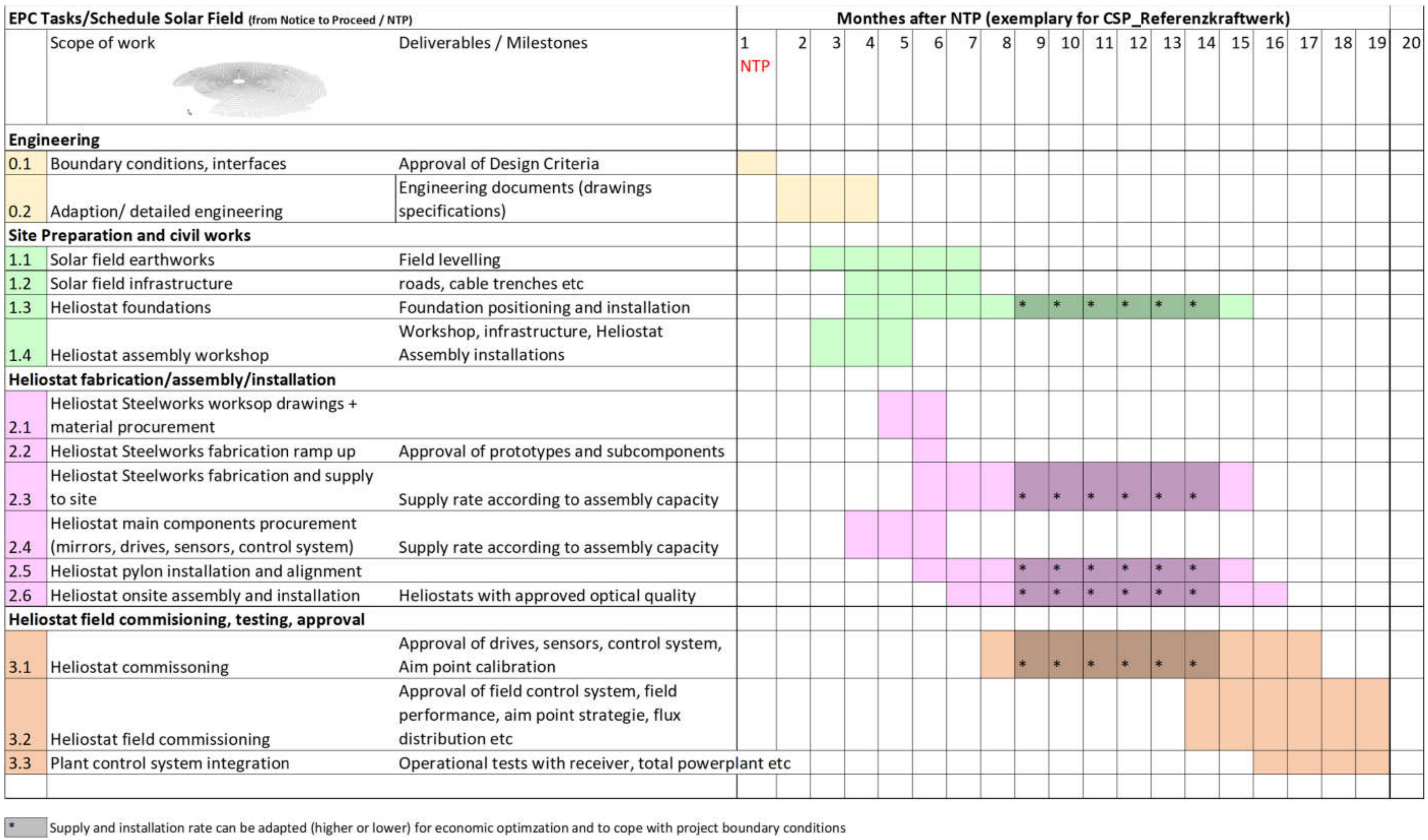


Figure 10: Exemplary Milestone and time schedule for Heliostat Field

4.2.3.2. Heliostat field optimization

Heliostat designs from different suppliers differ in parameters like size, axes orientation, power demand, optical performance, aiming strategy properties and more. Also, receivers from different suppliers differ largely in performance and geometry. Therefore, it is advised to perform an optimization of the solar field – receiver configuration to achieve the specified performance with lowest possible cost.

First, the optimization goal needs to be specified. Typical goals are minimal levelized cost of electricity (LCoE) or maximal value of electricity taking time-of-delivery into account. To minimize LCoE, the layout optimization tries to maximise the annual usable energy absorbed by the heat transfer medium for a given investment (amount of heliostats, tower height, receiver type).

The following plant parameters need to be optimized with respect to the heliostat field:

- Field area (-> cost of land, tower height, visibility)
- Heliostat geometry, design and optical quality (Stellio has been optimized for large power plants (Keck, et al., 2020))
- Receiver height and diameter
- Allowable flux levels on the receiver depend on receiver panels, load factor and wind
- Level of high and low dumping (minimum and maximum thermal receiver load)

Design optimization of tower height

The tower height is an important design parameter: Higher towers typically shorten the path length of the reflected light, reduce atmospheric attenuation, lead to smaller heliostat focal spots and can increase intercept. Typically, this increases the average optical efficiency of the heliostat field. The higher tower allows for denser fields which require less ground area. This can lower acquisition and site preparation cost.
However, in the examined range [200 – 275 m], the higher tower leads to higher CAPEX (higher mechanical load, more installation effort) which grow faster than the tower height (Weinrebe, et al., 2019). Higher towers cause higher operation cost due to parasitic consumption for HTF pumping against a bigger pressure head. The higher tower will also cast more shadow.
A higher receiver with more compact field will receive a higher power supply around noon and suffer from more shading in the morning and afternoon. This can lead to dumping losses due to too high and too low power. A lower tower typically shows a flatter power supply over the day.
The specification requires the assessment of the trade-off between performance and cost.
For the CSP reference plant, a 200 m tower height (ground to receiver centroid) was chosen on the basis of LCoE. The wide heliostat field allowed for a long, stable production for many hours of the day with a relatively small noon peak. The high power dump can be avoided by the selection of pumps (6 x 20% rather than 3 x 50%) and a sophisticated aim point strategy

using the reserves in the receiver's flux limits. The smaller pumps allow to use the load range from 0.15 – 0.3 of design load, but they are specifically more expensive.

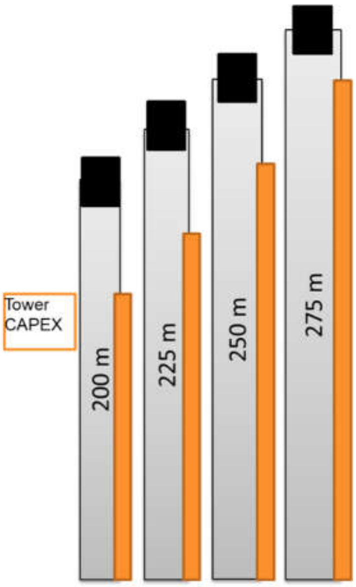


Figure 11: The sketch shows the examined tower heights and the over-proportional growth of tower-CAPEX (tower cost from (Weinrebe, et al., 2019)).

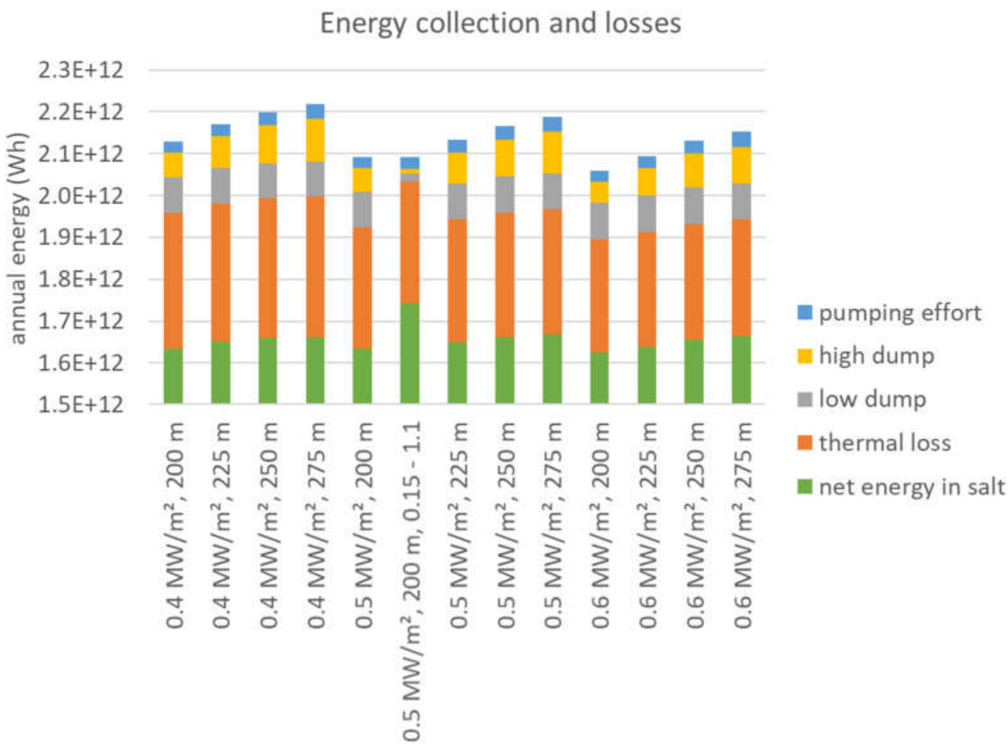


Figure 12: It is essential to consider the operation to account for low/high dump. Only the consideration of the full system (heliostats, receiver, pumps, BoP), its performance and cost allows to find a techno-economic optimum.

Design optimization of field and receiver geometry

The heliostats should occupy efficient positions in the field, but they need to supply the reflected power to the receiver and are affected by the flux constraints of the respective receiver section.
The layout optimization adapts the field geometry and aim point strategy to cater to the optimization target (e.g. annual usable energy captured by HTF). It can therefore be efficient to move heliostats from one sector to another if the corresponding receiver panel is already “full” and excessive aiming would cause more expensive spillage loss.

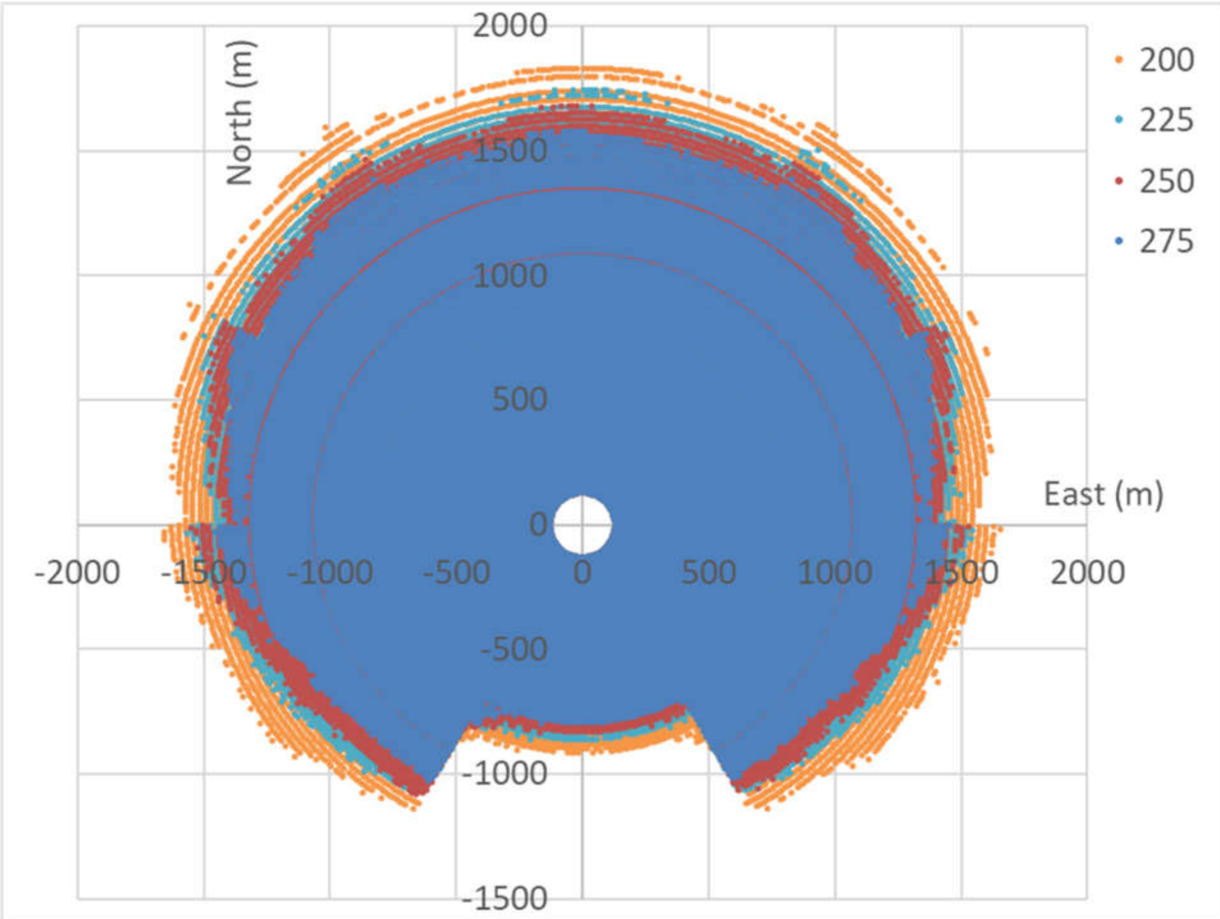


Figure 13: The graph shows for an intermediate design how higher tower heights lead to more compact fields. The void in the south stems from the very low flux limit in this particular receiver variant which would impose too high aiming losses.

As the wind increases, the heliostats’ slope and tracking errors grow. Therefore, it is mandatory to consider typical wind during the field layout process to model flux distributions and intercept efficiency appropriately.
If the annual net energy is the optimization goal, it is important to consider the receiver efficiency to fairly weigh part and full load operation typically in morning/evening and noon.

Operation and aim point strategy

The heliostat field concentrates irradiation on the receiver, but this needs to happen in a tightly controlled way.
The major disturbances on the field side (clouds, wind, sun position) change the reflected power of each heliostat and the area of intercept. The operation and salt flow as well as the wind chill change the power demand and flux limits of the receiver.
An aim point control is necessary to operate heliostat field / receiver system safely and efficiently (Gross, Landman, Balz, & Sun, 2019).

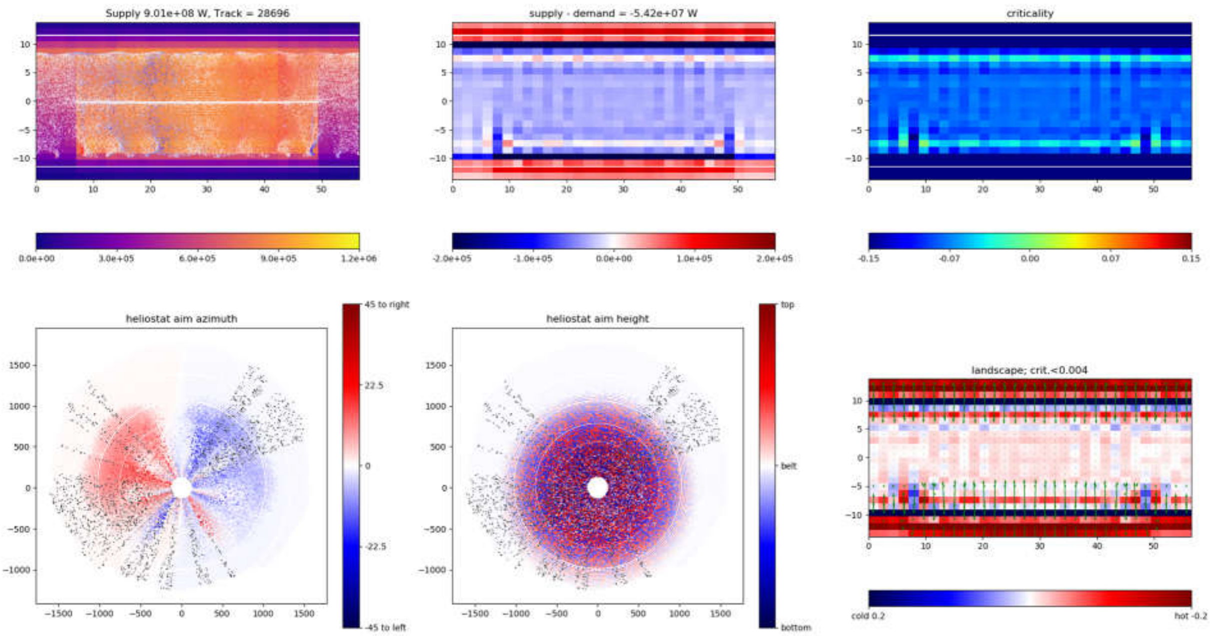


Figure 14: Snapshot of Aim point strategy dashboard. The control finds aim points to operate the receiver safely (i.e. below the prescribed flux density limits) at 115 % design load.

The aim point strategy proved its value in ensuring a safe and efficient operation. It is strongly recommended to request a powerful aim point strategy from heliostat field / receiver supplier.

Complementary photovoltaic field

A complementary photovoltaic field with approx. 10 MW_p capacity can cover most of the parasitics of HTF pumps, heat tracing and heliostat field. The levelized cost of self-produced PV electricity are much lower than average grid electricity prices and reduce the plant's OPEX and consequently the LCoE of the CSP electricity.

Auxiliary planning tasks for complete field layout

The complete field layout design also comprises the planning and costing of:

- Infrastructure (runoff, evaporation ponds, roads, power evacuation lines)

- Power and communication infrastructure (trenches, cables or autonomous, wireless solutions).
- Auxiliary PV field to cover day-time parasitics of CSP plant (pumps, heliostats, heat tracing)
- Heliostat cleaning system
- Meteo stations

4.2.3.3. Performance Warranties

Specified performance values of the solar field need to be tested and approved at the end or after construction and commissioning. In general, it is the EPC contractor's duty to prove these and verify it along the agreed performance warranties.
It is custom that preliminary acceptance tests are conducted with subcomponents of the CSP plant, the heliostat field being one of them. Usually, the solar field is handed over after the successful preliminary acceptance to the O&M team of the owner (Mehos, Price, Cable, & Kearney, 2020).

The basis for a well performing heliostat field is the single heliostat which has to perform "correctly". In order to describe and measure the performance of a single heliostat, the "SolarPACES Guideline for Heliostat Performance Testing" (DLR, Instute of Solar Research, 2020) has been developed by a group of R&D and industry experts during the last years. However, at the end, the performance of the whole field, which means the superposition and interaction of all heliostats determines the energy collected in the aperture of a solar central receiver. For that reason, a second guideline is currently outlined: The "SolarPACES Guideline for Heliostat Field Performance Testing" (DLR, Instute of Solar Research, 2020). Both guidelines aim to be commonly agreed protocols between R&D centres and industry in the field of heliostat performance testing (Röger, Blume, Schlichting, & Collins, 2020). The guidelines serve as a pre-standard as long as international standards (e.g. IEC) are not yet available.

The preliminary acceptance procedure of the heliostat field is usually followed by the final acceptance procedure. This test comprises the complete CSP plant and covers a longer operation time of several months, one year or more. During the test the plant has to achieve the warranted overall performance and reliability by comparison of measured performance data with data of the warranted performance prediction model. Final acceptance is not discussed in this chapter.

SolarPACES guideline for heliostat performance testing

The SolarPACES Guideline for Heliostat Performance Testing focuses on the definition of parameters and performance testing of single heliostats during a limited time period. Measurement techniques or other techniques to derive the heliostat parameters are

suggested. Durability issues are treated in this guideline only in the sense that the heliostat performance can be tested from time to time.
Accelerated ageing and durability tests are not in the scope of this guideline. Although performance testing of a whole heliostat field (consisting of several heliostats with blocking/shading effects, aimpoints issues, etc.) will be based on the "Heliostat Performance Testing" guideline, the aspects of interaction of the heliostats in a solar field will be treated in a separate document "SolarPACES Guideline for Heliostat Field Performance Testing" (DLR, Instute of Solar Research, 2020).
The objective of the guideline is to serve as a commonly agreed protocol between EPC and contractors in the field of heliostat performance testing.

The guideline contains an internationally reviewed, concisely defined parameter list to escribe heliostats and quantify and measure their performance. It focuses on the definition of parameters and performance testing of single heliostats during a limited time period. Measurement techniques or other techniques to derive the heliostat parameters are suggested.
Sample data sheets of a heliostat test conducted according to the guideline are presented in Appendix 9.6

SolarPACES guideline for heliostat field performance testing

The interaction of the single heliostats in a solar field (blocking/shading effects) and the conditions of operation (e.g. cosine effect, atmospheric conditions, soiling, aimpointing) does not allow taking single heliostat performance by the number of heliostats. (Röger, Blume, Schlichting, & Collins, 2020)
The heliostat fields and distances are large, and the number of heliostats is enormous. Procedures to define and test these additional aspects are defined in the "SolarPACES Guideline for Heliostat Field Performance testing" (DLR, Instute of Solar Research, 2020).
A recently formed American Society of Mechanical Engineers (ASME) committee is working on Performance Test Code1 52 – Concentrating Solar Power Plants that should supplant this Guideline within several years.
The guideline covers the system boundaries as marked here in red. It does not involve receiver, power supply etc.

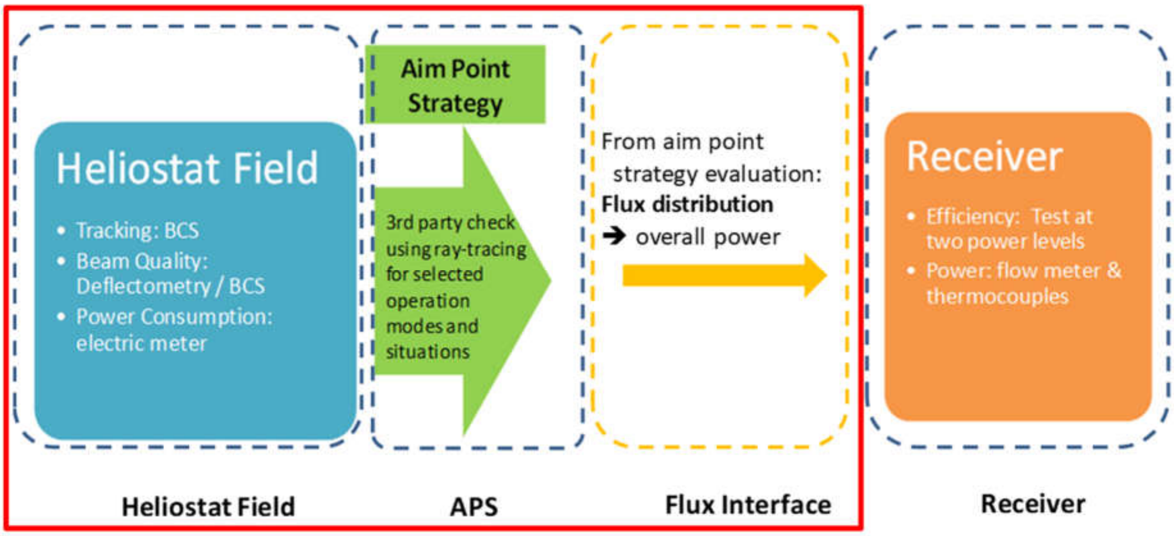


Figure 15: Scope of the SolarPACES Guideline for Heliostat Field Performance Testing (red frame)

The following topics are part of the acceptance procedure (among others):

- Prechecks for acceptance qualification (individual heliostats are already accepted see chapter above
- Instantaneous field status requirements for dynamic acceptance tests
- Safety Checks
    - Communication loss
    - Power loss
    - Emergency Defocus
    - Emergency Stow
    - Emergency Stow Time Requirement
    - Uninterruptible Power Supply (UPS)
- Tracking Accuracy
- Flux distribution
- Overall power
- Slope Error
- Reaction Time (Latency)
- Reaction to Contradictory Commands
- Power Demand

4.2.3.4. Exemplary Design specification for reference site

Complete specifications see also Appendix 9.3.

No.	Spezifikations	Unit	Value	Remark
	Heliostat			
1.	Heliostat Type	[-]	2-axes trackingachsiger multi facet glass-metal Heliostat, mounted on pylon	Stellio
2.	Apertur width	[m]	~ 9 m	
3.	Apertur height	[m]	~ 9 m	
4.	Number of mirrors per heliostat	[-]	10 + 1	horizontal x vertical
5.	Reflektive area of single mirror	[m²]		
6.	Optical height (Pylon)	[m]	~4.5	Center of heliostat
7.	Total reflektive area per heliostat	[m²]	48.5017	
8.	Reflectivity HFLCAL (annual mean)	[%]	89.34	HFLCAL input as product of reflectivity, cleanliness, availability: 0,94*0,96*0,99
9.	Beam quality	[mrad]	3.664	HFLCAL input as sum of slope error, tracking error, sun shape error
10.	Canting	[-]	On-axis	
11.	Electricity consumption tracking	[kW]	~0.02	Demand of single heliostat
12.	Slope error	[mrad]	1.06	1 dim, v_wind < 4 m/s
13.	Tracking error	[mrad]	0.6	V_wind < 4 m/s
14.	Root mean square deviation of sun-shape	[mrad]	2.23	

No.	Spezification	Unit	Value (V1.1)	Remark
	Solar field			
	Solar Multiple (SM)	[-]	1.5	
1.	Shape	[-]	360°	Sur.: 360°; N / S: North- / Southfield
2.	Number of Heliostats	[-]	30'927	1.5 km² net mirror area
3.	Optical efficiency @DP	[%]	66.9	
4.	Electricity consumption tracking	[kW_{el}/m^2]		
5.	Distance tower – first row	[m]	100	Abstand vom Mittelpunkt zu erster Reihe (RTURM)
6.	Land usage	[km²]	7.36	

Figure 16: Heliostat field exemplary design specifications

4.3. Receiver

The target of this chapter is to design a commercial receiver for the defined power plant size. Special focus is on an engaged optimization of the heliostat field and the receiver itself.

4.3.1. Task and design parameters for the receiver

Relevant parameters for receiver design are summarized in following enumeration:

- Allowable incident flux density
- Material selection
- Part load situations
- Investment and operational costs
- Manufacture and assembly
- Easy to maintain

According to state of the art this solar receiver should be designed as external one operated with solar salt as heat transfer fluid. The operation salt temperature ranges from 290 °C up to 565 °C. As market analysis showed, a typical plant size is of about a nominal electric power of 200 MW_e. Taking the desired full night operation into account a nominal thermal capacity of 700 MW_{th} results for the receiver.

4.3.2. Design study and technical optimization

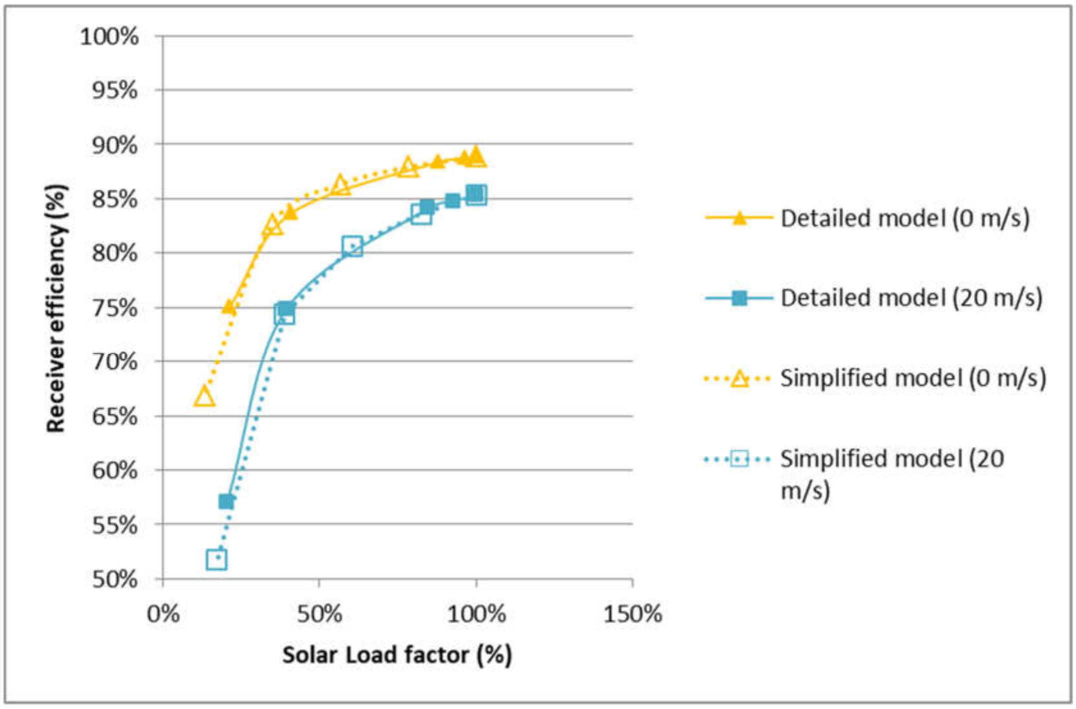


Figure 17: Receiver efficiency as a function of solar load and wind velocity

Nine different variants for a 700 MW_{th} receiver are designed on a thermo-hydraulic basis. These receiver designs show mean flux densities varying between 400 and 600 kW/m². They are aimed at either optimizing costs or optimizing receiver efficiency. This is either achieved by reducing the overall absorber size and the number of welds or by increasing the flow velocity inside the absorber tubes, which generally leads to more welds.

The receiver efficiency as a function of load and wind velocity of each variant is computed using an analytical receiver model. In this model local salt temperatures are computed for each panel based on a local energy balance of each axial element. The model considers absorbed solar radiation, forced convective heat transfer to the salt based on Nusselt-correlations (VDI, 2006), IR losses to ambient and convection losses to ambient (VDI, 2006). The increasing receiver efficiency with increasing load factor is depicted in detail in Figure 17. The model was validated by a detailed thermal FEM model (Frantz, 2017). Furthermore, the pressure drop, and hence the required pumping power was estimated (VDI, 2006). For each receiver variant a cost estimation was made. Based on this data the thermo-optical annual efficiency and LCOH of the variants is simulated.

Out of the 9 thermo-hydraulic configurations, three designs were selected to be integrated in the thermo-optical simulation of heliostat field and receiver described in chapter 4.2.3.

Based on the resulting optimized field layout a final receiver design is deducted by techno-economic evaluation. For this evaluation points like material demand and availability, pressure loss, construction effort, durability, lifetime and road transport were taken into account.

The allowable flux density of the receiver results from a lifetime evaluation. This evaluation is done by an analytical approach based on the procedure proposed by Smith (Smith, 1992).

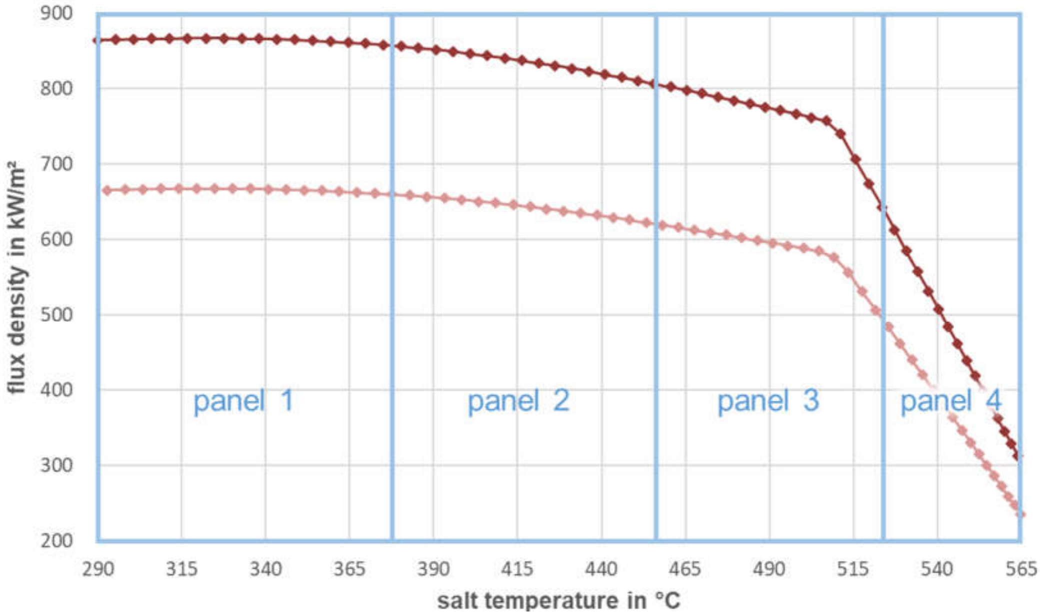


Figure 18: Allowable and mean flux density over flow path

The calculation is based on a given salt temperature and the local allowable flux density. The allowable flux density again is calculated by the tube strain, introduced by temperature differences in the tube section, and the allowable strain selected out of fatigue curves. The load collective for entering this fatigue curves was deduced using a rainflow algorithm based on weather data of the location Morocco (Kistler, 1987). An extrapolation of this one-year weather data to 20 years of operation was done.

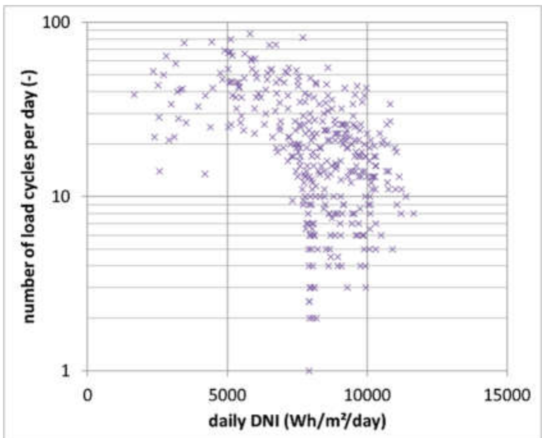


Figure 19: Number of load cycles per day as a function of daily cumulated DNI (Ouarzazate, Morocco)

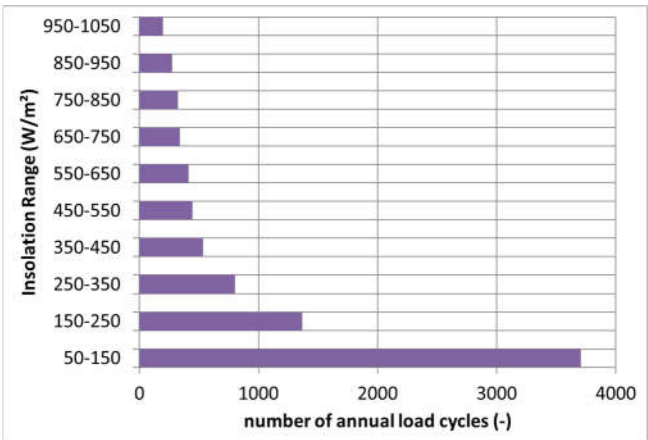


Figure 20: number of annual load cycles as a function of insolation range (Ouarzazate, Morocco)

In parallel, a second loop calculates the salt temperature change in every single receiver section. These results are passed on to the first one and can be used for converging this analysis. The parameters to be fulfilled are: mean heat flux, mean velocity and outlet temperature of salt. For a sophisticated analysis a utilization factor is inserted in this calculation. Without this factor in practical use of the receiver the allowable flux density would have to be applied to every single point of the receiver to reach the outlet temperature. The resulting flux densities for this receiver are shown in Figure 18.

4.3.3. Final receiver design

The final receiver design is derived by the described techno-ecomomic evaluation. Four panels are enough for each flow path to reach the required outlet temperature. The receiver is subdivided in a number of components suitable for road transport. The panels are for example divided into two parts just for better handling. Table 4 provides an overview of some more important key features and Figure 21 gives an impression of the intended panel configuration.

Table 4: Key features of receiver

Parameter	Value
Mean flux density [kW/m²]	536
Mean flow velocity [m/s]	3.36
Ratio height/diameter [-]	1.21
Number of panels [-]	8
Irradiated tube length [m]	22.8
Panel width [m]	7.2
Minimal part load [%]	19

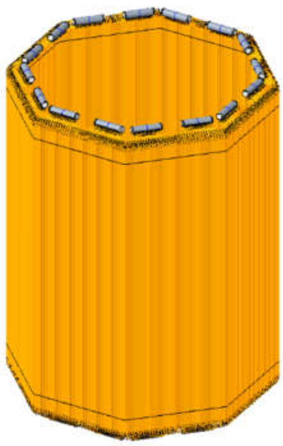


Figure 21: Panel configuration of the receiver

The analytical approach for determination of allowable flux density is now verified with a simplified panel configuration, but sophisticated Finite Element Method (FEM) simulation. The arising strain and stresses are evaluated by a lifetime analysis according ASME BPVC Section III.

The panel geometry is reduced to one absorber tube of 2 m in length, representing a section between two clips in commercial design. The ends of the section are forced to stay in their original plane, whereas an expansion in radial and longitudinal direction is allowed. Just one half of tube has been simulated due to axis-symmetric boundary condition. Lifetime of header, connecting pipes and other components are neglected for this validation, because of lower temperatures and stresses.

For a good balance of simulation effort and significance of results, three salt temperature bases are taken for evaluation at 290 °C, 506 °C and 518 °C. This values and their related allowable

flux densities can also be found in Figure 18. The tube temperatures are deducted from nominal thermal irradiation.
These three temperatures represent steady-state operational conditions at different panels. Each one is critical for a different damage mechanism as it can be seen in Table 5.

Table 5: Evaluated salt temperatures and the expected damage mechanism

Salt temperature	Description
290 °C	For fatigue due to high irradiation.
506 °C	For the combination of fatigue and creep due to already high tube temperatures and still high irradiation. It occurs before the film-temperature boundary condition (salt temperature at inner wall has to be lower than 600°C) get activated.
518 °C	For creep due to highest tube temperature.

Additionally, a salt pressure of 23 barg is applied inside the tube as well as earth gravity.
The simulation is done with a load collective derived from solar irradiation. The procedure to determine the occurring cycles is described above.

The investigations use inelastic material models. For the inelastic material model there is no detailed approach defined in ASME III. In literature different approaches can be found for solar applications (Barrett, 2015) (Barua, 2019). However, the material models should at least cover plastic deformations and thermal relaxation. The first one is important to account for strains due to high thermal stresses (secondary stress). Whereas the second one considers stress relaxation during steady-state operation.
Figure 22 to Figure 25 provide an overview of how equivalent stress is developing over time in the cross-section of the absorber tube exemplary for a salt temperature of 506 °C. Stress decreases over time, while strain rises over time. The tubes are all irradiated from the left side.

For creep-fatigue evaluation a path is placed on the irradiated side of the tube from outer to inner surface. Along this path temperature, local strain and principal stresses are read out for further evaluation.

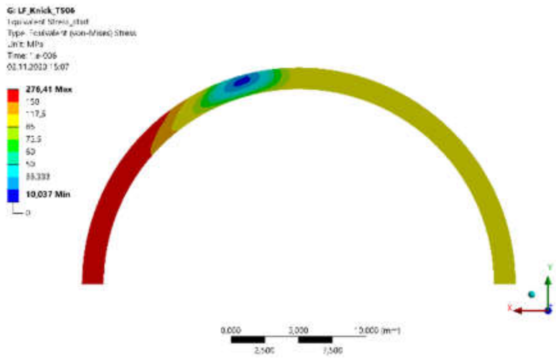


Figure 22: Equivalent stress in cross-section at initial conditions

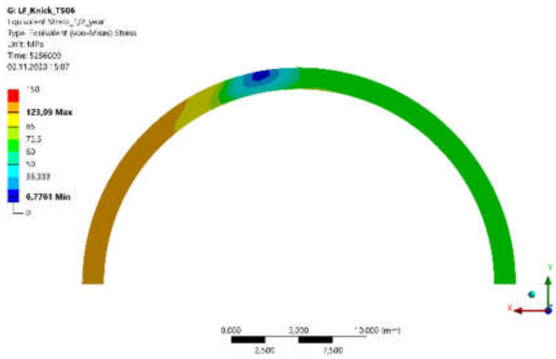


Figure 23: Equivalent stress in cross-section after 1/2 year

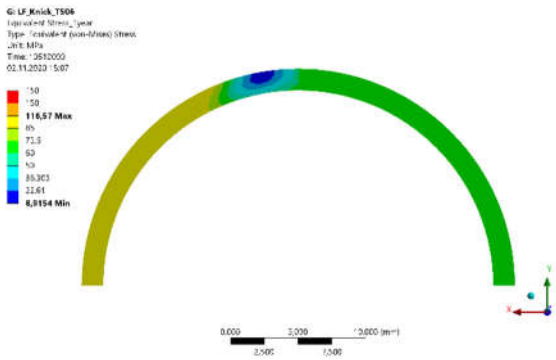


Figure 24: Equivalent stress in cross-section after 1 year

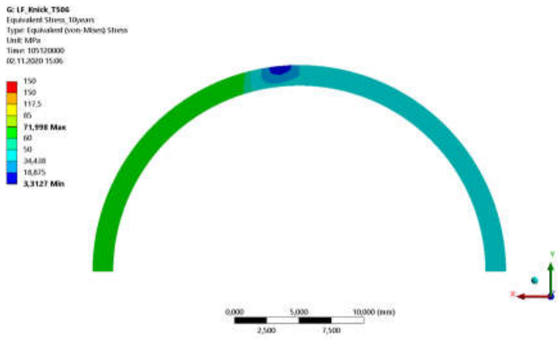


Figure 25: Equivalent stress in cross-section after 10 years

In ASME III the methodology of linear damage accumulation for creep fatigue assessment is presented. Thus, the total damage is calculated from the sum of the creep and fatigue damage according to formula (1). Thereby the fatigue damage is calculated for each cycle type j (j=1…p) by the quotient of occurring cycles n and allowable number of load cycles N_d. Simultaneously the creep damage is calculated for each time interval k (k=1…q) with constant stress and temperature by the quotient of interval duration Δt and allowable time duration T_d. The total damage must not exceed the permissible values from the creep fatigue envelope (ASME, 2019).

$$\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k \leq D \quad (1)$$

The local strain and stress components are used to determine the number of permissible load cycles N_d and the permissible time duration T_d. One change in formalism is done concerning permissible time duration. The relevant stress for determination of the allowable time duration is not reduced by the factor K'. This modification is feasible due to lower risk in solar application compared to nuclear ones. The change in factor is also proposed by different authors e.g.: (Berman, 1979) (Barua, 2019)

Comparison between analytical (allowable flux density) and FEM approach yields to some new finding:

For analytical approach creep damage was neglected, so the focus of comparison has to be set on fatigue damage. Life consumption is somewhat higher by the numerical approach. Reasons can be found in some conservative simplifications by numerical approach:

- Material model is implemented by the hardened cycle behavior, whereby lower stress values for the first few cycles are ignored.
- Fatigue evaluation is done with the highest strain values during operation time. Due to thermal relaxation, they occur at the end of receiver lifetime. A more realistic and reduced fatigue damage could be observed by a subdivided evaluation.

Discussing different boundary conditions, it also has to be mentioned that analytical approach is done by the assumption of straight tubes. In literature typical deflection curves are proposed (M. Laporte-Azcué, 2020). In Figure 26 they are compared to them of FEM model. These differences can lead to further deviations and have been taken into account for further simulations. Overall, even different boundary conditions are applied and the evaluation procedure is somewhat different the fatigue damage is in the same order of magnitude for analytical and FEM approach.

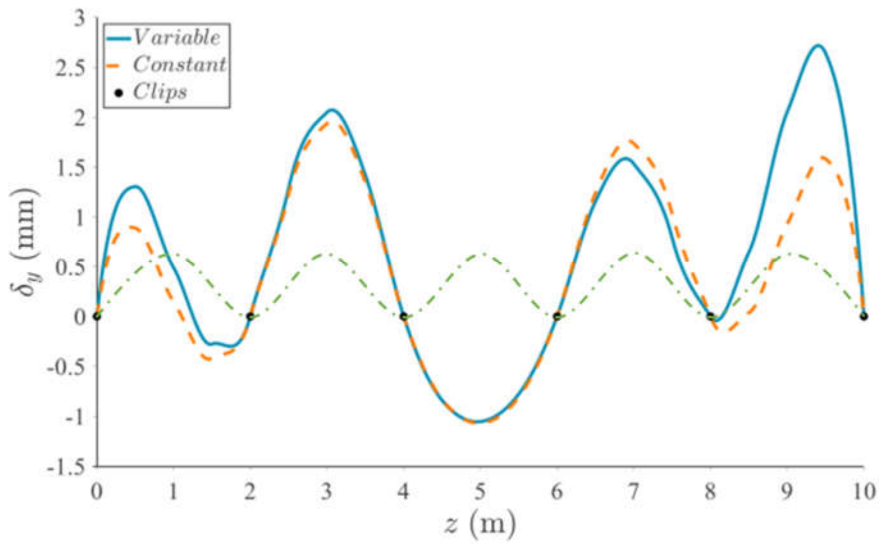


Figure 26: Schematic deformation of tube with 10 m length (Laporte-Azcué, 2020), enlarged by boundary condition set for FEM (green line)

Creep damage distributes in a relevant amount to component failure. For a pre-dimensioning tool (allowable flux density) it is feasible to neglect them, but a sophisticated lifetime analysis has to consider creep damage.

Further investigations with more detailed receiver geometry and refined evaluation process are going to be done. This will encourage our knowledge of receiver behavior and will provide clarity to what inspection interval is necessary for safe operation.

4.3.4. Operation of solar tower

The concept of operation consists of two separate parts: on the one hand the solar tower with heliostats as energy collection system and on the other hand turbine and steam generator as energy conversion system. Both parts are connected by the storage system. While the energy collection system loads the storage, the energy conversion system discharges it. To start the process some states must be passed through which are reached via transitions. States are characterized by their stability. Details of the conversion cycle are described in the parts steam generator and power block.

To operate the solar tower there are five states defined: solar tower off (standby mode), salt circuit standby (night mode), heliostat field standby and solar tower standby (receiver start-up and shut down) and solar (load) operation. The possible changes between states are shown in Figure 27.

During a long-term shut down, e.g. due to maintenance work or a weather forecast with hardly any direct normal irradiance (DNI), the solar tower including the heliostats is shut down. To collect solar energy, the following steps have to be absolved. The salt circuit is preheated up to 290 °C and then the cold pumps are started to fill the riser and downcomer. When the set point in the inlet vessel is reached, valve positions are changed so that the flow direction in the downcomer turns and corresponds to operation mode. Cold salt is pumped through the riser, receiver bypass and downcomer back to the cold storage tank. In the meantime, some heliostats are focused on the receiver and preheat the tubes. After both parts are in standby mode, the receiver is prepared for starting. The inlet vessel is pressurized and valves are opened to flood headers and absorber tubes. Then the serpentine flow is established by closing venting and draining valves. Salt flows through absorber tubes and solar operation can begin. More heliostats are focused on the receiver, following the flux density increases. When the plant is in solar (load) operation, the power and the outlet temperature of the receiver is controlled. The power arises from the position of the heliostats while a constant receiver outlet temperature is achieved by manipulating the massflow through the salt circuit. The pressurization of the inlet vessel allows a fast valve reaction to changing conditions.
If the receiver is shut down, the flux density is reduced, either by moving heliostats to the standby or stow position or by the available DNI based on the time of day. Some heliostats are still needed to prevent rapid cooling of the receiver. In the next step the receiver is drained and all heliostats can move to their stow position. Then the salt flow is directed through the receiver bypass which is reduced to a minimum at night mode. If the salt circuit has also to be drained, the entire solar tower is switched off.
In case of e.g. a station black out, the emergency flushing is triggered and the valves changes to their safety position. At the same time the heliostats get the command to move into stow position. The flux density reduces immediately. Cold salt flows out of the inlet vessel through the receiver. The driving force is the constant pressure in the inlet vessel, which is maintained by the emergency vessel as reservoir. After 30 seconds the emergency flushing is stopped

and the receiver valves are opened to drain and shut down the solar tower. The emergency flushing can start at any time - in any state and transition.

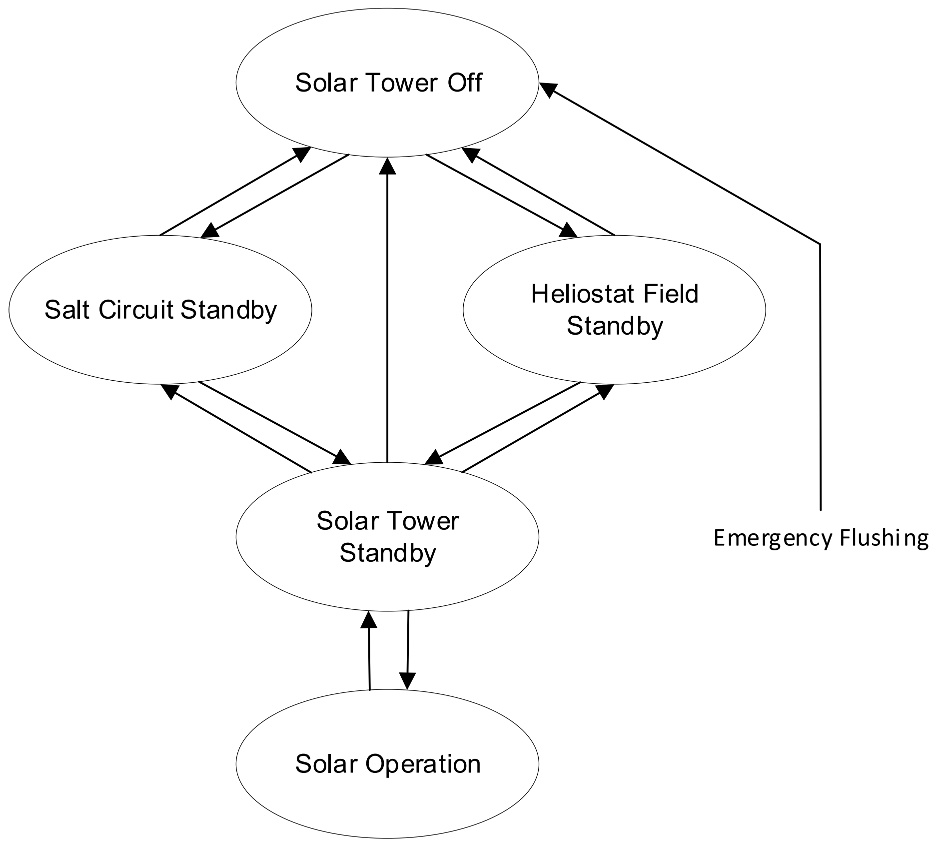


Figure 27: Overview of receiver operating states

The single states and transitions are described in Table 6 where the background of states is white and the one of transitions is grey. The starting procedure is recorded in the first column and shut-down procedure in the second. The five states are illustrated.

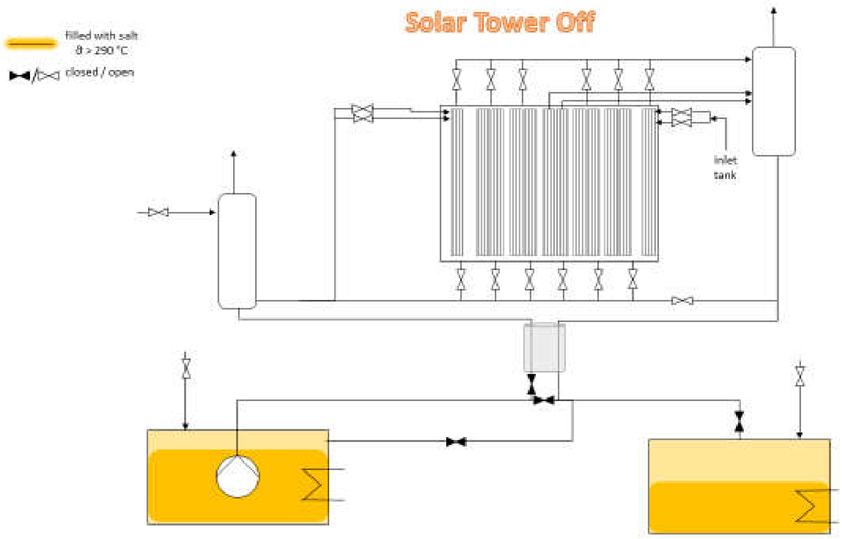
Table 6 Concluded states of subsystems of the energy collection system

Operating states

Starting procedure	**Shut-down procedure**

Solar Tower Off

Cold salt pumps are switched off and the total salt circuit including the receiver are drained (shown in the following figure). The trace heating of the salt circuit is turned off. All heliostats are in the stow position. The temperature of the components of the solar tower decreases slowly. The trace heating of the storage tanks hold the temperature above 290 °C.



Solar Tower Off → Salt Circuit Standby

The trace heating rise the temperature of the piping, inlet and outlet vessels up to 290 °C. Afterwards 2 of 6 cold salt pumps are started to fill the riser and downcomer at the same time until the inlet vessel has reached the setpoint. Then valve positions are switched so that the flow direction in the downcomer changes. Cold salt is directed through the salt circuit and the receiver bypass in the cold storage tank.

Solar Tower Off→ Heliostat Field Standby

The receiver ovens are switched on and preheat the headers at 290 °C. The heliostat position is changed from stow into standby position. Then some of them are focused to preheat gradually and uniformly the absorber tubes at 350 °C.

Salt Circuit Standby → Solar Tower Off

The level in the inlet vessel is decreased and the cold salt pumps are switched off. The salt circuit drains in the cold storage tank. After the salt circuit is salt-free, the trace heating are switched off except those heating the storage tanks.

Heliostat Field Standby → Solar Tower Off

The heliostat are moved to their standby position and then in their stow position. The receiver ovens are switched off.

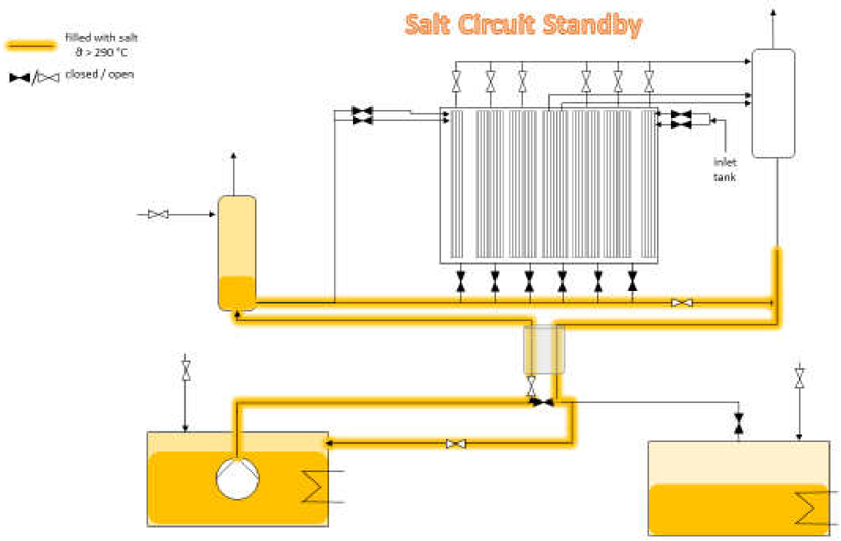
Emergency Flush out of all states → Solar Tower Off

All heliostats are moved in their stow position within 30 seconds. In the meanwhile synthetic air flows out of the emergency vessel in the inlet vessel. The salt still flows through the receiver so that it is continuously cooled.

	Then the components of the solar tower are drained.

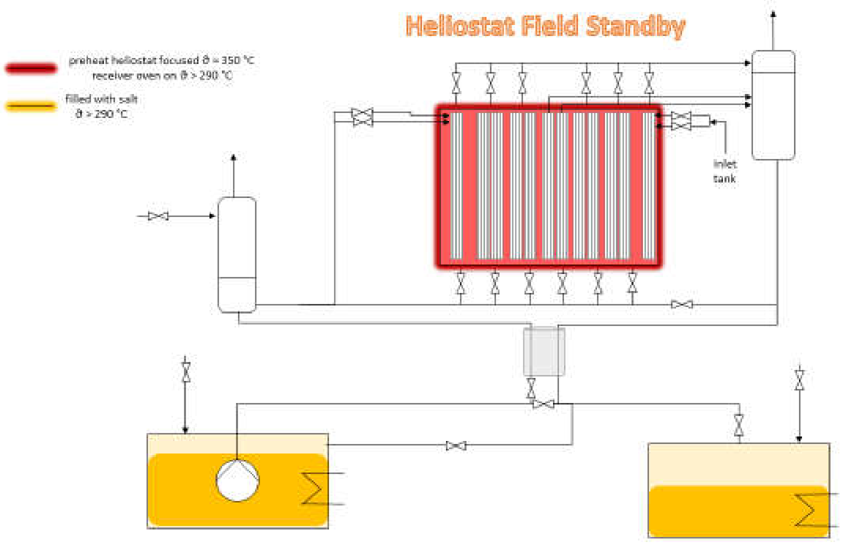
Salt Circuit Standby

At least one of the cold salt pumps delivers salt through the receiver bypass back to the cold storage tank. The heliostats are in stow position, standby position or are focused to preheat the receiver if applicable. The trace heating keeps the temperature of the salt circuit higher than 290 °C.



Heliostat Field Standby

The heliostats are in the standby position except those needed for preheating which are focused on the receiver. The receiver ovens keep the temperature above 290 °C. The salt circuit is drained, filled or cold salt flows through the receiver bypass.



Salt Circuit Standby and Heliostat Field Standby → Solar Tower Standby

In the case that the receiver is preheated to at least 290 °C and salt flows through the receiver bypass, the receiver is ready to be filled. At first the pressure in the inlet vessel is increased. Then the receiver panels and the outlet tank are flooded. The receiver bypass and filling pipes are closed so that a serpentine flow establishes in the receiver. At least the operating pressure is set in the inlet vessel. Salt still flows into the cold storage tank.
There is the option that the outlet tank is under pressure to minimize salt decomposition at temperature above 600 °C.

Solar Tower Standby → Salt Circuit Standby and Heliostat Field Standby

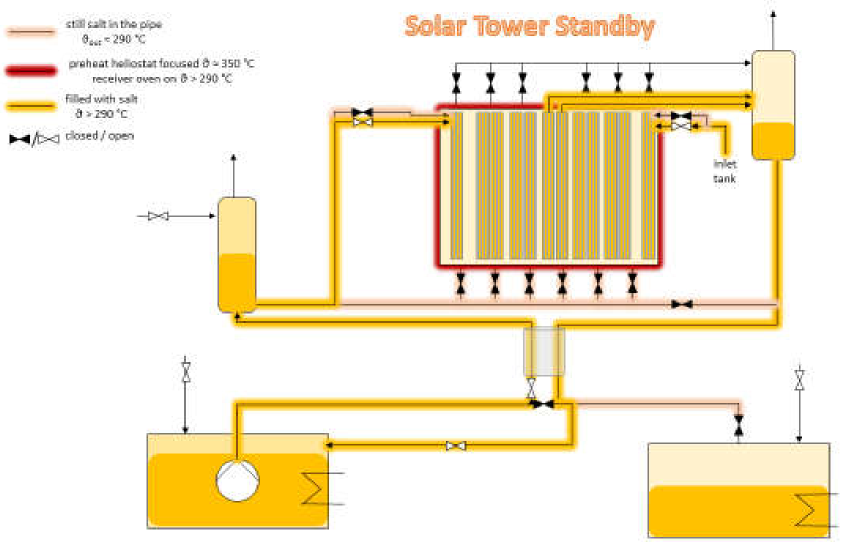
The receiver is drained without the downcomer level is dropping. Then the pressure in the inlet vessel is reduced and the salt circuit is flowed through the receiver bypass. Only some heliostats are focused to heat the receiver. All others move in standby position.

Solar Tower Standby → Solar Tower Off

The salt circuit including the receiver is drained. At first the receiver is emptied, then the level in the inlet vessel is reduced and afterwards the cold salt pumps are shut down. If the salt circuit is drained, all heliostats are moved in their stow position. Finally the trace heating is switched off.

Solar Tower Standby

Cold salt meandering through the receiver flows back into the cold storage tank. All heliostats are in standby position except those preheating the receiver. The trace heating keeps the temperature of the salt circuit at least 290 °C.



Solar Tower Standby → Solar Operation

The flux density is increased by focusing more heliostats. The receiver-outlet temperature is controlled to 565 °C. As soon as the

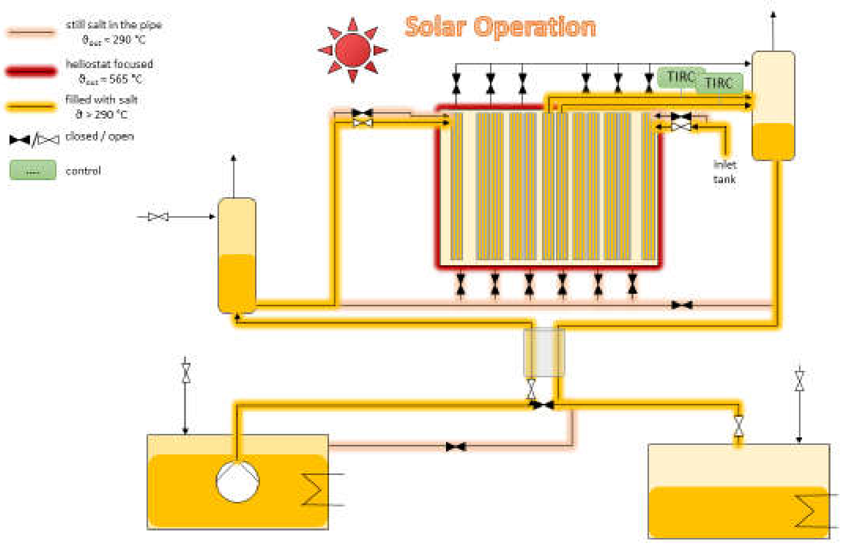
Solar Operation → Solar Tower Standby

The flux density is reduced so that the heat losses at the absorber tubes are compensated. As soon as the temperature is lower than 450 °C, valve position is changed

temperature rises above 470 °C the salt is pumped in the hot storage tank.	and salt flows in the cold storage tank. The cold salt pumps still supply the inlet vessel.

Solar (Load) Operation

Heliostats are focused and heat the cold salt to an outlet temperature of 565 °C which is controlled by the mass flow. The power control adjusts the position of the heliostats predictive using a sky camera to compensate for shadows. Parts of the salt circuit through which are in standby mode no flow are heat traced at a minimum of 290 °C.



4.4. Energy storage system

The energy storage system includes the following main components:

- Salt melting
- Cold salt storage tank (300°C): Cold salt tank, electric heaters, cold salt circulation pumps
- Hot salt storage tank (565°C): Hot salt tank, electric heaters, hot salt circulation pumps
- Foundation
- Drainage system
- Freeze protection system

This 2-tank storage system includes a cold tank, which stores cold salt from steam generator and supplies cold salt to solar tower receiver system. The design temperature is 400 °C. To reach a good part load behaviour of the solar receiver it is necessary to equip the cold tank with five salt pumps. The hot storage tank, designed for temperatures up to 593 °C, stores hot salt from the receiver and supplies hot salt to the steam generator system. In the peaker plant each hot storage tank is equipped with three pumps, each capable to deliver 25% of the nominal salt mass flow rate. Identical pumps are used for the night-operation system, but due to the lower salt mass flow rate to the steam generator each hot tank has two 50% pumps.

4.4.1. Salt chemistry and material choice

Beside the components, the salt chemistry and the material choice play a significant role to reach a high lifetime and availability. The chemical reaction system in nitrate melts is complex. Mostly all reactions are chemical equilibria, which influence each other. Moreover, in these reactions all components of the system like gas atmosphere, possible precipitations, and the selected steel material have to be considered. The most important reactions (equation 1 and 2) include the nitrate / nitrite equilibria adjusted by the oxygen partial pressure and the decomposition reaction of nitrite. The gaseous decomposition products nitric oxide and nitrous oxide form an equilibrium influenced by oxygen (equation 3). Alkali oxides form carbonates in contact with CO2 (equation 4) and are corrosive due to their ability to react with chromium at the steel surface (equation 5).

$$2\,NO_2^- + O_2 \rightleftarrows 2\,NO_3^- \quad (1)$$
$$2\,NO_2^- \rightleftarrows O^{2-} + NO + NO_2 \quad (2)$$
$$2\,NO + O_2 \rightleftarrows\ 2NO_2 \quad (3)$$
$$O^{2-} + CO_2 \rightleftarrows CO_3^{2-} \quad (4)$$
$$Cr + 1{,}5O_2 + O^{2-} \rightleftarrows CrO_4^{2-} \quad (5)$$

Above 350 - 400 °C the chemical reactions of equation 1 and 2 will adjust the system towards the decomposition products. This results in a change in the composition of the salt melt. Nevertheless, nitrate / nitrite salt mixtures are used above 500 °C without significant change of their physical and chemical properties in long-term operation due to appropriate process conditions (Federsel, Wortmann, & Ladenberger, 2015).
Solar salt, used as standard, has its maximum operation temperature at 565 °C (state-of-the-art). Even higher temperatures are possible but therefore the decomposition rate of the salt must be reduced by closing the system or adding technical air and or NOx to the system (under investigation). In the following work, we are focusing on the state-of-the-art system.
Beside the classic Solar Salt there are some other nitrate salts whose parameters are shown in Table 7. An alternative to Solar Salt is the Solar Salt EU. It is the eutectic mixture and following leads to the lowest melting point. It has to be considered that KNO3 is the more cost-intensive component, which increases the investment costs accordingly.

Table 7: Parameter of different nitrate salts

Molten Salt	Composition	Melting Point [°C]	Max. Operation Temperature [°C]
Solar Salt	60 wt.-% $NaNO_3$ 40 wt.-% KNO_3	240 °C	> 580 °C
Solar Salt EU	54 wt.-% $NaNO_3$ 46 wt.-% KNO_3	220 °C	> 580 °C
HITEC®	40 wt.-% $NaNO_2$	142 °C	530 °C

	53 wt.-% KNO_3 7 wt.-% $NaNO_3$		
HITEC® XL	48 wt.-% $Ca(NO_3)_2$ 45 wt.-% KNO_3 7 wt.-% $NaNO_3$	120 °C	500 °C
YARA MOST	41 - 43 wt.-% $Ca(NO_3)_2$ 42 - 44 wt.-% KNO_3 14 - 16 wt.-% $NaNO_3$	130-135 °C	525 °C

For HITEC® XL salt, temperatures above 420 °C are not recommended and is not of interest for CSP tower technology. The HITEC® max. operating temperature of HITEC® salt was investigated in detail by BASF [6] and set to max. 530°C. Above this temperature the salt loose its thermal stability. When comparing HITEC® salt with Solar Salt, the higher heat capacity of the former is noticeable. However, the procurement costs for HITEC® salt are about twice as high as for Solar Salt, which is due to the higher cost of the nitrite component. Only the YARA MOST salt has slightly lower costs. This three-component salt has a low melting point. YARA specifies the maximum operating temperature at 525 °C. It can be concluded that for the CSP tower application the state-of-the-art Solar Salt is the mean of choice due to the highest operating temperature and the low capital costs.
Due to the corrosivity of molten salt, the material choice for tanks and piping is very important. Molten nitrate salts begin to decompose at temperatures above 370 °C. Up to temperatures of 450 °C carbon steel is used. Above 450 °C it has to be switched to stainless steel to reduce the corrosion rates. Beside the thermal decomposition of the salt the chloride content of the salt itself has an effect on the corrosion rate. Following the chloride content should be below 100 ppm. In addition, the maximum contaminants concentrations from all sources shall not exceed the following:

Table 8: Maximum allowable contaminants concentrations

Contaminants	**Maximum Concentration (mass-%)**
Sulfate	0.75
Carbonate	0.10
Nitrite	1.0
Hydroxyl Alkalinity	0.20
Magnesium	0.001
Not melting substances	0.05

Several materials were investigated in the past considering corrosion behavior in isothermal tests up to temperatures of 565 °C. Above 450 °C austenitic steels must be used to reduce the corrosion rates. Materials like 316Ti, 321H, 347 show good corrosion resistance during static

conditions. Structural materials in CSP plants experience loading conditions such as thermocyclic conditions during filling and emptying of storage tanks. Bradshaw showed that stainless steels experienced 25 % to 50 % more corrosion during thermal cycling in comparison to isothermal exposures (Bradshaw & Goods, 2001). This is strongly depending on the chloride content of the molten salt.
Efforts are being made to achieve more stable oxide layers in the material by alloying aluminum and thus to further increase corrosion resistance. However, these materials are under development and are not further considered in this study.
For temperatures below 450 °C the corrosion rate is very slow so that ferritic steels can be used. Here the SA 204 Grade B is a very good choice.

4.4.2. Tank commissioning and salt melting procedure

Before starting the fusion of the salt and the charging into the cold tank, the walls and bottom of the salt tanks must be heated to a suitable temperature. There will be a preheater temporarily available, so that the combustion gases from the burner are injected into the tanks through one of the manholes via a nozzle. It consists of a gas burner installed in the salt tank in nozzle destined for this use that preheats the tank up to a temperature of 320 ºC. In addition, exhaust gases are evacuated through a vent located in the manhole. The burner will be used primarily in the cold salt tank and afterward it will be re-used in the hot salt tank.
The initial mode of operation of the Thermal Storage System consists in the initial loading mode of salt after they are molten. The mixture of 60 wt.-% of sodium nitrate and 40 wt.-% of potassium nitrate is supplied in solid form and its fusion is carried out prior to the start-up of the plant, which means they have to be dosed in the appropriate mixture, and melted in a melting unit.
The solids handling unit doses salt to the melting unit in a solid state, in the appropriate mixture and with an adequate grain size, in order to facilitate fusion and avoid downtime. To achieve this, the unit is equipped with mills that are joined by a lifter in addition to screens (8x8 mesh) arranged in series.
In this mode, all operations are carried out manually.
The fusion system consists primarily of a melting furnace and solids handling equipment. The fusion equipment starts-up once all equipment involved in the molten salt operation are prepared and the preheating of the cold salts tank and the lines involved during the filling of the cold salts tank is finished.
The fusing unit provides the buffer tank with molten salt if it needed. The transfer of the salt to the cold tank is carried out via vertical pump located in melting furnace. The discharge rate of the melting furnace to the cold tank shall vary during the start-up or in the presence of anomalies in the process. These flow rate variations will entail a control valve modulation, which must ensure a consistent average level in the tank. This average is defined in order for there to be a volume available for the return of the salt contained in the line toward the tank, in case of a power failure.
At the beginning of the fusion, the whole amount of salt is introduced to the cold salt tank. There are three different phases during the filling of the cold salts tank:

- Minimum level for the start-up of the pumps: For the start-up of the pumps, a minimum salt level must be reached. Once this level is reached, the recirculation of the salts may be carried out using one of the cold salt pumps.
- Submergence of the electric heaters: To activate the heaters, it is necessary that they are covered with salt, because otherwise the sheathing of these resistors would quickly reach the trigger temperature. The temperature probes of the heaters must thus be operational.
- Fusion and filling completion: Once the inventory of salt is melted, the fusion and tank filling process is finished.

4.4.3. Salt storage tanks

The storage tanks for molten salts are vertical cylinders. The cold storage tank is made of carbon steel SA 204 Grade B and the hot storage tanks are made out of 321H. Both are insulated in order to minimize heat losses through the walls.
To determine the size of the tanks, the salts volume by stored energy + minimum volume of salt pumps submergence + salts volume in exchangers and piping is considered as the total volume of salts to be stored. The following table shows the dimensions:

Table 9: Dimension of salt storage tanks

	Cold storage tank	**Hot storage tank**
Number	1	2
Outer diameter	59.6 m	44.3 m
Shell height	12.5 m	12.5 m
Max. filling height	11 m	11 m
Min. filling height	1 m	1 m

The maximum filling height of the tank is 12.5 m and the minimum salt height is 1.0 m.
The tanks have insulated walls and roof in order to minimize heat loss. The tanks are maintained at atmospheric pressure. The salt pumps are vertical, suctioning the fluid from the bottom of the tank and pump it to the receiver (cold salt pumps) or the steam generator system (hot salt pumps). This implies that the useful height of the tanks is directly related to the length of the vertical axis of the pumps.
The main components are:

- Salt pumps: vertical pumps, which are submerged with outboard motors and supported on an independent platform outside the tank.
- Salts distribution ring: Used to receive and distribute the salts in the receiving tank. It basically consists of a vertical tube that enters through the top of the tank and reaches the bottom, where there is a ring of the same diameter and is perforated along its entire length. In this way, the fluid is distributed at various points within the tank.
- Electric heaters: at the bottom of each tank, there are electric heaters to avoid salt freezing during emergencies.

- Emergency vents: for relieving overpressure coming from one SGS heat exchanger rupture, due to steam inlet in the salt system.
- Foundation

For manufacturing, design and construction of the tanks, the API 650 standard is taken as reference with expressly indicated exceptions and additional requirements. In addition, the internal piping associated with the tank, such as the sheaths of the heating resistors, the thermocouples system and the mixing and distribution system is assembled according to the requirements of the ASME / ANSI B31.1 standard for severe cyclic conditions, covering the special requirements for metal pipes and all the applicable requirements.

The roof will be self-supporting with an internal support structure (without welded to the roof plates), in order to avoid problems with the thermal loads. All welded joints of the vertical walls are full penetration welds with a butt weld. Abutting shell plates at horizontal joints have a common vertical centreline. The joints of the bottom section are full penetration welds as well, with backing plates. All joints of the lower area of the first plate of the cylinder are full penetration welds, excluding plates inserted in the joints of the bottom, where the thickness of the plate is too large and the full penetration weld could affect the characteristics of the bottom plate. In this case, the thickness of the weld seam is equal to the shell body.

The calculation analysis includes the following: Static charges + wind loads, static charges + seismic loads, hydraulic testing, static thermal load, local concentration of maximum stress due to any type of load. This criterion is applied to the tank itself and all internal piping, as well as to the brackets or clips, clamps and support brackets. A trafficable roof and an insulation density of 100 kg/m³ is considered for the design. Reinforcement patches are installed into the tubing and support clips with rounded corners and a ventilation hole to avoid any problems caused by differential thermal expansion and local stress concentrations at the weld beads where necessary.

4.4.4. Electric heaters

The salt tanks are equipped with electric heaters located below the minimum salt level. Horizontal sheaths installed to position the heaters. The heaters are placed inside the sheaths 0.4 meters above tank floor. The sheaths extend radially within the interior of the tanks, and are properly secured to the tank. All the necessary elements are provided to secure the sheaths. The clips are welded to the sheaths and tanks. When the heaters are operating, the temperature in the interior of the sheath may exceed 400 ºC in the tank. Special attention is given to the execution of the flange / pipe welds so as not to diminish the necessary rate for the resistors.

The first phase of filling the tanks is the most critical. To activate the heaters, it is necessary that they are covered with salt, because otherwise the sheathing of these resistors would quickly reach the trigger temperature. The gas burners are used to replace the thermal energy that is dissipated into the system to prevent freezing of the salts below this level. When the salt has arrived in the cold tank and reaches the appropriate level where the electric heaters are located, the resistors at the bottom will be turned on to ensure the permanence of the salts in the molten state and to replace the heat loss through the walls and the bottom. Each heater has two power stages and is equipped with three temperature sensors, one for the resistance elements of first power stage, another for the resistance elements of second power stage and the other one in contact with the sheath.

4.4.5. Salt pumps

The salt pumps are long shaft centrifugal vertical pumps (approx. 15 m length, placed on top of the salt tanks. The cold salt pumps are used to boost the salt at 290 ºC to the receiver, on the top of the tower into the inlet vessel.

Therefore, six cold pumps (6 times 20 %) and dependent on operation mode (see **Table 12**) four or six hot salt pumps are installed on a supported platform independent of the tank, located at an elevation of about 16 m.

Each of the cold salt pumps is 20 % of the required capacity and provides a maximum mass flow rate of 334 kg/s at a maximum head of 305 m. Five of the pumps will be in operation while the sixth will be held in reserve.

Each of the six/four hot salt pumps is 25 / 50 % (depending on plant size) of the required capacity and provides a maximum mass flow rate of 542 kg/s at a maximum head of 40 m. Four/two of the pumps will be in operation while the rest will be held in reserve.

The pumps will be variable speed driven by electric motor, placed out of the salt tank, so the total flow may be changed to deliver the adequate flow to manage a hot salt temperature of 565 ºC after the receiver depending on the available solar radiation at any moment in case of the cold salt pumps. The hot salt pumps flow is depending on the demand of the steam generator system.

4.4.6. Drainage system

The aim of the drain system is to empty the salt heat exchangers and lines and send this quantity via the drainage tank back to the cold salt tank. The drainage tank is raised a few centimetres over the ground and has a slope of min. 1 % that collects drainage coming from pipes and exchangers. The tank is thermally insulated by mineral wool and equipped with redundant electrical heat tracing featuring simultaneous connection capabilities.

4.4.7. Freeze protection system

Because the mixture of nitrate salts has a melting temperature of about 238 °C, it is essential to establish freeze protection to keep the salts at a minimum temperature of 255 °C.

For this purpose, the following levels of protection are established:

- Recirculation of salt
- Electrical heat tracing: all piping, drainage tank and heat exchanger components is electrically traced
- Electric heaters submerged in the dead space at the bottom of the hot and cold salts tank

The main purpose of the recirculation system is the homogenization of the temperature of the salts and avoid freezing, during the storage waiting hours.

One option is recirculation through heat exchangers. This option is for protecting the molten salt temperature and avoid freezing of salt of the heat exchangers and the interconnecting lines.

This entails recirculation using cold pumps through exchangers and return to the cold salt tank to compensate for heat losses of the lines.

A second option is recirculation over tanks. This option is for protecting the lower layers of the tank from freezing and avoid stratification of the molten salts inside the tank, so a homogeneous temperature in the whole tank is kept. This entails recirculation over tanks using pumps at minimum revolutions and the minimum flow (recirculation) control valves, available for each pump.

The heat exchangers, the drainage tank, the salt pumps, valves (bodies and bonnets) and the piping of the whole salt systems have electric heat tracing to prevent the salts from freezing. This tracing is activated automatically when the surface temperature sensors of the pipe or equipment detect a temperature below 265 °C or manually by the operator.

The temperature on the surface of materials/equipment will be monitored continuously in each section, with a low temperature alarm. The system is connected to the emergency services network that receives auxiliary power from an emergency diesel generator. This electric heat tracing system will essentially consist of an electrical resistor inserted into a metal sheath, temperature sensors and controllers. It is necessary to maintain the electrical heat tracing system in operation from its implementation to ensure the suitable temperature in the salts circuits to prevent the freezing of the salts. The electric heater and its function is already explained in chapter 4.4.4.

4.4.8. Investment costs

Different storage sizes were requested from various manufacturers. The following figure shows the feedback. The specific costs amount between 2.5 and 4.2 €/kWh_{th} salt content.

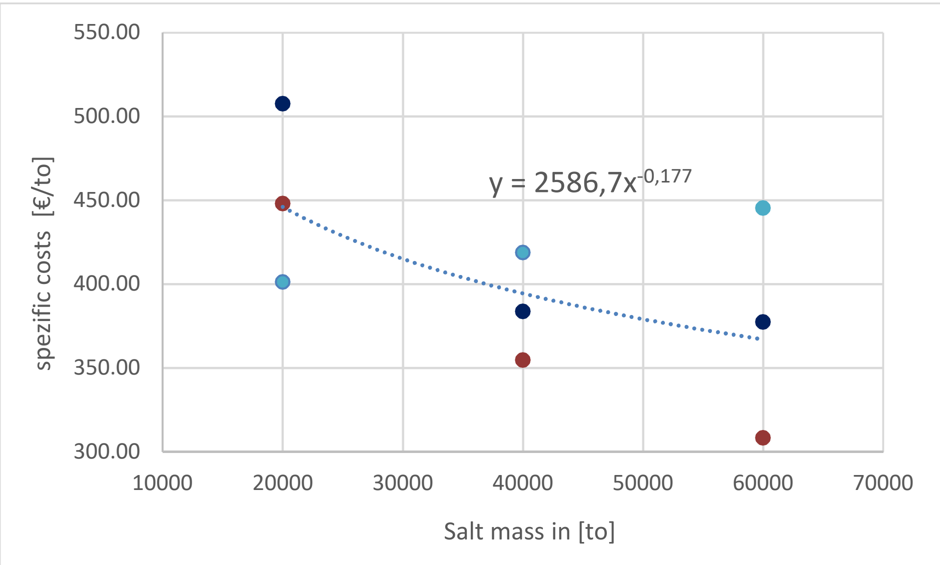


Figure 28: Specific Costs for hot and cold tank depending on salt content

The storage tanks are insulated with rock wool mats. A distinction is made between the insulation of the hot and cold tanks. The hot tank is insulated with an insulation thickness of about 500 mm, whereas the insulation thickness of the cold tank is reduced to 350 mm. The specific costs of the insulation are around 1100 €/m³ for the hot tank and 1000 €/m³ for the cold tank. In total the specific costs are about 0.7 €/kWh_{th}. The structure of the foundation is explained later, a typical arrangement is show in the following table. Variations may become necessary depending on the soil consistency. The foundation also contains the insulation to the ground.

Table 10: Structure of the foundation

	Hot tank	**Cold tank**
Bricks	250 mm	0 mm
Foamglas	400 mm	500 mm
Concrete	50 mm	50 mm
Compacted gravel	150 mm	150 mm
Sand	300 mm	300 mm

The costs for the foundation amount to approximately 1.6 €/kWh_{th} floor space.
In general, the hydraulics of the pumps differ depending on the shaft length, since the construction and the bearing arrangement becomes more complex with increasing shaft length. Shaft lengths up to 22 m can be manufactured but it has to be considered that longer shafts need changes in the fixing to prevent vibrations and oscillations. Reducing the shaft length to 15 m reduces costs by about 8 %. So, the specific costs for the pumps are in a range between 1 and 1.5 €/kWh_{th}.

Table 11: Pump costs

Hot salt pump 6 x 25 %	**Cold salt pump 6 x 20 %**
650.000 USD/Pump	500.000 USD/Pump

The costs of the heat transfer salt amount to approximately 850 €/to. Added to this are the costs for melting the salt. The specific costs for melting result in approximately 150 €/to. Bringing all the costs together including electrical heaters, balance of plant and markups the specific costs for the storage system are in a range between 20 and 22 €/kWh_{th}.

4.5. Molten Salt Cycle

The molten salt cycle consists of two parts: the charging and the discharging cycle. A storage system connects them, which is described in detail as part of the storage concept. The number of pumps results of the number of tanks, redundance as well as the part load to be fulfilled. While the receiver will operate in part load from 15 % to 110 %, the turbine's load varies between 25 % and 100 %. Table 12 shows the possible combinations. The receiver design specifies the required total mass flow of the cold salt pumps and the pressure in the inlet vessel, which, together with the solar tower height, gives the delivery head. The steam generator design with its pressure losses and altitude determines the head of the hot salt pumps while the power of the turbine defines the mass flow.

Table 12: Number of pumps depending on the number of storage tanks

Operation concept	Cold tank x 1	Hot tank x 1	Hot tank x 2
Night time operation	6	3	4
Peaker operation	6	5	6

The basic setup of the molten salt charging cycle shows Figure 29. The cold pumps deliver salt through the riser to the inlet vessel, which is placed upstream of the absorber tubes to provide the tubes with a sufficient salt flow. The control valves in the two parallel receiver feed lines are responsible for controlling the salt outlet temperature. Therefore, they have to react fast due to changes in solar heat input. To generate stable conditions the inlet tank is pressurized at around 20 barg. Thus, the cold pump head summarizes to 329 m. Furthermore, this vessel feeds the emergency flushing, which determines the vessel size. After passing the solar receiver, the salt enters the outlet vessel at atmospheric pressure, which acts as a reservoir to prevent the downcomer from draining. There is the option to superimpose the outlet tank to inhibit salt decomposition but both operation concepts do not consider this possibility. The volume of the outlet tank is determined by the emergency flushing time and the resulting mass flow rate. Within 15 seconds 90 % of the heliostats are defocused. To be conservative, the emergency flushing time is 30 seconds. Process engineering for these components was done by putting a high priority on safety concerns.

After passing the outlet vessel the salt enters the hot storage tank or is sent back to the cold storage tank, if the temperature is too low.

To convert the thermal energy, the hot salt pumps feed the steam generator system and by cooling down the molten salt the live steam is produced (discharging cycle). The cold salt flow is directed to the cold storage tank.

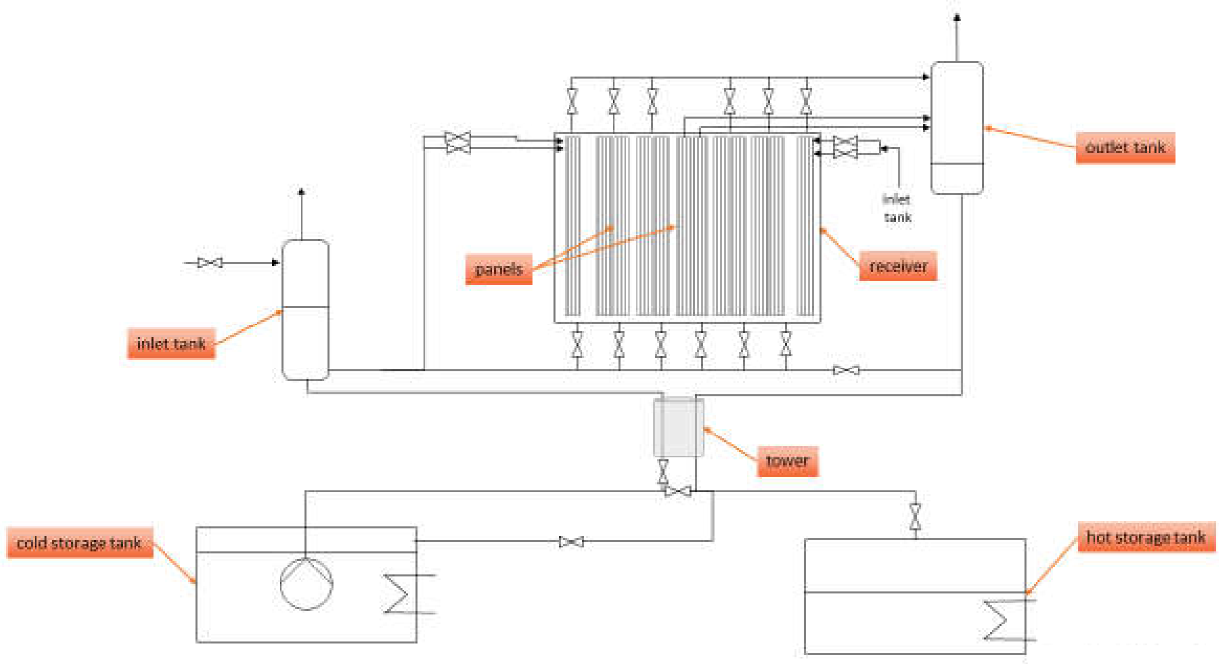


Figure 29: Process flow diagram of energy collection system

A basic layout of the reference power plant for the peaker option has been created and is shown in Figure 30. The heat exchanger trains of the steam generation and storage tanks have the same ground level so that a lower placed tank with an additional pump is scheduled for draining the heat exchangers. The storage and drainage tanks as well as the heat exchangers are located in a pit. Two heat exchanger trains feed one turbine, so there are four single units for the peaker option, which are combined in the layout. The two turbines are located in one turbine house. Turbines and heat exchangers are arranged close to each other to minimize the length of the steam pipes and thus heat losses, while the locations for water treatment as well as the tanks for raw and demineralized water are freely selectable. The dimensions correspond to the described components. The area for air-cooled condensers is located next to the turbine house. Placeholders have been added for administration and workshop.

The required place for the nightmode option is smaller than the place for the peaker option while the available place does not change. The nightmode option has only two trains of steam generation and one turbine with one air-cooled condenser.

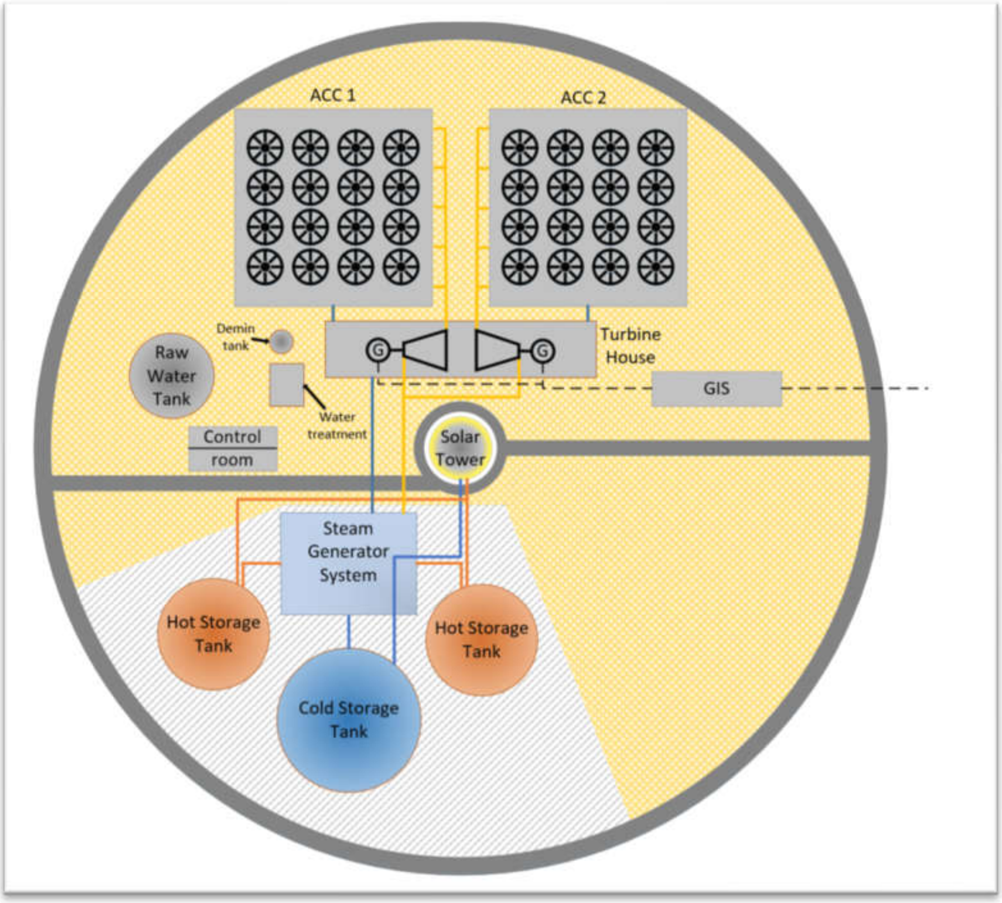


Figure 30: Plant layout in the center of the heliostat field for peaker operation 2 x 200 MW_e

4.6. Steam Generator

4.6.1. Design parameters for the steam generator

The maximum allowed temperature of molten salt makes it attractive to be employed as heat transfer fluid in CSP applications.

The purpose of a molten salt steam generator is to produce high pressure superheated steam while cooling down molten salt. The maximum and minimum allowed temperatures variate depending on the type of molten salt employed. The basis for the design, a binary salt compound of 40% potassium nitrate and 60% sodium nitrate, (often called Solar Salt) has a maximum allowed temperature of about 565°C. Theoretically, the minimum allowed temperature of this salt is about 240°C, which corresponds to its freezing point.

The analysis of the boundary conditions and their repercussions was the first step for the definition of the design parameters of the molten salt steam generator.

Analogue to fossil-fired steam generators, the following characteristics are pursued in the design of a molten salt steam generator:

- High steam temperature
- High steam pressure
- Low molten salt outlet temperature

For the current case study, the maximum molten salt temperature entering the steam generator was set to 560°C. On the other hand, as to avoid freezing, the minimum temperature of the molten salt leaving the steam generator was set to 290°C. At the water/steam side, both, the superheater and the reheater outlet temperature were set to 550°C.

Figure 31 represents the molten salt flow across the steam generator for the current case study. The superheater and the reheater are fed with high temperature molten salt coming from the hot tank, downstream these two heating surfaces the torrents are mixed and led into the evaporator. Downstream the evaporator, the molten salt is conducted into the economizer. Finally, the molten salt leaves the economizer and flows into the cold tank.

A once-through type steam generator of 100 MW_e was used as basis for the analysis of the parameter interdependencies; nevertheless, it is considered that the findings apply to natural circulation systems as well.

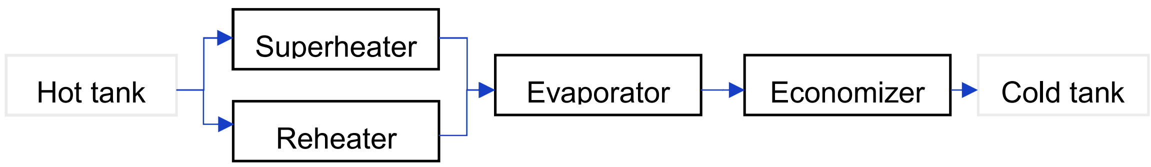


Figure 31: Scheme of the molten salt flow across the steam generator

Table 1 summarizes the results of different steam generator design cases. As can be seen, these results imply that:

- High steam pressures lead to molten salt outlet temperatures above the target (290°C)
- High feedwater temperatures lead to molten salt outlet temperatures above the target
- High pressure drop at the molten salt side leads to smaller heating surfaces but it also leads to molten salt outlet temperatures above the target
- A small pinch point leads to lower molten salt outlet temperatures but also to larger heating surfaces

Table 13: Summary of the analyzed design cases

Parameter				Design case											
				A	B	C	D	E	F	G	H	I	J	K	L
				221 MWth	223 MWth	220 MWth	222 MWth	222 MWth	224 MWth	224 MWth	218 MWth	218 MWth	221 MWth	227 MWth	227 MWth
				157 bar	131 bar	165 bar	140 bar	140 bar	120 bar	120 bar	165 bar	165 bar	140 bar	140 bar	140 bar
				245°C FW	245°C FW	245°C FW	245°C FW	245°C FW	245°C FW	245°C FW	275°C FW	275°C FW	275°C FW	245°C FW	245°C FW
				565°C salt	560°C salt	560°C salt	560°C salt	560°C salt	560°C salt	560°C salt	560°C salt	560°C salt	560°C salt	560°C salt	560°C salt
				5K pinch	0K pinch	5K pinch	5K pinch	10K pinch	5K pinch	10K pinch	10K pinch	5K pinch	5K pinch	5K pinch	5K pinch
Molten salt	Flow rate	Inlet/Outlet	kg/s	546,81	545,76	563,28	556,64	558,19	555,15	564,28	598,11	581,61	582,28	568,88	574,08
	Pressure	Inlet	bar	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00
	Temperature	Inlet	°C	565,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0	560,0
		Outlet	°C	297,8	289,5	301,4	295,7	296,5	293,1	297,4	318,2	311,2	309,1	295,7	298,1
	Pressure drop	Total	mbar	2497	1554	2578	693	656	614	510	612	855	735	708	2578
Water / Steam HP	Flow rate	Main steam	kg/s	77,60	77,60	77,60	77,60	77,60	77,60	77,60	82,98	82,98	82,98	80,88	80,88
	Pressure	Main steam	bar	157,00	131,00	165,00	140,00	140,00	120,00	120,00	165,00	165,00	140,00	140,00	140,00
		Eco inlet	bar	180,00	154,00	189,00	158,00	159,00	140,00	139,00	181,00	184,00	159,00	159,00	174,00
	Temperature	Eco inlet	°C	245,0	245,0	245,0	245,0	245,0	245,0	245,0	275,0	275,0	275,0	245,0	245,0
		Eco outlet	°C	352,1	340,8	358,2	345,4	345,5	334,2	335,0	352,2	340,6	345,9	344,2	350,7
		Eva outlet	°C	366,9	361,4	372,6	353,8	344,8	343,9	337,9	394,1	386,3	349,6	358,4	358,7
		SH steam	°C	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0
	Pressure drop	Eco	bar	2,8	4,1	3,0	1,6	1,7	1,1	0,9	1,1	1,0	1,6	1,5	2,8
		Eva	bar	6,0	6,0	5,2	3,6	3,1	4,4	3,7	3,8	5,5	4,0	4,1	6,6
		SH	bar	13,7	12,9	16,2	12,3	12,7	13,9	13,7	11,2	12,2	13,2	13,4	24,3
		Total	bar	22,4	23,1	24,4	17,4	17,5	19,4	18,3	16,1	18,7	18,8	19,0	33,7
Water / Steam MP	Flow rate	RH steam	kg/s	69,16	69,16	69,16	69,16	69,16	69,16	69,16	70,21	70,21	70,21	73,06	73,06
	Pressure	RH inlet	bar	37,80	37,80	37,80	37,80	37,80	37,80	37,80	42,00	42,00	42,00	37,80	37,80
		RH outlet	bar	35,80	35,80	35,60	35,80	35,80	35,80	35,80	40,00	40,00	40,00	35,70	35,70
	Temperature	RH inlet	°C	329,2	329,2	329,2	329,2	329,2	329,2	329,2	347,2	347,2	347,2	356,1	356,1
		RH outlet	°C	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0	550,0
	Pressure drop	RH	bar	2,2	1,9	2,2	1,9	1,9	1,9	1,9	1,8	1,8	2,0	2,1	2,1
Other	Tube mass	Total	ton	130	272	132	148	144	137	121	125	162	148	146	129
	Heating Surface	Eco	m²	1.786	5.725	1.864	2.163	2.226	1.590	1.272	1.272	1.272	1.972	1.908	1.669
		Eva	m²	1.359	3.180	1.165	1.431	1.113	1.590	1.209	1.431	2.862	1.431	1.590	1.262
		SH	m²	738	1.209	932	1.272	1.336	1.209	1.209	1.145	1.272	1.209	1.272	1.126
		RH	m²	1.563	1.340	1.563	1.340	1.340	1.340	1.340	1.388	1.388	1.570	1.340	1.340
		Total	m²	5.445	11.454	5.523	6.206	6.015	5.729	5.029	5.236	6.794	6.181	6.110	5.397
	Dimensions d x L	Eco	mm	2616 x 13984	3349 x 27360	2616 x 14592	3349 x 10336	3349 x 10640	3349 x 7600	3349 x 6080	3349 x 6080	3349 x 6080	3349 x 9424	3349 x 9120	2616 x 13072
		Eva	mm	2616 x 10640	3349 x 15200	2616 x 9120	3349 x 6840	3349 x 5320	3349 x 7600	3349 x 5776	3349 x 6840	3349 x 13680	3349 x 6840	3349 x 7600	2616 x 9880
		SH	mm	2616 x 5776	3349 x 5776	2616 x 7296	3349 x 6080	3349 x 6384	3349 x 5776	3349 x 5776	3349 x 5472	3349 x 6080	3349 x 5776	3349 x 6080	2616 x 8816
		RH	mm	3960 x 5320	3960 x 4560	3960 x 5320	3960 x 4560	3960 x 4560	3960 x 4560	3960 x 4560	4101 x 4560	4101 x 4560	4101 x 5320	3960 x 4560	3960 x 4560
System	Useful heat		MWth	221	223	220	222	222	224	224	218	218	221	227	227

Taking into account the above-mentioned points, the design case K from Table 13 was picked as basis for the design parameters of the steam generator, which means:

- Feedwater temperature of 245°C
- Main steam of 140 bar and 550°C
- Reheater steam outlet temperature of 550°C
- Molten salt inlet temperature of 560°C
- Molten salt outlet temperature of about 296°C

4.6.2. Material selection

There are multiple studies about materials and their behaviour in contact with molten salt mixtures. However, the boundaries (temperatures, time of exposition and flow conditions) make a direct comparison between the results of the studies a demanding task.
It is considered, that for a binary molten salt an acceptable corrosion behaviour can be achieved using:

- Carbon steel such as 1.5415 for temperatures below 450°C
- Stainless steel such as 1.4571 for temperatures above 450°C

4.6.3. Comparison of steam generator designs

Different steam generator (SG) types were analysed taking the design parameters of chapter 4.6.1 as basis.

4.6.3.1. Natural circulation SG

In a natural circulation SG the difference of densities between water and water/steam mixture is the driving force for the water circulation.
The natural circulation SG has a steam drum, in which the separation of water and steam from the water/steam mixture coming from the evaporator takes place. The steam drum is connected to the evaporator through several pipes (downcomers and risers). The economizer warms up the feedwater (sent to the drum) to a temperature suitably below the saturation point.
The saturated steam from the drum is sent to the superheater, in order to achieve the parameters required by the turbine.
Figure 32 shows the circuitry built by the main components in a natural circulation SG.

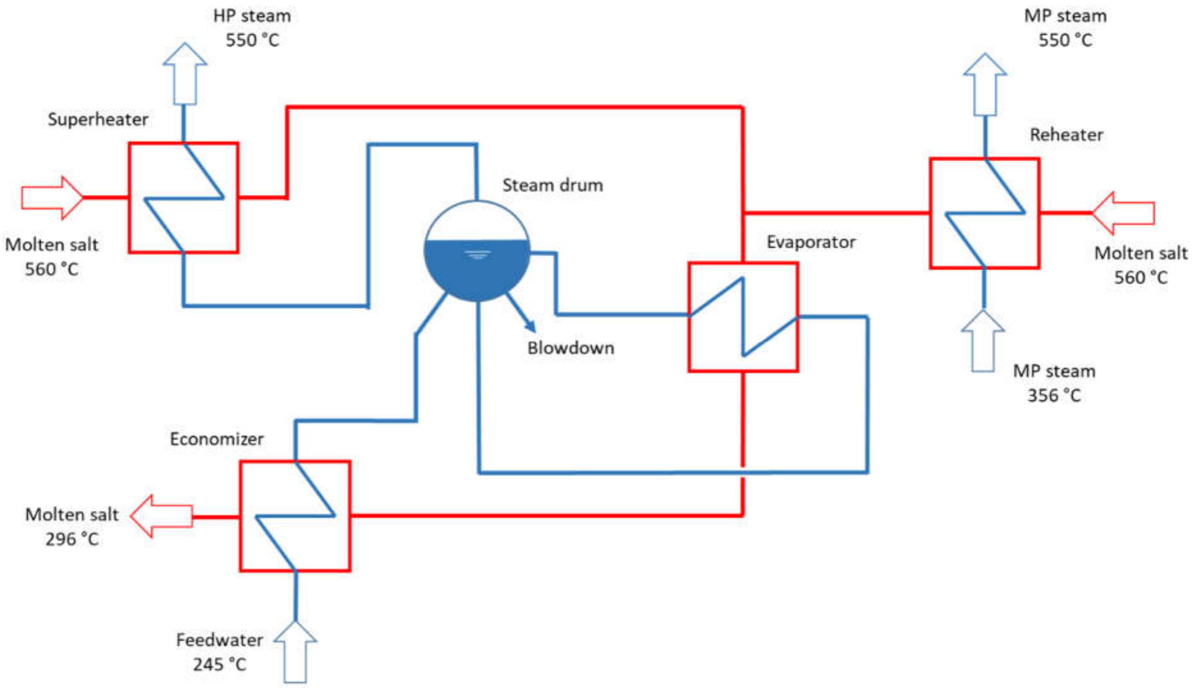


Figure 32: Scheme of a natural circulation SG

The approach for the natural circulation SG was analysing the heating surfaces one by one. At the end, the chosen design resulted from the combination of the most suitable components. The evaporator was the first heating surface examined as to judge a suitable design concept. Three different types of bundle allocations inside a vessel were considered:

- U-tube
- Straight tube
- Tubes connected through headers

Figure 33 shows sketches of the above-mentioned bundle types (from left to right: U-tube, straight tube, header type).

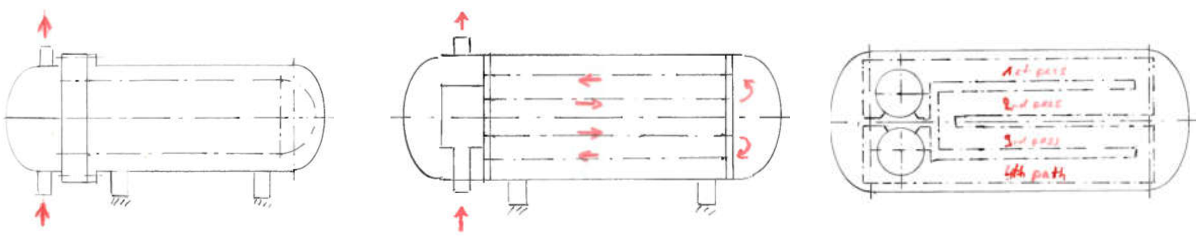


Figure 33: Bundle type sketches

In which concerns the media, following configurations were considered:

- Water/steam (w/s) at the shell side and molten salt at the tube side
- Water/steam at the tube side and molten salt at the shell side

Additionally, single and multiple passes of tubes were investigated. The tubes have an outer diameter of 26.9 mm and the following pitches were considered:

- 32 mm – 30°
- 39 mm – 30°

- 42 mm – 30°

A set of different design concepts resulting from the combination of the above-mentioned aspects were compared among each other. Table 14 summarizes the results of the estimated cost comparison of the design concepts for the evaporator.

Table 14: Summary of the analysed evaporator design concepts

Concept	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2
Bundle type	U-tube	U-tube	U-tube	Straight tube	Straight tube	Straight tube	Header type	Header type
Pass				One shell – twin pass	Two shells – single pass	Two shells – single pass	Two passes	Four passes
Pitch	32 – 30°	32 – 30°	39 – 30°	42 – 30°	42 – 30°	42 – 30° 32 – 30°		
Medium shell side	w/s	Molten salt	w/s	w/s	w/s	Molten salt	w/s	w/s
Medium tube side	Molten salt	w/s	Molten salt	Molten salt	Molten salt	w/s	Molten salt	Molten salt
Estimated cost comparison	100%	68%	129%	106%	109%	92% 63%	188%	162%

As can be seen, the concepts having the molten salt at the shell side show the lower estimated costs. This is related to the lower working and design pressure involved and the corresponding smaller wall thickness.

The concept 1.2 is considered as the most suitable for the evaporator, because of the low estimated cost and because of the estimated engineering effort. The concept 2.3 with reduced pitch also shows low estimated cost, but since it represents a reverse temperature situation compared to the standard application, FEM analysis of the tubesheet and the connection to shell would be necessary; which would mean an increase of the efforts in engineering compared to the selected concept 1.2.

A similar design concept analysis was done for the other heating surfaces of the steam generator.

Table 15 summarizes the results of the estimated cost comparison of the design concepts for the economizer.

Table 15: Summary of the analysed economizer design concepts

Concept	1.1	1.2	2.1	2.2
Bundle type	U-tube	U-tube	Straight tube	Straight tube
Quantity	3	3	6	6
Pitch	32 – 30°	42 – 30°	32 – 30°	42 – 30°
Medium shell side	Molten salt	Molten salt	Molten salt	Molten salt
Medium tube side	w/s	w/s	w/s	w/s
Estimated cost comparison	100%	136%	120%	158%

The concept 1.1 was selected as the most suitable for the economizer, not only because of the low estimated cost, but also because of the low number of necessary equipment compared to the other concepts.
Table 16 summarizes the results of the estimated cost comparison of the design concepts for the superheater. The superheater design concept “header type” (number 3) takes into account a meander heating surface embedded in a quadrangular frame inside a cylindrical vessel as shown in Figure 4.

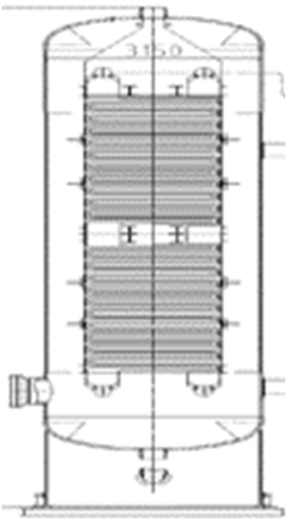


Figure 34: Meander heating surface sketch

The concept 1.1 was selected as the most suitable for the superheater, not only because of the low estimated cost, but also because of the low number of necessary equipment compared to the other concepts. The concept 2.1 shows low estimated cost, but since it represents a reverse temperature situation compared to the standard application, FEM analysis of the tube sheet and the connection to shell would be necessary; which would mean an increase of the efforts in engineering compared to the selected concept 1.1.

Table 16: Summary of the analyzed superheater design concepts

Concept	1.1	1.2	1.3	2.1	2.2	3
Bundle type	U-tube	U-tube	U-tube	Straight tube	Straight tube	Header type
Pass	4 paths	4 paths	2 paths	One shell – twin pass	Multi shell – single pass	
Quantity	2	2	4	2	8	1
Pitch	32 – 30°	39 – 30°	32 – 30°	32 – 30°	32 – 30°	
Medium shell side	Molten salt	Molten salt	Molten salt	Molten salt	Molten salt	Molten salt
Medium tube side	w/s	w/s	w/s	w/s	w/s	w/s
Estimated cost comparison	100%	132%	96%	88%	157%	116%

The moderate steam pressure and pressure drop in the reheater opened the chance of analysing the alternative of having the molten salt at the tube side.
Table 17 summarizes the results of the estimated cost comparison of the design concepts for the reheater. The reheater design concept “header type” (number 2) resembles the sketch from Figure 34.

Table 17: Summary of the analysed reheater design concepts

Concept	1.1	1.2	1.3	2
Bundle type	U-tube	U-tube	U-tube	Header type
Pass	4 paths	2 paths	4 paths	
Quantity	2	4	2	1
Pitch	32 – 30°	32 – 30°	42 – 30°	
Medium shell side	Molten salt	Molten salt	w/s	Molten salt
Medium tube side	w/s	w/s	Molten salt	w/s
Estimated cost comparison	100%	107%	92%	250%

The concept 1.1 was selected as the most suitable for the reheater. The concept 1.3 shows a lower estimated cost, but since the difference is relatively small, it was preferred to keep the homogeneity of the other heating surfaces, which means having the molten salt at the shell side.

4.6.3.2. Once-through SG

The once-through SG has water or steam at the tube side within the entire system. A forced flow circulation is established through the heating surfaces with the assistance of a pump, so that preheating, evaporation and superheating take place inside the tubes.
As to carry out the start-up processes more efficiently, the heating surfaces of the evaporator and superheater are separated. A separator vessel is placed at the mentioned point of separation of the mentioned heating surfaces. Through this component, the water that has not evaporated during start-up is separated from the water/steam mixture and fed back into the economizer heating surface with the help of a circulation pump, so the energy remains in the system, shortening the start-up processes.
There are many options for the design of the tube bundle. The meander heating surfaces are simpler and cheaper to manufacture than others (such as helix heating surfaces, for instance). A noticeable disadvantage of this design is that the meander bundle has a rectangular cross section; as a result, the volume in the cylindrical pressure vessel cannot be optimally used, which leads to large evaporator dimensions.
The high density of molten salt leads to a quite low volumetric flow rate, which means that in order to establish adequate flow velocities at the salt side, the heat exchangers should have a small free cross-section.
The small free cross-section in a meander heating surface (Figure 4) leads to a relative high number of bends. Since normally higher mass flow rates and thus higher pressure drops at the water/steam side are allowed for once-through steam generators, it was assumed that the aspect of the number of bends could be disregarded.
Taking all the above-mentioned characteristics into account, the approach for the design concept was to have all the heating surfaces as meander, and to allocate them minimizing the number of vessels. This results in three vessels:

- Economizer and evaporator
- Superheater
- Reheater

Figure 35 shows the circuitry built by the main components in a once-through SG.

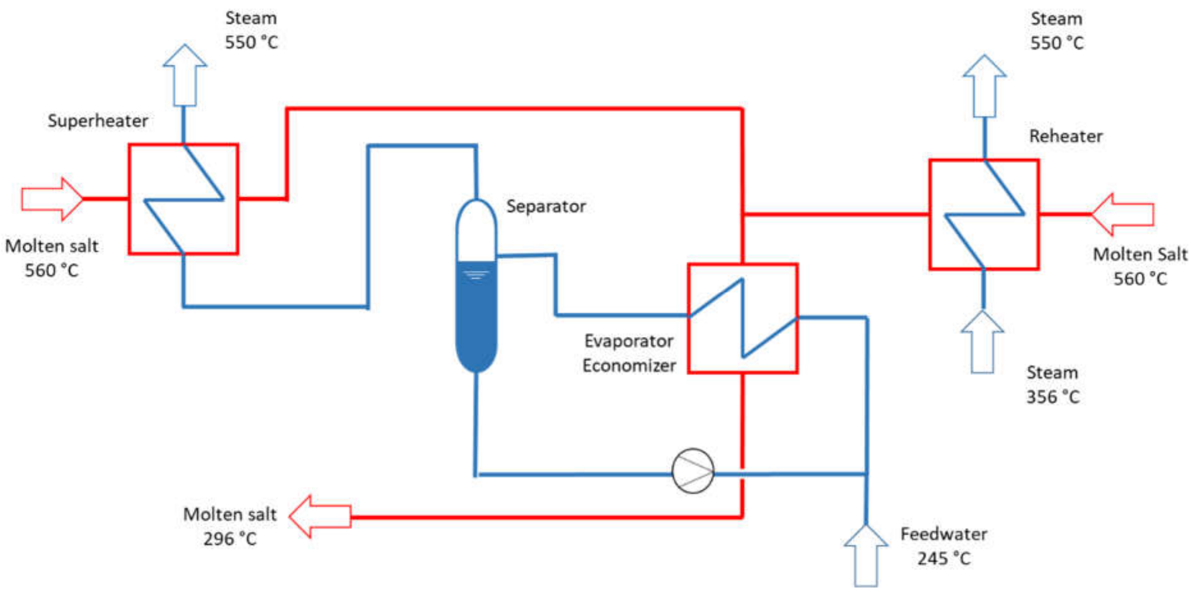


Figure 35: Scheme of a once-through SG

The reduced number of main vessels brings the opportunity of having fewer interconnecting pipes and thus fewer valves than in the proposed natural circulation SG.

4.6.4. Selected SG design

The once-through SG has in general some inherent advantages compared to the natural circulation SG. The most crucial advantage is that because of the small size and small wall thickness of the separator vessel (compared to the steam drum), higher gradients can be achieved (about 10 K/min; whereas by the natural circulation 5 K/min are allowed). This allows rapid start-ups and fast load changes.
Nevertheless, since the power plant of the current case study is supposed to work mostly at a constant load, the advantages of the once-through SG are not decisive.
In addition, the boundaries of the case study would made necessary, that the circulation pump of the once-through SG remains active until relative high part loads.
Finally, it has been assumed, that the relatively small and simple components allocating the heating surfaces of the natural circulation SG could be repaired or even substituted with less effort and time, if necessary. Therefore, the natural circulation SG seems to be the most appropriate design for the current case study.

4.6.5. General arrangement

The selected 100 MWe natural circulation SG is composed by the following main components:

- 1 Steam drum
- 3 Economizer vessels
- 1 Evaporator vessel

- 2 Superheater vessels
- 2 Reheater vessels
- 1 Start-up preheater
- 1 Circulation pump

The 200 MW_e CSP plant would have two of these units. The components are arranged in a three-floor structure as shown in Figure 36. The economizer (third vessel), the evaporator, the superheater (second stage) and the reheater (second stage) are at the bottom of the structure. The economizer (second vessel), the start-up preheater, the superheater (first stage) and the reheater (first stage) are at the platform in the middle of the structure. The economizer (first vessel) and the steam drum are at the top of the structure.
The vertical distance between the steam drum and the evaporator has been chosen in order to enable an adequate water/steam circulation through the evaporator during operation.
The placement of the vessels has been made as to facilitate the filling and draining activities.
As to avoid freezing of the molten salt, the different elements in contact with molten salt have trace heating (shell of the vessels, interconnecting piping, valves, etc.).
The start-up preheater is a device, which would be active just for the initial preheating of feedwater.

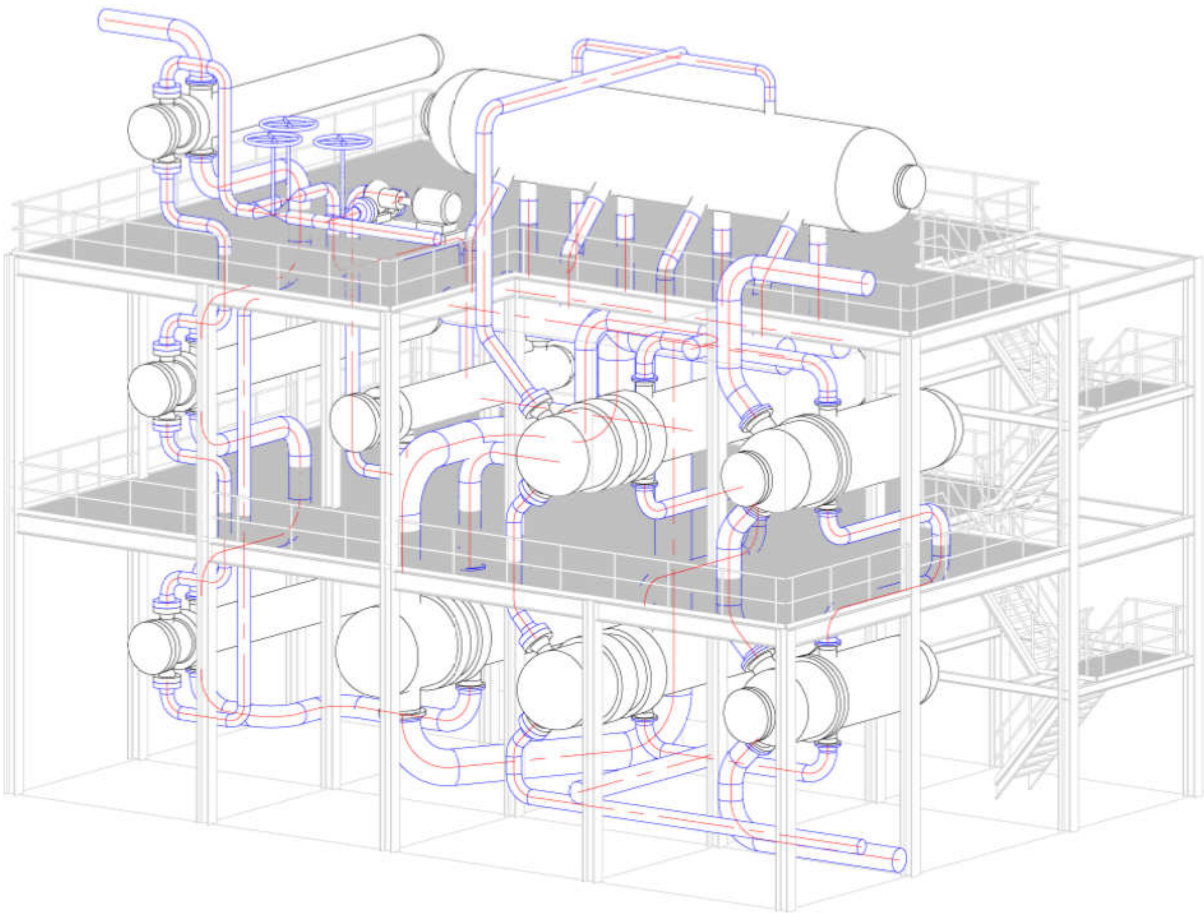


Figure 36: General arrangement of the selected natural circulation SG

4.6.6. Operational concept

Once the erection of the SG has been finalized, as usual for any other manufactured pressure equipment, the SG will be subject of a variety of pressure tests in order to ensure the integrity of its components and pipeline.
Subsequent to the boiler pressure test, cleaning of SG must be performed with care and thoroughness so as to prevent of on-line damage.
Once all the regular tests have been performed, the activities for the commissioning can take place.

4.6.6.1. Preheating

In order to minimize the risk of freezing of molten salt, the preheating of the SG is a prerequisite for the filling process. The preheating is meant to bring all the parts in contact with molten salt to a temperature between 240°C and 270°C. The shell part of the vessels and the interconnecting piping can be preheated by the electrical trace heating. However this is not practical for the inner parts of the vessels (such as the heating surfaces), because the heat transfer could be done just by radiation; which means that in order to bring the inner parts to 270°C the shell would have to be at a considerable higher temperature. Therefore, it is more suitable to combine the initial preheating of the feedwater with the preheating of the heating surfaces.

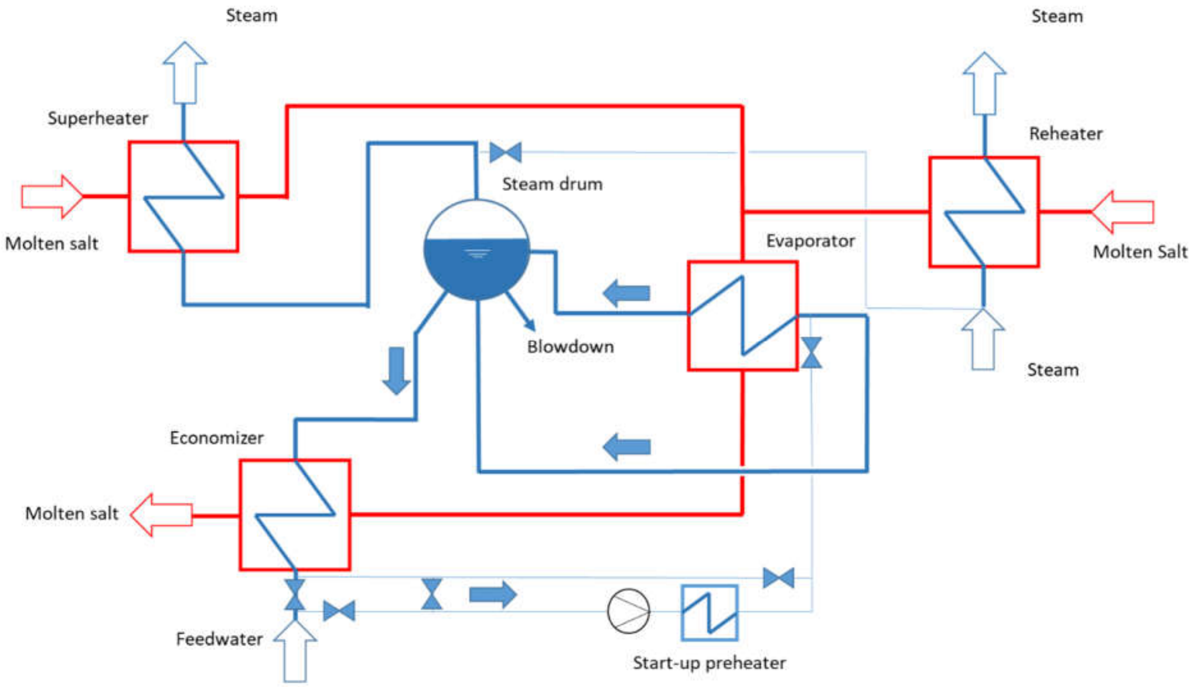


Figure 37: Scheme of an initial preheating

The preheating of the feedwater and the heating surfaces can be done with the assistance of auxiliary steam; in absence of a source of auxiliary steam, a start-up preheater has been planned. This component is placed between the economizer and the evaporator, downstream a circulating pump (as illustrated in Figure 37).

After filling the steam drum, the start-up preheater and the water/steam side of the economizer and the evaporator with feedwater, the circulation pump establishes a circulating circuit among these components. The flow through the economizer is done in opposite direction (compared to the one present during normal operation).
The water temperature will rise continuously with the heat input of the start-up preheater. With the beginning of boiling of the water at ambient pressure, the first steam will be produced and directed to the superheater and reheater. The piping sending steam to the reheater is only active during preheating and start-up instances.
The produced steam will gradually increase the pressure within the system. Within rising pressure, the saturation temperature increases and the warming up of the SG heating surfaces takes place.
With a 700 kW start-up electrical preheater the preheating process will take about 25 hours.

4.6.6.2. Filling process

Once the components of the SG have reached a stationary temperature appropriately above the salt crystallization temperature, the filling of the molten salt into the heat exchangers can take place.
Molten salt from the cold salt tank (at a temperature of about 290°C) will be pumped into the superheater and reheater; after that consecutive filling of the evaporator and economizer takes place.
There are vent pipes which are only active during the filling process. The enclosed air is pushed out of the SG through the molten salt flow and is discharged through the vent valves into the vent pipes and from them into the cold salt tank.
After a couple of minutes of having molten salt coming out of the economizer into the cold salt tank, the vent valves can be closed and the start-up of the SG is feasible.

4.6.6.3. Start-up process

Once all the SG vessels are filled, a minimum constant flow of cold molten salt is established through the SG.
After that, a minimum constant mass flow of feedwater is pumped into the economizer. A minimum temperature of 245°C of the feedwater is granted by the high pressure preheat sub-system of the power block. In absence of it, colder feedwater could be warmed up in the start-up preheater.
The temperature of the molten salt sent to the SG will be gradually increased. Because of the wall thickness of the SG components, an increase of 5 K/min in the temperature is feasible. That means that within almost one hour, the temperature of the salt flowing into the superheater may be increased from 290°C to 560°C.
The produced steam will raise the pressure and temperature within the SG as a consequence of the increase in temperature of the incoming salt. With rising steam pressure in the system, it is expected that at the end of the start-up procedure the steam flowing out of the

superheater reaches a temperature of about 550°C and a pressure of 65 bar, enabling the turbine synchronization (25% of the nominal load).

4.6.6.4. Normal operation

When the start-up procedure is completed, the conservation of the temperature of the feedwater by means of the preheat sub-system of the power block should work continuously. In order to change the load conditions of the SG, an increase of the pressure of the produced steam at a rate of about 5 bar/min may be feasible, with a constant live steam temperature of 550°C over the whole load range. This means that changing the load of the steam generator from 25% to 100% may take approximately 15 minutes.

During normal operation, the control of the live steam temperature is done by a spray water attemperator downstream the superheater. The control of the reheater steam outlet temperature is performed by a control valve setting the amount of molten salt flowing through the reheater.

The SG works with constant pressure up to 25% load and with sliding pressure between 25% load and 100% load. With an incoming molten salt temperature of 560°C, it is expected that the molten salt outlet temperature oscillates between 271°C – 300°C within the operation range. Table 18 shows a summary of parameters for the different load cases of the SG during normal operation.

Table 18: Summary of the SG load cases

Parameter				Load cases			
				100%	75%	50%	25%
				239 MWth 140 bar 245°C FW 560°C salt	182 MWth 105 bar 251°C FW 560°C salt	130 MWth 66 bar 251°C FW 560°C salt	69 MWth 65 bar 255°C FW 560°C salt
				12K pinch	9K pinch	9K pinch	6K pinch
Molten salt	Flow rate	Inlet/Outlet	kg/s	**608,52**	**445,20**	**298,31**	**158,89**
		To RH	kg/s	**299,27**	**187,43**	**114,36**	**57,54**
	Pressure	Inlet	bar	**10,00**	**10,00**	**10,00**	**10,00**
	Temperature	Inlet	°C	**560,0**	**560,0**	**560,0**	**560,0**
		Outlet	°C	**300,8**	**289,4**	**272,0**	**271,2**
	Pressure drop	Total	mbar	**1781**	**1064**	**549**	**146**
Water / Steam HP	Flow rate	Main steam	kg/s	**82,92**	**66,24**	**46,65**	**24,40**
		Spray water	kg/s	**0,00**	**0,32**	**0,30**	**0,19**
		Circulation	kg/s	**414,61**	**329,59**	**231,73**	**121,02**
	Pressure	Main steam	bar	**140,00**	**105,00**	**66,00**	**65,00**
		Eco inlet	bar	**146,00**	**110,00**	**70,00**	**67,00**
	Temperature	Eco inlet	°C	**245,0**	**250,6**	**251,2**	**255,0**
		Eco outlet	°C	**334,8**	**316,2**	**285,0**	**282,0**
		Eva outlet	°C	**338,9**	**316,7**	**284,9**	**281,9**
		SH outlet	°C	**550,2**	**554,7**	**556,8**	**558,1**
		Main steam	°C	**550,0**	**550,0**	**550,0**	**550,0**
	Pressure drop	Eco	bar	**1,5**	**0,9**	**0,5**	**0,1**
		Eva	bar	**0,3**	**0,2**	**0,1**	**0,0**
		SH	bar	**3,2**	**2,9**	**2,4**	**0,7**
		Total	bar	**5,0**	**4,1**	**3,1**	**0,9**
Water / Steam MP	Flow rate	RH steam	kg/s	**74,87**	**58,15**	**40,26**	**19,98**
	Pressure	RH inlet	bar	**40,50**	**30,77**	**21,47**	**10,65**
		RH outlet	bar	**37,40**	**27,74**	**19,30**	**9,66**
	Temperature	RH inlet	°C	**328,9**	**378,9**	**392,3**	**329,3**
		RH outlet	°C	**550,0**	**550,0**	**550,0**	**550,0**
	Pressure drop	RH	bar	**2,9**	**2,4**	**1,7**	**0,9**
System	Useful heat		MWth	239,1	182,4	129,9	69,2

4.6.6.5. Standby mode

The SG can be blocked for short periods of time. That would mean a temporal stop in the steam production, so that a new start will be possible soon.
At first, the molten salt mass flow and the steam mass flow have to be reduced until the minimum load level (about 25% of the nominal load). A gradual steam pressure reduction (up to 5 bar/min) has to be achieved as well.
After that, the temperature of the incoming molten salt has to be reduced within a rate of 5 K/min. In order to achieve this temperature reduction, part of the incoming molten salt will be delivered from the cold salt tank. Final reduction of the temperature of the molten salt will be achieved, when the entire molten salt flowing through the SG comes from the cold salt tank. The pressure on the steam side has to be kept at the value of the saturation state corresponding to the temperature of the incoming molten salt. This means that by a molten salt temperature of 290°C, the steam pressure should be about 75 bar.
At that point, the feedwater flow into the economizer will be cut. The water contained in the economizer and evaporator will eventually evaporate completely (depending on the standby duration). The electrical trace heating will remain active to compensate heat losses in the SG as to prevent crystallization of molten salt.
As a way to reduce the use of the molten salt storage even more, the molten salt content of the steam generator could be drained once the steam pressure has been reduced to 75 bar and the feedwater flow have been cut. The water content in the system could remain above the crystallization temperature of the molten salt for about 8 hours. Although the mentioned alternative will save some molten salt from the storage, the necessary time for a new start will be slightly higher than in the first description.

4.6.6.6. Antifreeze mode

An alternative to the standby mode (blocking of the SG) is the antifreeze mode. It is thought as a special routine for overnight shutdowns with the attempt to keep the whole water/steam circuit warm and to prevent air from entering the closed loop water circuit. This could include the production of a minimal steam mass flow through the SG. But this procedure requires clarification of involved constraints, like: disposable energy content from the salt tanks to allow a minimum load operation; adequacy of the feedwater pump to deliver a required minimum continuous feedwater flow; constraints and restrictions of the condensate system and related components in regard to low load operation.

4.6.6.7. Shutdown of the SG

A similar procedure to the one described in the standby mode should be taken for a prolonged outage; but in this case, at the end of the operation the molten salt (once it has reached about 290°C) should be evacuated through the drainage lines and the water/steam side should be depressurized and drained.

The drainage at the salt side is caused by the static head of the salt in heat exchangers. The salt is drained through the drainage piping with a sufficient inclination towards the terminal points. The drainage pipes are situated at the lowest points of the interconnecting pipework within the SG. All drainage lines are equipped with drainage valves that remain closed during all other modes of operation.
Once the molten salt has been removed, the trace heating will be turned off. After that, the SG will cool down gradually. After a prudential time, the SG will be depressurized through the valves towards the blowdown system. The residual water content will be evacuated into the condensate system.

4.6.7. Cost estimation

Within the main components mentioned in chapter 4.6.5, the interconnecting piping, insulation, valves, instrumentation and steel structure, the steam generator will have a specific cost of about 110 €/kW$_e$.

4.6.8. Back-up heater

As to ensure the availability of dispatch from the power plant into the grid, a back-up heater could be implemented.
There are basically two forms of implementing the back-up heater: parallel to the receiver or parallel to the steam generator.
Having a back-up heater parallel to the receiver would mean heating the molten salt between the cold and the hot tank. Such arrangement represents a way to cope a problem at the solar field or receiver. The molten salt could be heated using fossil fuels or electricity.
In case of having a problem in the steam generator, a back-up heater parallel to the steam generator would be the solution. That means, producing steam somewhere else. Taking into account the steam parameters of the case study, the back-up heater would have to be a fossil fuel fired unit. It is considered, that this option should be disregarded, since it would represent paralyzing the whole solar part, converting the plant in a “pure” conventional one. Within the proposed steam generator configuration (2 units of 100 MW$_e$) the risk of absence of steam production is mitigated, since it is presupposed that one unit would remain available.
Although it seems to be better to have the back-up heater for heating the molten salt, the decision of including it or not in the power plant is meant to be subject of punctual characteristics of the location of the plant. This includes for instance: availability of a particular fossil fuel, subsidized prices, etc. Therefore, it was decided not to analyze this topic in detail.

4.7. Power Block

The energy received by the solar tower and stored within the salt tanks is used by the power block to generate electricity. Therefore, heat from the salt system is transferred to the water-steam cycle in the steam generator, as described in the previous chapter.
In the following sections, the general design of the water-steam cycle (WSC), the steam turbine (ST) and the air-cooled condenser (ACC) will be introduced. Afterwards, nominal and part-load operation will be described and a cost estimation for the power block will be provided.

4.7.1. Water-steam cycle

The water-steam cycle (WSC) basically describes the 'Clausius-Rankine-Cycle'. A state-of-the-art WSC designed for CSP applications is shown in Figure 38. This WSC consists the following main components:

- Steam Generator
- High pressure steam turbine
- Low pressure steam turbine
- Air cooled condenser
- Low pressure preheater (LP-PH 1-3)
- Deaerator
- High pressure preheater (HP-PH 1-2)

The boundary conditions of the steam generator such as pressure drop and minimum inlet temperature are based on the design by Steinmueller, as described in Chapter 4.6.
The live steam from steam generator enters the HP-turbine in design operation with 140 bar and 550°C. The HP-turbine has a bleed, from which a small share of steam can be piped to the HP-PH2 to ensure the minimum economizer inlet temperature of the steam generator. The minimum economizer inlet temperature combined with a minimum temperature difference within the heat exchanger defines the saturation temperature and pressure of the steam which is required for the HP-PH2. The WSC is designed such as the reheat pressure corresponds to the required saturation pressure of the HP-PH2. Thus, in design operation, the HP-turbine bleed is not active because the outlet pressure of the HP-turbine is high enough to feed the HP-PH2 with steam.
However, in part load operation in which the life steam pressure decreases, steam from the HP-turbine bleed or even from live steam can be used to ensure the minimum economizer inlet temperature in all operation cases.

The main steam flow through the HP-turbine expands to the outlet pressure and leaves the HP-turbine to be reheated within the steam generator. The reheat temperature is similar to the live steam temperature. The reheated steam enters the LP-turbine through which the steam is expanded to the condenser pressure. The LP-turbine has 5 bleeds for feedwater preheating.

The condenser pressure is defined by the air-cooled condenser and thus, also by the ambient conditions.

The preheating system is designed to minimize exergy losses while heating up the condensate to steam generator inlet conditions. To achieve this, heat from steam is transferred in several steps to the condensate / feedwater in order to reduce the temperature difference between heat transferring and heat receiving medium. Thus, the ‘Clausius-Rankine Cycle’ is adapted to the ‘Carnot Process’, by which the cycle efficiency is increased. However, the grow in efficiency decreases with the number of preheaters and goes towards a limit. Therefore, the number of preheaters chosen was based on a technical and economic analysis.

The thermodynamic parameters of the WSC in nominal load are shown in Figure 39. The temperature-entropy diagram allows for a better understanding of the preheating, steam generation and expansion processes within the water-steam cycle.

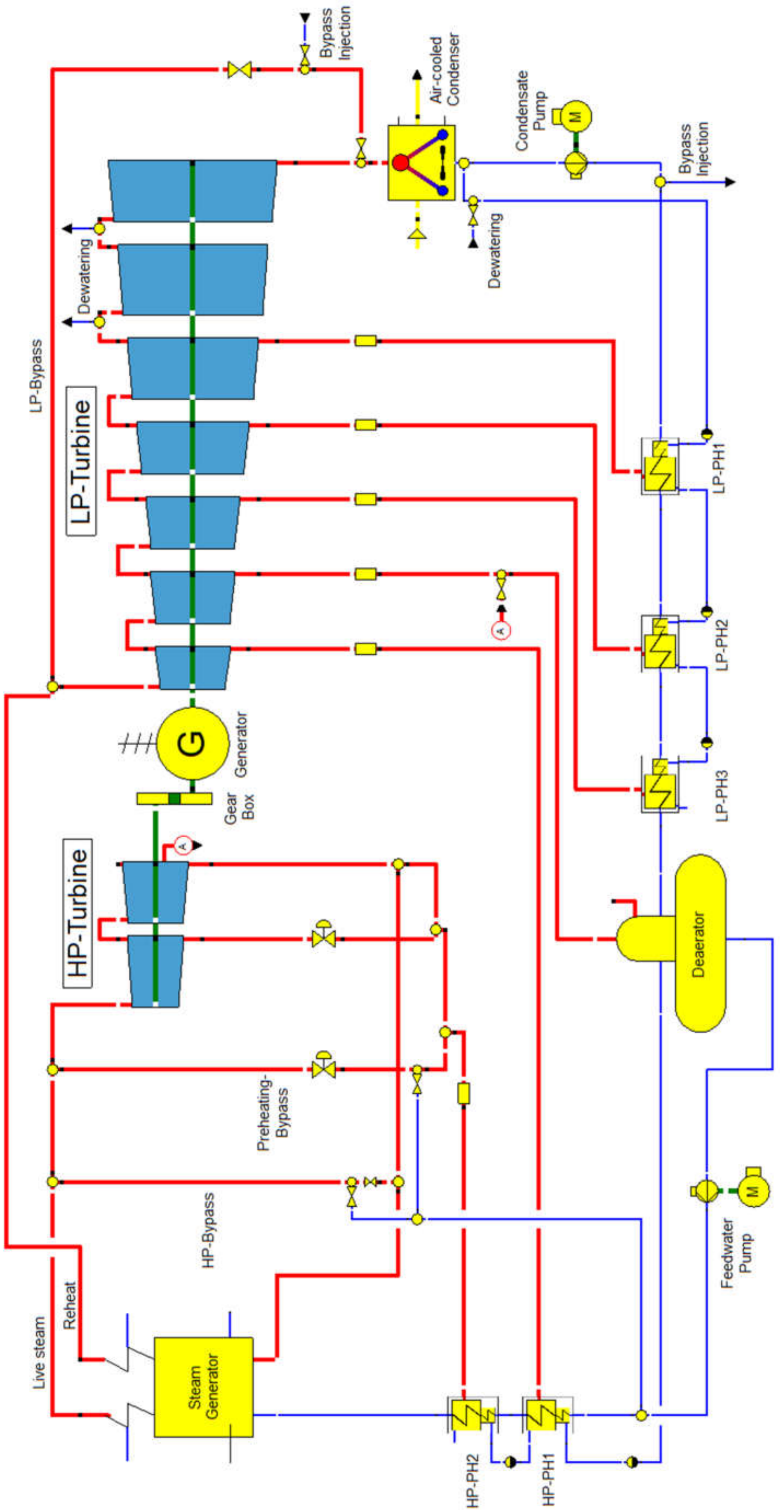


Figure 38: Scheme of water-steam cycle

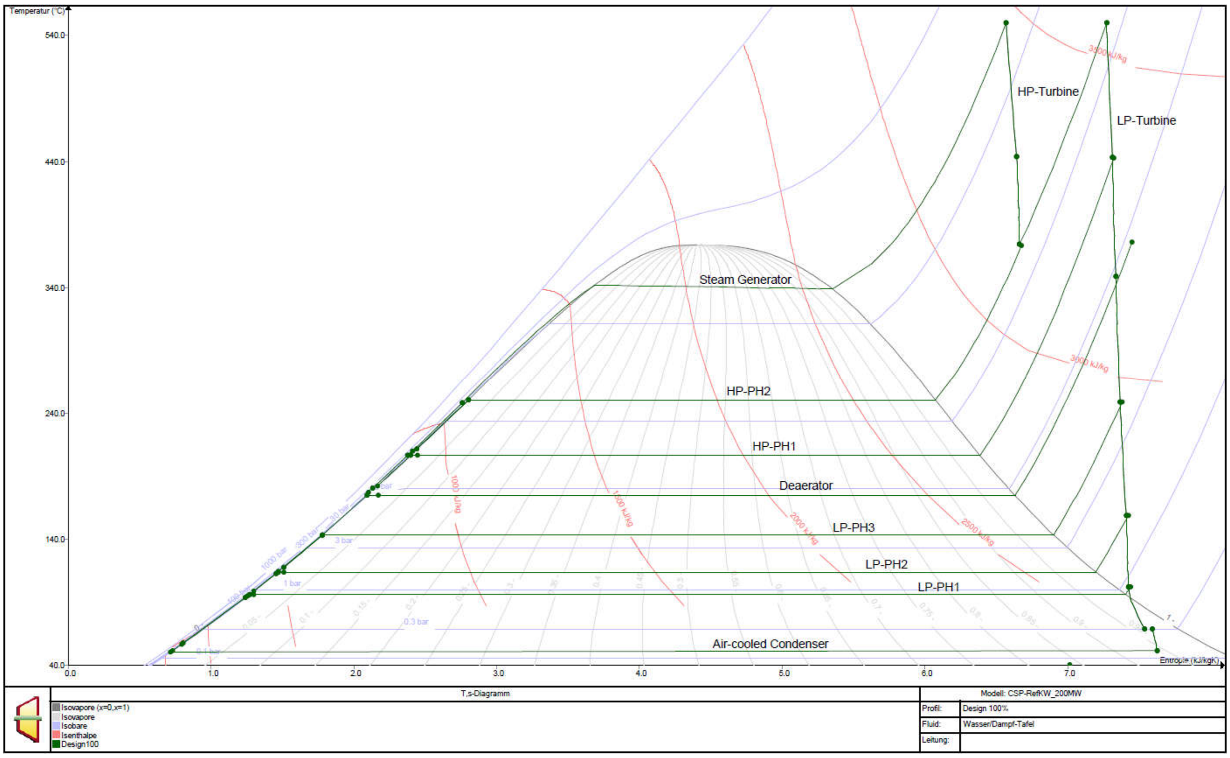


Figure 39: T,S-Diagram for nominal load

An exemplary arrangement of the generator train including HP-turbine, gear-box, generator, LP-turbine and Condenser is shown in Figure 40. In this configuration, the generator is located in the centre, between HP and LP turbine. The gear-box transmits the higher rotational speed of the HP-turbine to the generator frequency.
The LP-turbine has an axial exhaust leading to the Condenser. Figure 40 shows an exemplary train arrangement with a water-cooled condenser. In the considered reference case, an air-cooled condenser is used due to limited water resources. The air-cooled condenser cells are located outside the machine house, as shown in Figure 30.

The pipes below the HP and LP turbines feed the condensate / feedwater preheaters with steam from the steam turbines. The preheaters can be located directly below the generator train in order to reduce the distances and pressure losses. The deaerator is usually placed on higher level to ensure a geodetic pressure on the suction side of the feedwater pump. This is necessary to avoid cavitation at the pump wheel.

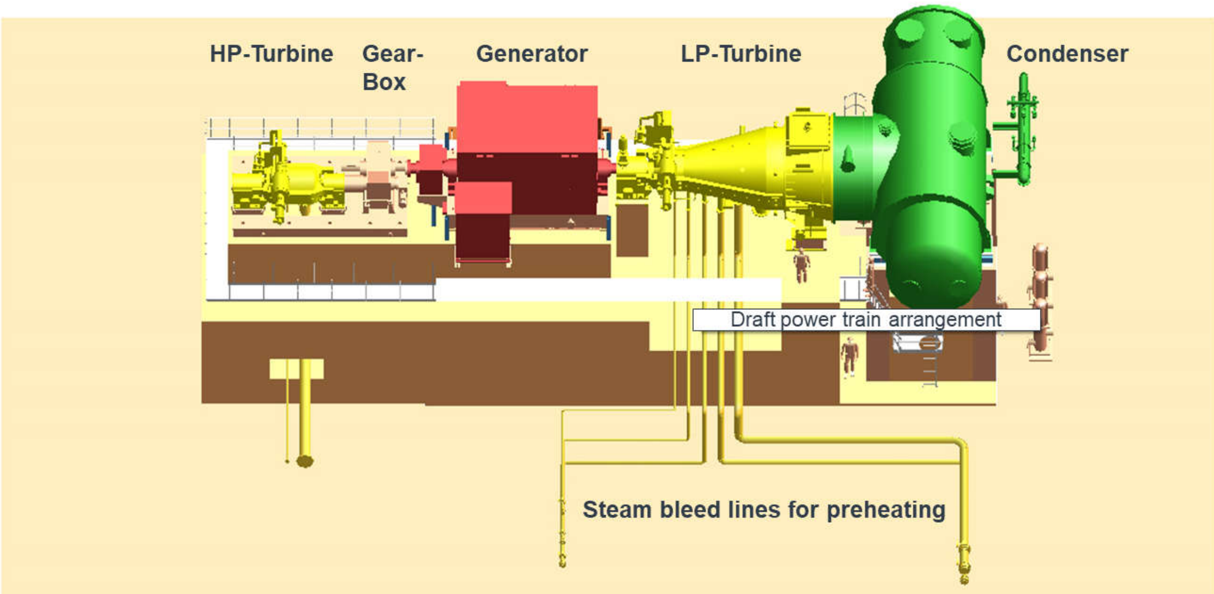


Figure 40: Draft of generator train arrangement

Details regarding the steam turbine design and the air-cooled condenser (ACC) as well as operation conditions in part load operation will be provided in the following sections.

4.7.2. Steam turbine

The steam expansion process transfers energy from steam to mechanical energy in the steam turbine. The expansion can be divided in several steps which take place in several steam turbine parts. A subdivision of the steam turbine in several parts can have different advantages in terms of constructional design, process design, rotor-dynamic behavior, transportation, etc. In most of the CSP applications with a steam reheat a two-part design is used for the steam turbine.

4.7.2.1. High-pressure steam turbine

The high-pressure steam turbine is designed as a high efficiency MST080 from MAN Energy Solutions. An exemplary HP steam turbine is shown in Figure 41.

The target electrical power output of the power block was evaluated in the techno-economic analysis in Chapter 5 and defined as 200 MW_e.
The steam inlet parameters for the high-pressure turbine are 140bar, 550°C and about 174 kg/s mass flow in nominal load, which are expanded to a reheat pressure of 41 bar. This leads to a mechanical power output at turbine flange of about 55 MW.

The HP-turbine is a reaction steam turbine with one control wheel and 12 reaction blading stages. The turbine blading is characterized by state-of-the-art 3D blades with high efficiency.

The power plant operates mainly in sliding pressure control. Only for strong part load operation of 50% load and less, the power plant control switches to a constant pressure mode. In order to control the pressure and mass flow at the steam turbine inlet, control valves and a control wheel are used in the HP steam turbine.

Due to the high pressure and relatively low volume flows, the rotational speed of the high-pressure steam turbine was set to 5000 rpm. Thus, the number of turbine stages inside the HP turbine can be reduced. However, due to the higher rotational speed a gear box is necessary to couple the HP turbine with the electrical generator, as shown in Figure 38 and Figure 40. The gear-box leads to a friction loss, which has been considered for the performance calculations.

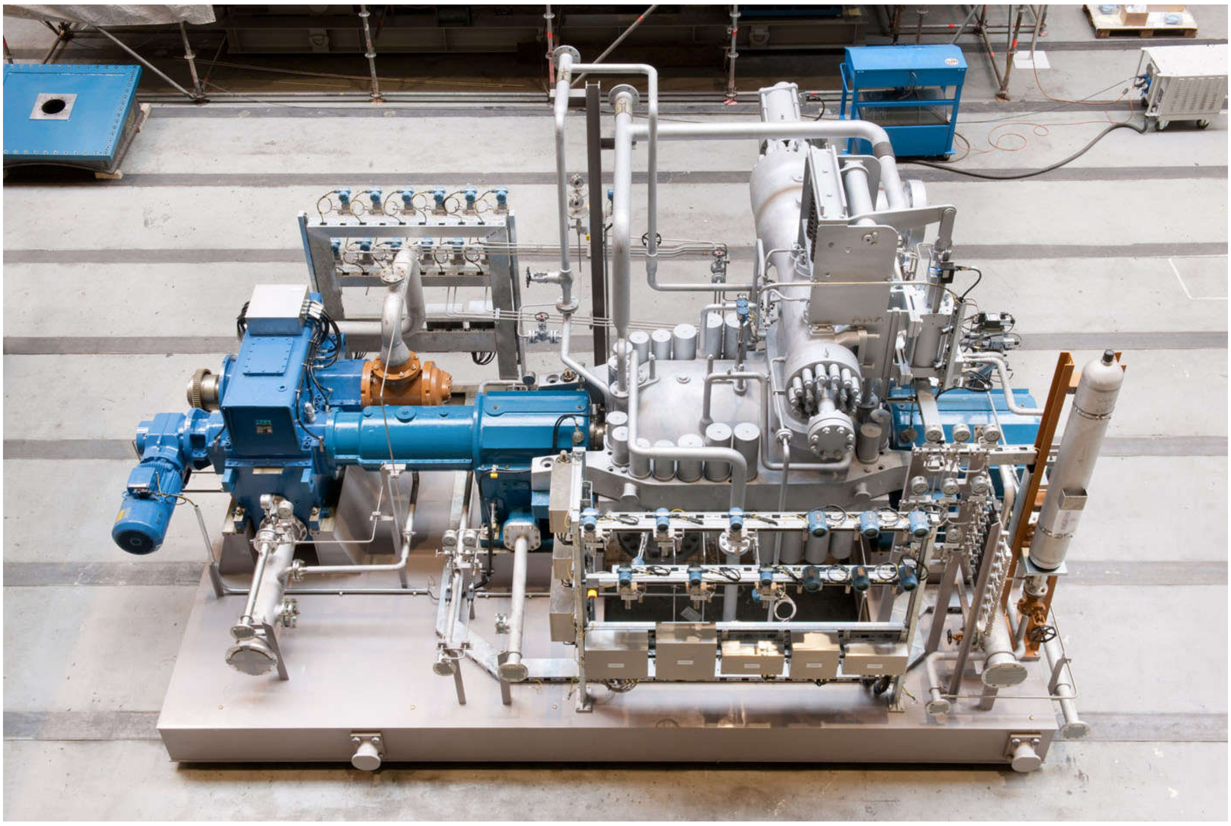


Figure 41: Exemplary MAN HP-steam turbine

4.7.2.2. Low-pressure steam turbine

A MAN MST120 is used to expand the steam after the reheat from about 37 bar and 550 °C to a condenser pressure of 130 mbar at nominal load.

The steam flow through the LP-turbine is directly depending on the HP-turbine exhaust flow. Therefore, no additional control valves are necessary. Thus, the LP-turbine has no control wheel. The LP-turbine rotates with 3000 rpm, which corresponds to the generator frequency in North-Africa.

The LP-turbine has 5 steam bleed lines which feed the HP-preheater 1, the deaerator and three LP-preheaters. The main steam flow leaves the turbine in axial direction to the ACC, as shown in Figure 40. In design operation, the LP-turbine generates about 160 MW power at the turbine flange, which is nearly triple the power of the HP-turbine.

The LP-turbine is also a reaction turbine with in total 28 high efficiency blades. The exhaust area with 6.3m² is comparatively low for a steam turbine of this power class, which is due to the high exhaust pressure and the hot ambient conditions at the site.

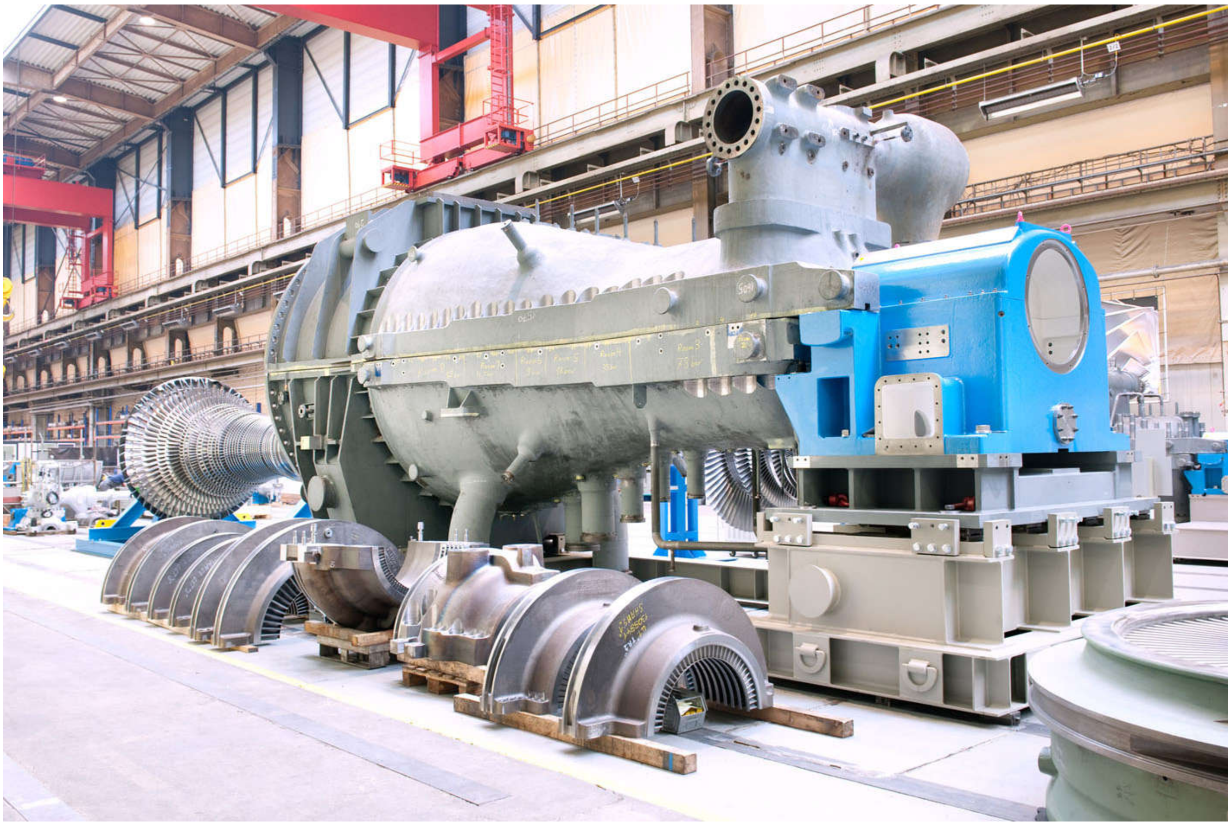


Figure 42: Exemplary MAN LP-steam turbine

4.7.3. Air cooled condenser

The air-cooled condenser is designed for 130mbar condensing pressure in design operation. The ambient conditions are assumed as 30°C and 60% air humidity during the night, when the CSP power block is running. The cooling air leaves the air cooler with about 40°C.

In order to increase the efficiency in part load operation, the ACC is designed with controllable fan speed as well as the possibility to switch single air cooler cells off. Due to this, the power consumption of the air cooler cells can be reduced significantly if the steam mass flow and thus the cooling rate shrinks.

In design operation, the power consumption of the ACC is about 6600 kW, which is distributed to in total 15 air cooler cells.
In part load operation, the fan speed of the air cooler is adapted in a first step to control the turbine exhaust pressure. If the turbine exhaust pressure decreases, the power output of the LP-turbine increases due to the lower enthalpy at the cold end. However, a reduction of the fan speed of the air coolers lead to a strong decrease in their power consumption. Thus, the overall control has to be optimized to control the condensing pressure in order to maximize the power output.

In addition, the load of the LP-turbine increases with decreasing exhaust pressure. In order to protect the last stage blades against overload, the minimum condensing pressure has to be limited. This limit was set to 100mbar for the current design.

The air cooler fan speed will be initially controlled in part load operation down to 50% load. However, the air coolers require a minimum fan speed for safe operation. Thus, single air cooler cells will be shut off to control the condensing pressure and to ensure the minimum pressure of 100mbar, if the load is further decreased.

4.7.4. Operation of power block

4.7.4.1. Net efficiency in design and part load

The net efficiency of the power block is the most important measure to evaluate the operation. In general, the net efficiency of the power block is affected by the operation mode of the steam generator (sliding pressure / constant pressure mode), the steam turbine efficiency, the condensing pressure and the internal power consumption of ACC, pumps, etc.

The power block net efficiency depending on the load is shown in Figure 43. In design operation at 100% load the net efficiency is 41.5%. In a load range between 100% and 75% load, the net efficiency drops only slightly. At 50% load the net efficiency is still high with about 40%. However, below 50% load, the net efficiency decreases strongly down to 36.7% at minimum load of 25%.

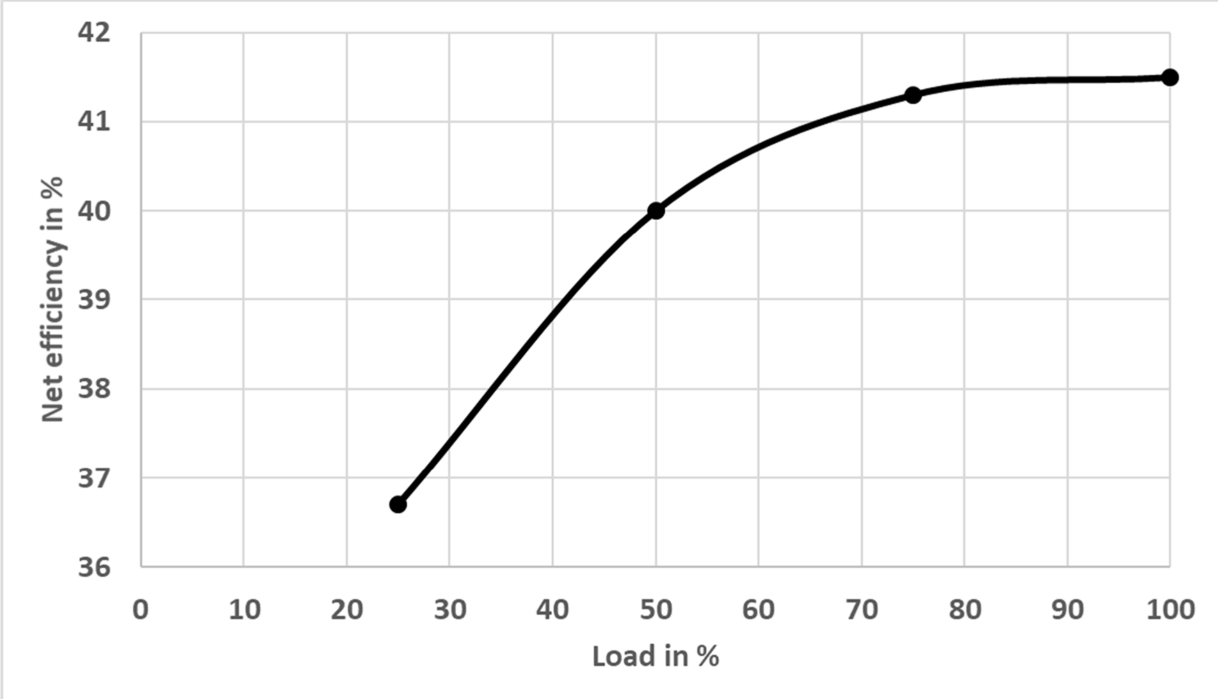


Figure 43: Power block net efficiency depending on load

The operation of the power block is controlled by the steam generator in a sliding pressure mode over a wide operating range between 100% and 50% load. In this operating range the ACC is controlled by the air cooler fan speed, which enables partially to compensate a decrease of efficiency in this part load range. In part load operation between 90% and 70% load, the HP-preheater 2 can be operated efficiently with steam from the HP-turbine bleed line, as shown in Figure 38.

From about 50% load and below, the operation mode switches to constant pressure control due to a defined minimum pressure limit of 75 bar at the steam generator outlet. In order to keep the live steam pressure constantly, control valves at the HP-turbine inlet are used, which leads to throttling losses. Also, the efficiency of the steam turbines drops in low part load operation. In addition, the HP-PH2 has to be served with live steam and the condensate pressure stays at its lower limit of 100mbar, which loads to no further compensation effects due to a reduced exhaust pressure. All these effects lead to the comparably strong decrease in the net efficiency below 50% load.

4.7.4.2. Start-up process

The start-up process has to be distinguished between the daily start-up in normal operation and an initial start-up for commissioning or after service / maintenance or power plant shut down over a longer period.

In the daily start/stop operation, the steam turbine and steam generator are still hot, due to a short cool-down period. This enables a fast start-up process without any pre-heating duration. As soon as the steam generator exports steam of sufficient quality to the steam turbine, the steam turbine and generator can be ramped-up in order to be synchronized with the electricity net. Afterwards, the steam mass flow can be increased to raise the load.
In order to ensure a sufficient minimum steam temperature at the steam generator inlet, the last HP-preheater HP-PH2 in front of the steam generator will be served with live steam during low load operation up to 70% load. Between 70% and 90% load the HP-PH 2 can be served from the HP-turbine bleed line which will be replaced by exhaust steam from the HP-turbine at more than 90% load.

For an initial start-up or a cold start after a long shutdown period, the steam turbine has to be pre-heated. This can be done with steam from an auxiliary boiler, which is also used to heat up the steam generator, for example. As soon as the steam turbine has a sufficient temperature, it can be ramped-up to nominal rotational speed. However, the load raise is depending on temperature gradients inside the steam turbine which lead to increasing start-up times with rising previous shut-down duration.

4.7.5. Cost estimation / Balance of Plant

The total costs of the power block are estimated as 850€/kWh including the following subsystems:

- Steam Generation System (as described in Chapter 4.6)
- Steam Turbine Generator Island
- Blowdown System
- Cooling Systems
- Condensate System
- Feedwater System
- Auxiliary Cooling Water System
- Steam Piping, Insulation, Valves, & Fittings
- Fuel Gas Handling & Metering System
- Water Treatment System
- Power Distribution Systems
- Back-up Power Systems
- Instruments and Controls System
- Fire Protection System
- Foundations & Support Structures
- Buildings
- BOP Mechanical Systems
- BOP Electrical Systems

4.8. Balance of Plant

4.8.1. Instrumentation and Control Equipment

The Instrumentation & Control (I&C) system will control and supervise the whole plant. It is based on a Distributed Control System (DCS) that acquires data from the field devices and after processing them, sends output signals to valves, actuators, motors and other field devices to influence the process according to the control algorithms programmed in the system. A modern state of the art I&C system will be used for the plant providing the result of the latest development in the instrumentation and control of modern power plants including the hardware, the software and the operation principles.
Special attention in relation to the I&C system is paid e.g. to the following aspects:

- Plant Identification System, Labelling and Colour Coding
- Codes and Standards
- Requirements in the Electrical Specifications for cables and cable laying
- Specific requirements of substation control and Load Dispatch Centre connection
- Explosion Hazard Requirements (ATEX)
- Safety Instrumented System requirement (SIL)
- Cyber Security
- Earthing system
- Master Key System

The design and manufacture of all I&C equipment will comply with the latest editions of the ISO and IEC Standards and Recommendations.
Part of the I&C system is the Human Machine Interface (HMI) system. It consists of operator station PCs, monitors with screen pointing devices (e.g. mouse or trackballs) and printers. It will allow the operator to operate, monitor and supervise the plant and auxiliaries from central control room (CCR). Additional it should be capable to support the optimization of the plant performance as well as a cost-efficient predictive maintenance for the whole plant with an asset management functionality.
In the CCR all operator stations and services for all necessary applications will be provided. The control desk of the shift engineer shall be located central to enable a general overview to all activities. Storage elements for primary documentation and literature for the staff has to be integrated ergonomically. The large wall-mounted screen device will be installed with other displaying units in front of the operators to enable the best functional overview.
The number of conventional elements will be limited to the necessary minimum like emergency stop pushbuttons and big size indicators for main values.
Metering is used for process control and performance monitoring. All measurements shall be displayed locally and monitored, displayed and logged by the DCS system.
Metering will be used e.g. to the following:

- Electrical power (active and reactive) from each generator.
- Electrical power (active and reactive) for the unit transformers.
- Total electrical power (active and reactive) imported and exported from/to the Grid.
- Current and voltage measurements for all key equipment.

- All important process values (pressure, temperature, vibration etc.)

Within the HMI system a management information system (MIS) will be implemented. The MIS will have additional the function to support the optimisation system and plant asset management system (PAMS).
Furthermore, the alarm system as well as the plant and equipment interlocking and protection system are part of the functions performed by the DCS.

4.8.2. Closed/Auxiliary Cooling Water System

The closed or auxiliary cooling water system, as an intermediate cooling cycle, shall transfer heat generated in various plant equipment components via the cooling water cooler to the auxiliary cooling towers. For the cooling water cooling and distribution of the system, cooling water coolers with pumps will be used.
The closed cooling system for the unit will serve the following equipment:

- • Turbine oil coolers;
- • Generator cooler;
- • Feed water pumps;
- • Condensate pumps (if necessary);
- • Compressor plant;
- • Sample coolers;
- • Other necessary consumer.

Auxiliary Cooling Towers
On the primary side, the closed cooling water cooler shall be supplied with water from the auxiliary cooling towers. These towers are assumed to be of induced-draft type, multi-cell, in-line design with air water counterflow principle provided by the fans. The towers are of concrete or treated timber structures (depends on site/country-specific conditions).

Expansion Tank
A constant inlet pressure to each closed cooling water system will be assured by means of a closed cooling water expansion tank, located sufficiently high. Water losses will be compensated by make-up water from make-up water system, regulated by an automatic water level controller.

4.8.3. Service and Control Air System

The service and instrument air system will produce and deliver all compressed air required for all associated equipment of the Power Plant and associated systems for the following:

- Service air for operation of mechanical air tools, wrenches, etc., during all modes of unit operation and for maintenance purposes.
- Instrument air of high purity, oil-free and moisture-free compressed air to all pneumatically operated plant instrumentation and control devices.

Each compressor of the system is consisting of separate air intake ducting including individual inlet air filters and silencers. The air will be fed from the compressors via air coolers (after coolers) to the air receivers and air dryers. The consumption of air is mainly intermittent. Therefore, the air receivers together with the distribution pipe work have to serve as a pressure accumulating system against pulsation.

4.8.4. Chemical Dosing and Sampling

4.8.4.1. Chemical Dosing

This description addresses the general technical requirements of chemical dosing to control the water chemistry of the water/steam and cooling cycles to avoid corrosion and depositions (scaling).
Adjustment of the pH-value of the condensate and boiler feed-water can be done by the injection of ammonia. The injection points for the ammonia solution shall be best near the feedwater and at the condensate pumps located. An oxygen scavenger chemical can be injected into the boiler feedwater lines to reduce the oxygen content of the cycle water. Tri-sodiumphosphate can be added to avoid deposits of hardness in the boiler tube system. The injection point for the tri-sodiumphosphate solution can be e.g. at the feedwater lines and some other points of the system.
For adjustment of the pH-value and to avoid corrosion, a suitable corrosion protection agent can be injected into the closed cooling system near the circulating pumps. In the open cycle cooling system suitable chemicals can be added to reduce biological fouling causing corrosion, heat transfer reduction, and health issues.
For the chemical dosing skid mounted units with preparation/dosing tank chemical unloading pump or bag unloading facility, adequate number of dosing pumps, and dosing pipelines will be used.

4.8.4.2. Sampling for Water / Steam Cycle

A Sampling System for the Water / Steam Cycle is needed to supervise and maintain the quality of condensate, feed-water, boiler water and steam. It enables the safe, reliable, efficient and economic operation of the steam cycle and its equipment.
The duty of the sampling system is to collect samples from various locations to cool the samples, reduce the sample pressure and to perform automatic/manual sampling and continuous chemical analyses as required. Cooling water for the sample coolers shall be provided from the closed cooling water system.
Samples will be performed e.g. at pump discharge, at lines after chemical feed, deaerator, boiler drum, superheated and reheated steam, closed circuit cooling water, etc.
Beside the analysers also e.g. temperature, pressure, and flow indicators as well as valves are used at the sampling locations/lines. Usually the sample racks will be located in the turbine hall. If applicable for the steam generator there will be a separate location (e.g. container). As analysing equipment e.g. pH, conductivity, dissolved oxygen, and silica analysers will be used.

4.8.5. Water Treatment System

The water treatment system consists of the following sub-systems:

- portable & service water
- water demineralisation
- industrial waste water
- sanitary waste water

4.8.6. Potable and Service Water System

The function of the potable and service water system is to provide a secure supply of potable and service water for the own requirements of the power plant. Potable water shall be provided from outside the plant by trucks or other treated water sources. The treated water shall be stored in one potable water tank which can be also the source for the fire-fighting water, in case there will be some dedicated design to ensure the save firefighting water supply. Also, service water for the plant’s own requirements can be taken from the potable water tank. Separate potable water and service water grids are common for the Plant’s internal requirements
The potable and service water system contain e.g. several tanks, transfer pumps, service and potable water grid, etc.

4.8.7. Water Demineralisation System

The water demineralisation system covers beside the demineralisation station also the regeneration station with chemical storage tanks, the regeneration wastes neutralisation station, and the demineralised water tanks.
The main task of the desalination plant and the associated equipment is to produce from e.g. treated water demineralized water to compensate for water losses in the steam/condensate system.
Equipment for the system will be e.g. booster pumps, candle filters, ion exchangers, mixing ejectors, neutralisation pumps, and tanks. There should be two trains of system available so that during normal operation one train shall be in operation and one train in regeneration/ standby. The neutralised effluents of the demineralisation plant will be transferred by pumps to the waste water treatment system. Special care will be taken for the easy and safe handling of the chemicals and for the acid and caustic protection of all mechanical and civil components.

4.8.8. Industrial Waste Water Treatment System

The systems will serve the needs of the entire power plant and provide treatment of all drains and waste waters released by various plant installations and operations.
The system will provide oil/water separation, neutralization, clarification, sludge thickening and dewatering, and filtration of the waste water generated by various plant operations. The waste water from the following sources will be e.g. treated:

- Drains contaminated with chemicals from sumps of water treatment plant, chemical laboratory, chemical storage and handling facilities, floor drain at machine sets, boiler area, battery room, stack drain, compressor wash waters, etc.;
- Steam generator area drains;
- Turbine area drains (incl. emergency diesel unit area);
- Switch yard building drains;
- Backwash water from e.g. the candle and sand filters;
- Regeneration wastes from the water demineralisation system;
- Steam generator blow down; and
- Any other drains.

The treated waste water (not including regeneration effluents from Water Demineralisation System due to their high salt content) can be pumped to the recycle water tank for irrigation reuse. The removed solids and sludge from the waste water treatment facilities can be collected in suitable containers and disposed of in e.g. a landfill.
The System contains e.g. dosing system for chemicals, distribution pumps for al streams, conditioning tanks with mixers, reaction tank and clarifiers, oil removal system, sand filters, sludge pumps, thickener and dewatering, etc.

4.8.9. Sanitary Waste Water Treatment System

A sanitary waste water drainage and treatment system will be used to collect and treat the sanitary waste water from the power plant area. The sanitary sewage at the power plant area shall be collected from the plant buildings and conveyed through closed drains to the sanitary waste water treatment facility at the power plant area. The system will be of a suitable size based on the number of personnel (plant operational personnel and security personnel during several shifts per day) working on the Site.
The sanitary waste water system will be of a biological treatment configuration and will contain e.g. screens, pumps for different streams, chemical dosing, blowers, sediment and sludge collection, treated water tank, etc.

The dosing of chemicals will be adjusted to provide sterilisation of the effluent but still enable later re-use for e.g. irrigation.

4.8.10. Fire Protection System

The fire protection system will cover all fire protection installations, comprising structural fire protection and fire resistance ratings for building structures, fire detection and alarm system and all other firefighting installations, to offer protection for all installations power plant.
The complete fire protection system will be designed, installed, tested and taken into operation in accordance with the codes and standards of NFPA (National Fire Protection Association, USA).

The design and extend of buildings, civil structures and all fire protection installations is based on a fire risk evaluation, determining hazardous areas, fire areas and means of egress and must adopted to conform to local regulations.
Firefighting water shall be taken from the service / firefighting water storage tank, in which a minimum amount of water will be available at any time for firefighting purposes only to cover the demand of water required for fighting the maximum risk for a certain duration.
The fire protection system contains e.g. firefighting pumps (electrical motor and diesel engine driven), jockey pumps, a ring network system, hydrants, hose stations, sprinkler and spray systems, water/air pressure vessel with air compressors, extinguishers of suitable types, etc.
The HVAC part of buildings/structures (as e.g. ventilation and air conditioning systems, ducts and dampers) will be harmonized with the fire protection part to ensure an adequately smoke exhaust.
For the fire detection and alarm system a digital and intelligent, centralized or modular fire system is assumed in accordance with NFPA 72.

Optional a firefighting truck and an ambulance car can/should be available related to the firefighting (and safety) system, depending on local regulations or interests of the plant owner.

4.8.11. Heating, Ventilation and Air Conditioning System

The heating, ventilation and air conditioning (HVAC) system for the buildings and structures designed for the power plant ambient conditions will be mainly follow the local regulations as well as the Occupational Safety and Health Administration (OSHA) definitions/guidelines.
Equipment for the HVAC system will be beside the heating, air-conditioning, and ventilation e.g. extract air roof fan units, chilled water piping, fan coil units, split air conditioning, condensate drainage, fire dampers, sand/dust traps, thermal insulation, guard grills, automatic control system utilising Direct Digital Control (DDC), etc.

4.8.12. Cranes, Hoists and Lifting Devices

Several cranes, hoists and lifting devices are used in the power plant related to dedicated duties. Each lifting equipment will be capable of handling the heaviest part and the part with a certain overall height and length installed in the subject building/area. E.g. the following equipment is assumed for the power plant:

- overhead travelling crane in turbine building
- monorail for feedwater pumps
- overhead crane for water treatment system
- monorail for aux. cooling water pumps
- monorail for air compressors
- overhead traveling crane for workshop building
- plant fork lift truck

Each crane will be capable of handling the heaviest part and the part with a certain overall height and length installed in the subject building/area.
The huge overhead cranes will be provided with walkways, platforms and guard handrails along the bridge rails and cleaning/maintenance facilities as well as an escape walkway.

4.8.13. Workshop Equipment and Installation Mobile Equipment

Within the power plant a warehouse with mechanical workshop, electrical, instrumentation and control (I&C) workshop and laboratory equipment will be available. The main task will be to allow the staff to perform all maintenance and inspection work predominantly independent from every other outer assistance.
It is the intention that the machine tools, hand tools, meters and all other apparatus will enable the station maintenance staff to carry out all repairs, overhauls, testing and inspection of the plant installed.
Within the workshop a proper material store as well an oil and grease store will be located.

4.8.14. Laboratory

The main purpose will be the analysis work done on all kinds of water for the power plant such as water for the water/steam cycle (condensate, feed-water), clear water, cooling water, waste water, etc., as well as the major tests and analyses of lubricants and transformer oils.
The laboratory contains e.g. laboratory workplaces (wall-working table, chemical-cabinets with air exhaust and with refrigerator, storages, etc.), laboratory equipment, chemicals and consumables for laboratory use, and safety devices.

4.8.15. Generator Connection

The connection of the steam turbine generator to the generator circuit breaker, the unit transformer and the tap to the unit auxiliary transformer will be implemented with an isolated phase busduct system. Additionally, one set of isolated phase busducts required for generator neutral connection will be installed in the generator.
A set of current and voltage transformers will be used for the implementation of the generator electrical protection.
The generator circuit breaker will be of a type with an arc quenching medium in single-phase enclosure with associated disconnector, instrument transformers as well as surge arresters and capacitors.

4.8.16. Power Transformers and Power Distribution System

As transformers the following equipment is considered:

- ST- Unit Generator Step Up Transformer
- ST- Unit Auxiliary Transformers

- Start Up Transformer
- Auxiliary Transformers

Transformers will be used to step up or down the voltage as required for transmission to the grid and for feeding the plant house load.
For power distribution the plant is equipped with an MV and LV power distribution system.
The MV auxiliary power supply for the power station will be provided by connection of the Unit Auxiliary Transformer to the unit MV switchgear. The MV switchgears will be installed in an electrical room of the plant control building.
Auxiliary transformer will be used for the step-down voltage to the 400V (Low Voltage) level.
For the LV power distribution system several switchgear and boards, i.e. main distribution boards, sub-distribution boards, MCCs, etc., as required for the plant will be installed.
Further a 400V UPS AC system, a DC system, and an emergency AC system will be part of the LV power distribution system.

4.8.17. Earthing and Lightning protection system

The earthing system design shall satisfy the safety and functional requirements of electrical equipment, neutral transformers and accessible conductive metal parts, which might accidentally become energized, through the connection to the main earthing system.
All the buildings and structures shall be protected against lightning hazards with a lighting protection system.

4.8.18. Chargers, Batteries and Inverters

For each control voltage required for individual systems batteries, battery chargers, inverters and converters will be implemented in the plant. Equipment for the following systems are may be foreseen:

- 400V UPS AC System, e.g. for systems requiring UPS AC power.
- 220 V DC System, e.g. for power, control and protection equipment
- 110 V DC System, e.g. for substation and switchyard, control, and protection equipment
- 48 V DC System, e.g. for I&C equipment
- 24 V DC System, e.g. for switchyard equipment

Each battery/equipment shall be designed to allow for normal operation as well as for safe shut-down of the entire plant in case of a total black-out.

4.8.19. Emergency Diesel Generator Unit

The Plant will be equipped with an emergency Diesel generator unit. The Diesel generator unit is providing electrical power to the essential auxiliaries/ consumers of the Plant required for safe shut down and standby of the plant in the event of loss of grid supply.

It is presumed that the diesel generator units feed into the main emergency switchgear. The capacity of each diesel generator will be enough based on the system demand. In any emergency case, at least the operation of following systems plus the necessary common auxiliaries will be covered:

- Turbine shaft turning gears
- Turbine emergency oil pumps
- Boiler outlet isolating valves
- Generator seal oil pumps
- Lube oil pumps for STG, boiler feed water pumps
- Control oil pumps
- Battery chargers and inverters
- Uninterruptable Power Supply
- STG control systems
- Remote control system
- Lighting system of control building, substation and important electrical/electronic rooms
- All provisions for security systems like:
    - Security lighting
    - Monitoring and supervision
    - Gates, etc

4.8.20. Lighting System

The plant will contain a complete lighting system, with the individual components as e.g.:

- Lighting main and sub distributions
- Maintenance power supply
- Lighting fixtures with lamps and tubes
- Flood lighting for outdoor illumination
- Road lighting and walkway lighting
- Power socket outlets
- portable lamps incl. loading station
- Cabling, wiring, lighting switches, and sockets, etc.

The lighting system is required for indoor and outdoor, with small power and maintenance power supply for all equipment, buildings, structures, sub-station, roads and outdoor operation areas.

The electrical lighting system is divided into the categories normal lighting system, emergency lighting system, and security lighting system. Each lighting system will be fed from dedicated power supply systems.

4.8.21. Aircraft warning lighting

The tower will be equipped with suitable means for possible installation of aircraft warning obstruction lights as per the International Civil Aviation Organization (ICAO) requirement stated in Annex 14, Chapter 6 of the "International Standards and Recommended Practices - Aerodromes".

4.8.22. Gas Insulated Switchgear

The Gas Insulated Switchgear (GIS) is designed for indoor operation with an insulating gas which allows to build up efficient switchgear in limited spaces. It will be of a modular construction, wholly gas insulated.
The design of the GIS buses, including the supporting structures, will be supposed to handle the following minimum (simultaneous) loads:

- Operating and dynamic loads of equipment such as switches and circuit interrupting devices.
- Dynamic short circuit forces produced by the maximum three-phase design fault located at air entrance bushings or a single phase line-to- ground fault internal in the GIS.
- Forces due to temperature variations.
- Forces due to gas pressure.

The equipment as circuit breaker, enclosure and conductor expansions, gas compartments, gas filters and seals, gas barriers and supporting insulators, gas monitoring and alarm circuits, enclosures, pressure relief equipment, position indicators, gas storage, filling and evacuating plant, leaking detectors, disconnectors, etc. are supposed to be part of the GIS system

4.9. Civil Works

The following criteria have been considered in the conceptual design and served as a base for layout and cost evaluations. These criteria need to be complemented by local regulations and rules, e.g. the applicable civil codes. Figure 30: Plant layout in the center of the heliostat field for peaker operation 2 x 200 MW_e indicates the location of key equipment, but is far from complete. A full conceptual layout should be prepared after selection and further optimisation of the conceptual plant.

4.9.1. Civil Design Criteria

The dimensions of all buildings will provide adequate space for the safe installation and proper operation and maintenance of all plant and equipment. Each room containing machinery or electrical equipment will be provided with means of access suitable for moving the largest item of equipment in and out of the room.
Areas, where spillage of chemicals, oil, brine or other corrosive material is likely, will be provided with protective treatment / finish to prevent damage to the environment and the plant.

All buildings and structures will be made of non-combustible or fire-resistant materials.
In order to avoid an uncontrolled fire spread inside a building, which would result in a considerable or total loss of the building and equipment, and to provide safe escape routes for the personnel, the buildings will be subdivided into various fire areas, also called fire zones, separated by approved fire resistant barriers and elements, such as fire walls, fire resistant ceilings, doors, dampers and fire partitions.
Fire walls, ceilings and partitions will have in general a fire resistance rate of not less than 90 minutes, except for oil-insulated transformers installed indoors, for which the fire barriers will have a fire resistance rate of not less than 2 hours.
Any other walls or ceilings, for which a fire resistance rate is not required or applicable, will be made smoke tight.

Regulations regarding safety and health like OSHA applies. Primary access to platforms attached to vessels and to auxiliary service platforms will be by means of stairs.
Primary access to main operating levels, main service levels and roofs of buildings supporting major equipment requiring frequent attention of operating personnel by stairs.
Structural members subjected to flexure will be designed to have adequate stiffness to limit deflections or any deformations that affect strength or serviceability of a structure adversely.
The maximum allowable deflections of structural members will be in accordance with the relevant design standards and/or the limits prescribed by the machinery manufacturers (whichever is less).
The superstructures and foundations subjected to vibrations (the primary source of these vibrations being the unbalanced forces generated by rotating or reciprocating equipment) will be designed such that vibrations will be neither intolerable nor troublesome to personnel, and will not cause damage to the machine or structure.
The natural frequency of the whole of the superstructures and foundations or parts thereof and all structures adjacent thereto will not coincide with the operating frequency of the vibrating plant.
The differences between frequencies and the dynamic analysis of the superstructures and foundations will be in accordance with the relevant design standard.
Foundations will be designed to withstand the imposed dead and live loads and to restrict settlements, such that the overall and differential settlements do not exceed specific criteria. These criteria being determined by the plant design and operational requirements.
Foundations for machinery, including those for turbines, will resist the static and dynamic imposed loads, and ensure that the predicted natural frequencies of the foundation system, machine frame and machinery are compatible.

Foundation design will ensure that:

- The machine can operate efficiently and reliably without vibration or misalignment detrimental to trouble-free operation;
- The foundation itself suffers no damage or settlement sufficient to cause the machine to malfunction or to affect alignment;

- The waves propagated through the soil by vibration of the foundation cause no harm to persons or adjacent structures, pipe work and sensitive machinery or disrupt processes;
- The foundation provided is an economical solution meeting all necessary requirements.

Settlements, both overall and differential produced by static and dynamic loading will be maintained within limits defined by the plant supplier to ensure efficient and reliable machinery operation during the life of the Plant.

4.9.2. Steam Turbine Building

The steam turbines, turbine generator and auxiliaries will be housed in the Steam Turbine Building consisting of a turbine generator hall and auxiliary bays.

The building will be a hot rolled structural steel frame structure or adequately designed Reinforced Concrete structure totally enclosed with a combination of insulated precast concrete wall panels and walls of trapezoidal metal profiles on insulated steel liner trays and metal cladding roofing system. The turbine table and the operating floor will be a continuous reinforced concrete slab with openings for equipment handling. The area of the turbine generator hall will be served by overhead travelling bridge crane spanning the hall and travelling the entire length of the building. The crane will be sized to handle the heaviest maintenance lift (which should include removal of generator rotor, plus 10 per cent allowance for rigging) and, in addition to the main hoist, will be provided with an auxiliary hoist of not less than 10 tonnes lifting capacity. The deaerator, storage tanks, and other auxiliary equipment will be housed in the mechanical auxiliary bay.

The foundation of the turbine generator area will consist of a reinforced concrete mat and may require to be supported by piles to suit the geotechnical conditions. The ground floor will be a heavy-duty reinforced concrete coated with heavy duty non-skid paint coats finish slab on top of the foundation mat. The finish slab will be sloped to floor drains or drainage trenches. The turbine table structure will be designed to withstand the turbine and generator rotor weights. The operating floor will have enough space to overhaul the turbine and generator at the same time.

Floor openings will be provided at all levels for lowering and lifting of equipment to the ground / intermediate floors using the overhead travelling cranes. Either a permanent opening or removal gratings will be provided at all floors for accessing equipment through overhead cranes.

The information of the turbine available does not allow calculating the cost of the foundation in this phase. The estimations hereby are based on previous experiences with equipment of similar characteristics.

The basic requirements of the design of the foundation of the turbo-generator group aim to make sure that it works with no unacceptable vibrations during the normal good working of the equipment and guarantee the structural integrity of the assembly floor-foundation in accidental situations. In addition, and consequently, the design of the foundation should:

- Avoid that natural frequencies of the assembly floor-foundation-equipment are close to the frequencies of the equipment operation.
- Guarantee that the stiffness of the foundation keeps an alignment within the acceptable values in all the conditions of the operation.
- Minimize the transmission of the vibrations around the foundation through a convenient insulation and vice versa, and avoid that the foundation transmits vibrations to the environment or even better, make them be absorbed by the foundation.

The foundation dimensions and shape will be adjusted to the requirements imposed by geometry and auxiliary equipment trying to maximize the stiffness of the foundation block and the geometric absorption of the soil. Slender elements that may suffer localized vibration and section abrupt changes and which may cause a concentration of tension or anomalous behaviours will be avoided in the foundation.

For the design, an assembly floor-foundation-equipment model and a dynamic analysis will be carried out by means of finite elements. Each element will be represented by its elastic and geometric characteristics

The parameters of the soil will be studied in different levels between maximum and minimum values of those indicated in the geotechnical report and at least ±10% of the central value. Dynamic loads indicating the Manufacturer of the equipment or those deducted from the unbalance criteria proposed in Rules ISO or API applicable to the speed range of operations if they are higher will be used.

At least, the following accidental situations will be considered:

- Shortcut
- Vibrations of the machines in a critical speed.
- Vibrations of the machine at the level specified by the vibration limiter.
- Vibrations of the machine in design limit conditions (break of blades…)
- Seism

The following acceptance criteria will be considered:

- Pressure on the soil lower than 50% of acceptable pressure.
- Contact surface between the foundation base and the soil 100% in all conditions.
- Wide vibrations in service: lower than established limits by the manufacturer in each point or those established by Rule ISO 10816 for the type of machine.
- Deformations lower than the limits established by the manufacturer.
- Structural integrity without permanent deformations in accidental situations.
- As additional criteria, natural frequencies of the assembly out of the interval 80%-120% of the operation frequency and 90%-110%, considering the double frequency operation will be found out. If any of the natural frequency is in this range the resonance case will be studied and the previous accepted criteria will be used.

All the information and proposals gathered are preliminary and must be revised after a detailed study of the soil under the tanks in order to determine the resistant and elastic characteristics.

4.9.3. Boiler

The boilers will be supported by a hot rolled structural steel frame which will include access to all levels of the boiler.
The ground floor will be reinforced concrete slabs with drains to provide general surface water drainage and as required for equipment drainage. Drainage from equipment containing oil or chemicals will be collected in separate plant drainage systems and treated accordingly.
Access floors, platforms and walkways will be provided at various levels throughout the height of the structure.

4.9.4. Central Control Room (CCR)

The primary function of the Central Control Room is to provide a control room and control equipment enclosure. It will include beside the Central Control Room a programming room, a shift engineer room, a training room, a meeting room, a document room, an archive room, offices, tea kitchen and sanitary rooms, switchgear rooms, battery room and cable spreading floors. Often the CCR is placed in the administration building covering all these assemblies.

4.9.5. Water Treatment Plant

The water treatment plant will be housed in a structural steel building with a facade combination of insulated precast concrete wall panels and trapezoidal metal profiles on insulated steel liner trays and a metal cladding roofing system.
It will accommodate MCC room, Control room, tea kitchen, sanitary rooms, Storage, Water Testing Laboratory, Truck Unloading Area. Part of the water treatment are the neutralization pits before moving waters to the evaporation ponds.
Acid and caustic bulk storage tanks will be located in curbed areas to contain any leakage of these chemicals. Curbed areas will be protected with chemical resistant tile finish. Safety showers and eyewash fountains will be located in close proximity to these areas.
Floor drains will be provided and directed to the neutralization sump.
The neutralization pit will be of reinforced concrete construction with special coating on all exposed concrete surfaces for protection against corrosion.
A monorail and hoist system will be provided for servicing and handling of equipment.

4.9.6. Pump House

Large pumps may be housed in shelters. Pumps will be supplied and installed complete in accordance with pump manufacturer's instructions including piping, valves, instrumentation, power supply and control cabinets.

The pump areas will have overhead swivel arm type cranes or similar to provide handling of the pumps and other equipment during installation and maintenance. Crane rails, buffer end stops and down-shop power conductors will be installed for the crane’s full travel length. The cranes will be designed to be capable of lifting the heaviest piece of equipment, which will be installed. The local controls for all pumps, jockey pumps and air compressors for the accumulators will be located within air-conditioned control boxes.

4.9.7. Air Cooled Condenser

The ACC foundations will be reinforced concrete structures. The size and the thickness of the structures will be varying according to the ACC loads and size.

4.9.8. Receiver Tower

The tower will be a circular reinforced concrete structure. The diameter and the thickness of the tower walls will be varying according to the height of the tower.
The tower will be executed by slipform method.
Inside the tower several platforms will be placed. These platforms will be supported by both metallic structures and reinforced concrete structures.
Auxiliary and piping support platforms will be metallic structures. For electrical equipment, reinforced concrete structures will be foreseen.
A steel staircase and a service/passenger lift of sufficient capacity and speed serving all levels up to the receiver will be installed. The load capacity will be at least 1500 kg.
On top of the receiver a crane for the receiver assembly, maintenance and disassembly with a capacity of 10 tons and telescopic arm with continuous swivel capacity (360°) will be installed.
The connection of the support structure of the receiver to the concrete tower core will be made with embedded plates in the concrete structure.

4.9.9. Heliostat Foundations

The most economic foundation concept largely depends on wind loads onto the heliostat, soil conditions at site (see also chapter 4.1) and also on local costing conditions (steel cost, shipping transportation cost, local industries etc.)
For the reference concept a foundation with micro piles (driven ductile iron piles) was assumed. Depending on the project conditions this could be replaced also by hollow concrete piles or standard concrete pile foundations.

4.9.10. Molten Salt Tank Foundation

The foundation of the salt tanks must accomplish the following functions:

- Avoid an excessive warming of the soil underneath the tank, which may change its nature provoking alterations in the volume and/or in the resistance performance.

- Try to keep an evenness base for the construction of the tank.
- Provide an even base for the construction of the tank.
- Avoid the differential settlements that may damage the stability of the tank shell or may create some unacceptable tensions in it
- To control the instantaneous or creep settlements, that may damage the connections of the tanks with other elements.
- To minimize the loss of heat that may worsen the performance the plant.

The tank shell will be supported by a concrete ring foundation. The tank bottom will be supported on a sand bed for an even load distribution.
Between and below the concrete foundation an insulation layer of well compacted bed of inert granular material or clay will be placed. It will be confined with a perimeter steel sheets ring preventing the insolation bed to spread because of the pressure effect and avoids negligible settlements. The steel ring will avoid the contact between the natural soil and the rainwater and the insulation material, which can provoke an important increase of the loss of heat.
Below the insulation layer galvanized steel pipes will be placed in a sand bed. The pipes will be extended to the surface on both sides to create a natural draught for the discharge of the heat in the ground.
It is almost impossible to avoid heating of the soil located under the foundation of the tank up to temperatures over 100 ºC only by means of insulation: the ratio between soil conductivity and insulate hardly exceeds the relation 10/1 and the ratio between the thickness of the soil layer that is affected by temperature and the thickness of the insulation have the same order of magnitude so that the expected leap of temperature (approximately 380 ºC) is distributed more or less equally between the soil and the insulation. 200 ºC temperatures are expected at the base of the tank foundation with normal insulation thickness.
If the soil does not accept 100 ºC, a refrigeration system must be installed. As a refrigeration system increases always the loss of heat, it is preferred to avoid installing it.
According to the previous considerations, the creation of salt tanks foundation based on proposals in Rule API 650 for the hydrocarbon storage tanks of similar dimensions are considered. They are to be adjusted to the special characteristics of the stored product (high density and high temperature).
The supporting base of the tanks is formed by a well compacted bed of inert granular material confined with a perimeter steel sheets ring which is used as a beam and prevents the insolation bed to spread because of the pressure effect and avoids negligible settlements. The steel ring will avoid the contact between the rainwater and the insulation material, which can provoke an important increase of the loss of heat.
The salt tank foundation outlined here is preliminary and must be revised after a detailed study of the soil under the tanks in order to determine the resistance and thermal characteristics expected during the operation of the plant as well as the changes in volume due to the warming.

4.9.11. Buildings

The following main buildings are considered within this concept within the central area:

- Main electric building
- TES electrical building
- Water treatment plant building

These buildings may be combined or attached if convenient.
In addition to the above-mentioned buildings, further ones are considered for different use.
Some of these smaller buildings are:

- Compressed air
- Control post for the fire protection system
- Container of the chemical dosage of the cycle
- UPS container
- Container of emergency diesel
- Container of sample system
- Marquee for solar protection of the additive tanks.

Some of these constructions will be modular.

Workshop

The Workshop Building will be structural steel building with a facade combination of insulated precast concrete wall panels and trapezoidal metal profiles on insulated steel liner trays and a metal cladding roofing system. The workshop is placed outside of the central area and solar field, but within the plant fenced boundaries. Often the origin of the workshop building is with the heliostat assembly building.
It will accommodate mechanical workshop, electrical workshop, instrument workshop, welding workshop, material stores, tool stores, offices, meeting room, tea kitchen, toilet rooms, shower and locker rooms.
The minimum ceiling height in the Electrical and Mechanical workshops will be not less than 10 m. They will be equipped with an overhead crane.

Warehouse and Storage

The Warehouse and Storage Building will be structural steel building with a façade combination of insulated precast concrete wall panels and trapezoidal metal profiles on insulated steel liner trays and a metal cladding roofing system. The Warehouse and Storage Building is placed outside of the central area and solar field, but within the plant fenced boundaries.
It will include high storage racks, heavy parts storage, unloading area, chemical storage room, partially covered material storage yard, offices, tea kitchen and sanitary rooms.
An overhead crane spanning the main storage area and the unloading area will be provided.

<u>Administrative Building</u>

The Administration Building will be a reinforced concrete structure with masonry walls.
The primary function of the Administration Building is to provide a fully functional and comfortable workplace for the plant management and administrative staff. A canteen will be located inside the Administration Building. The CCR is usually on the top floor of the administration building.

<u>Fire Station</u>

The Fire Station will be structural steel building with a façade combination of insulated precast concrete wall panels and trapezoidal metal profiles on insulated steel liner trays and a metal cladding roofing system.
The building will provide workspace for the firefighting staff and parking /storage for fire apparatus, vehicles, equipment etc. It will include furthermore two offices, three relief rooms, tea kitchen, toilets, shower and locker rooms.
The garage will provide space for two firefighting trucks and an ambulance car.
The Fire Station may be placed outside the solar field, but within the plant fenced boundaries. It depends on local conditions, if firefighting and emergency services can be shared with neighbouring plants or city civil services, for this concept a fully equipped station is considered.

4.9.12. Earth Movement

This concept does not consider earth movements. The purpose of earth movement is to fully maximize the materials extracted for the execution of backfilling that must be performed; it is therefore not necessary to transfer materials to the dump or obtain external contribution materials for the site. In case, earth-movement should be kept as small as possible. There only is earth movement where the top soil slope is locally greater than 5%.
The earth-movements would consist in leave the field with a maximum locally slope of 5%. Also, due to the natural run-off of the field, it is necessary to divert some of them in order to avoid the heliostat foundations.

4.9.13. Evaporation Ponds

Two evaporation ponds have been considered to collect the effluent from the plant. They will be located outside the solar field close to the border of the site.
The selected topology for the standard cross-section is a height of 1 m. The ponds will be allowed to fill to a depth of 0.5 m, with a reserve of 0.5 m to the crown on the least favorable side. The inner and outer embankments of the ponds are 2H:1V.
The ponds will not be filled from any other sources than those regulated from the plant and any direct rainfall over the surface area. In order to eliminate excesses, an overflow with an effluent threshold will drain into a perimeter channel.

The standard cross-section consists of two impermeable geo-membranes made from high-density polyethylene (HDPE) 1.5 mm thick, laid over a geo-textile sheet on the face in contact with the membrane and a draining layer below. This item is fitted over a layer of sand layer 0.15 m thick on the embankments and on the base.

4.9.14. Erosion and Dust Control

This concept does not consider erosion and dust control measures, as they're depending on local conditions. Certain protection measures can reduce erosion. These are divided into two categories: plantation on site and/or the installation of several hydraulic facilities.
Hydraulic facilities refer to traditional agricultural engineering techniques, which are based on the following principles:

- Limit the concentration of runoff
- Channel water flow
- Protect areas where floods and deposits at the wrong moment could cause a significant damage.

Discharge to the courses over the various draining points of the platform will be protected by means of stone rubbles, executed with the appropriate dumping angle. A zone is thereby arranged for the regulation of each draining flow before it comes into contact with the natural course, thus minimizing the erosion of the natural courses.
The dust generation during the construction will be primarily due to the passage of machinery and vehicles along the paths on site. Periodic irrigation of paths is a regular practice to avoid dust.
The main paths of the power island will be paved once the plant is built.
In the solar field which may generate dust during mirror cleaning operations in the maintenance paths, the speed of circulation of these paths is very low and if necessary, the irrigation of maintenance paths will be included as part of the maintenance operations.

4.9.15. Storm Water Management

Solar Field Drainage
The drainage system is designed such the run-off is allowed to flow naturally. Run-off will be collected in channels. As the local conditions for rain and flash floods are not specified, only a marginal run-off system is considered.

Power Block Rainwater Treatment
Rain water susceptible to drag oils (and for those service waters periodically used in "off-line" washings and cleaning) will be conducted to a first rain water concrete tank (10 first minutes). Then, waters polluted by hydrocarbon will be pumped to a hydrocarbon separator of coalescent type. The sludge and hydrocarbon will be removed and stored for its later management. Treated water will be driven to the effluent treatment plant, where will be joined with the rest of flows for its later sending to evaporation pool.
The storm water of the power block will be discharged to the run-off system of the solar field.

4.9.16. Urbanization

Urbanization is depending on local requirements and the desire to present an appealing and attractive power plant. Beside technical requirement, developing the urbanization, including the course of roads, the surfaces, and esplanades, is a matter of taste and demand by the owner, but not further considered or detailed in this concept.
Basically, the urbanization of the Power Island will be as follows.

- Characteristics of the surfaces:
  - Walkways: Typical reinforcement Pavement 10 cm thick, and 1 m width.
  - Roads: The road pavement structure will be supported by the sub-base, course and surfacing. The surfacing will be asphalt.
- Typical Section for a road (asphalt) in the Power Island
  - Concrete paving: The road pavement structure will be supported by the sub-base, course and surfacing. The surfacing will be concrete (15 cm thick).
  - Crushed Stone: 10 cm thick with crushed run sub-base 15 cm thick. The components will be gravel paving, well graded with an average size of 25 mm.
- Main Access Road (Asphalt)
  The road pavement structure will be supported by the sub-base, course and surfacing. The surfacing will be asphalt and will be 7 m width (1.5 m shoulder). We considered a North, southeast, and southwest road.
- Solar Field Roads (Crushed Stone)
  The purpose of roads is to allow access to the various facilities that are within the premises, depending on their location in the complex and future purpose, differentiating the following types of service roads:
  - External perimeter road. Surrounds the entire plant and will have a width of 4.0 m.
  - Central paved road (North – South). The service road is defined by the centre of the platform and runs from north to south. It will also be 4.0 m wide.
  - Interior roads (Circular). Service road will run in the interior of the solar field. Depending on the arrangements of the heliostats the roads may run circular or close to the anticipated figure. They will have a width of 4.0 m.

4.9.17. Spill Containment Structures

For the plant two different oily water networks are considered:

- Oily Water.
- Process Water.

All of these networks are buried, and the characteristic for all of them are the followings:

- Around all possible points of leak a slab (kerbed) will be defined.
- These slabs will have open channel drains and collection sumps, and will be covered with hot dip galvanized mild steel gratings of adequate size and strength.

- Drainage at tankage areas will be designed slope away from the tank pad towards a drainage trench located adjacent to kerb to prevent water accumulation around the foundations. The slope will be minimum 1 vertical to 100 horizontal.
- The location, size and capacity of the manhole, sump, oil separator, valve pit, ... will be determined and calculated to cover the requirements of the project.
- The dimension, materials, slopes of the buried pipes will be determined and calculated to cover the requirements of the project.
- The Salt Tanks zone will be pumped from there to the BOP drainage system (process water).

4.9.18. Temporary Construction Areas

The Contractor will provide his own and sub-contractors staff and the Owner with temporary Site facilities during the construction period.
Temporary facilities are assumed to be located outside of the plant. No considerations are made e.g. for laydown areas, temporary facilities, parking or other necessary installations during construction until final urbanization.

5. Techno-economic Analysis

5.1. Methodology, tool, and detailed boundary conditions

Today CSP plants are tailor-made units which are designed for each individual site and operating scenario. This is done by performing annual yield calculations for a "typical meteorological year" with hourly or even finer temporal resolution. This is different from the design of conventional thermal power plants, for which the design is made for some distinct operating points (e.g.: nominal load, some part load points, and some special operating conditions like maximum load and operation at high ambient temperature). The annual yield calculation for CSP plants helps to find the system configuration with least cost for the site and the desired operating scheme and to deliver input for the economic evaluation of the plant by owners and financing partners.
Annual yield calculation for CSP projects is done during different project stages with different targets:

- Prior to the call for proposal a feasibility study is made by the project developer or its consultant, in order to find the boundary conditions for the proposal
- During the preliminary design of the plant, bidders are doing it to optimize their design and check the matching with proposal requirements
- After commissioning it is used to check the plants performance against the guarantee values.

The annual yield calculation in this study may be compared to one done during a feasibility or a prefeasibility study. It is using general boundary conditions rather than specific requirements of an individual site. Nevertheless, it needs to be done for a certain site and for a certain meteorological dataset. Therefore, the project partners have chosen the Ouarzazate site in Morocco where three large CSP plants are already in operation. This site may be considered as "typical" due to its latitude and direct irradiance resource of about 2500 kWh/(m²*year), which is good but not outstanding. Since the "CSP-Reference Plant" shall be suitable for different sites and different solar resources, the result of this techno-economic analysis cannot be given as one single LCOE value but rather as a LCOE range depending on several parameters like: actual financing conditions, latitude and DNI resource, actual time window for delivery of electricity to the grid, as well as other specific boundary conditions not mentioned yet.

The annual yield calculation for this study was done with the software tool greenius (DLR, 2020). This tool has been developed at DLR since several years and it is customized to perform fast calculation of the technical performance and economical figures of merit for different renewable energy systems. The software itself as well as more details about the models are available from the website (DLR, 2020). The calculation is done on an hourly basis for a full year using a typical meteorological data set with this temporal resolution for the specific site of interest. Finer time resolutions of 30, 15, or 10 minutes are also possible, as well as multi-year simulations.

Annual performance modelling of CSP plants is not yet standardized but several approaches and models exist, most of them not publicly available but undisclosed by the owners. Currently there is no official standard for annual performance modelling of CSP plants available but there is a guideline published by SolarPACES (SolarPACES, 2017). greenius is following this guideline to a large extend but not completely since it has been designed and implemented years before the publication of this guideline.
In the past, validation tests have been done by comparing greenius results with operational results from SEGS VI. Another validation was a model comparison performed under the auspices of SolarPACES (SolarPACES, guismo project, 2011) in 2010 and 2011 where 10 annual performance models for parabolic trough plants from different research organizations and companies have been compared. The results of this model benchmarking were undisclosed due to the preferences of some companies involved in this comparison. Two benchmarking rounds have been done in guiSmo and greenius was involved in both rounds. The first round showed that input data and boundary conditions must be defined very carefully in order to get comparable results. The second round revealed a range of ± 6.5 % between the calculated annual gross and net output of 7 models. Actual measurements of the annual performance were not available for this benchmarking since the simulation was not based on real operation conditions. greenius' results were about 2 % lower than the mean annual output of the 7 models considered in the final comparison. For solar tower systems there was no distinct benchmarking but greenius has been used in several solar tower projects (e.g. due diligence studies) in which annual performance data was provided by potential suppliers. Comparison of greenius results with this undisclosed supplier's data makes us confident that the greenius results for solar towers are within a similar accuracy as those for parabolic trough power plants.

One important task of this annual yield calculation is the definition of the thermal storage nominal capacity, which fits well to the other plant components and the envisaged operating schemes. In CSP plant configuration with fixed power block design power, fixed solar field and receiver size, as well as fixed operating scheme, one may find a thermal storage capacity, which leads to the lowest LCOE. This is due to the fact that a smaller thermal storage will often be fully charged and thus may lead to yield losses since the solar field could produce more heat but this excess heat cannot be stored and thus the heliostats must be defocused. If the storage capacity is larger than the optimal capacity, it often has spare capacity which causes investment costs but is not used most of the time. Thus, the LCOE are increased compared to the optimum. Figure 44 shows this typical U-shaped LCOE curve. The exact position of the LCOE minimum is of course depending on the specific costs of the plant components. So higher specific costs for the thermal storage will shift the minimum towards smaller storage capacity and vice versa. Figure 44 shows only one curve, but other ones could be added by varying the solar field aperture area. By this method one can find the optimal design combination for both parameters: solar field aperture area and thermal storage capacity. In this study, the least cost solar field aperture has been fixed in advance, so there is no need to do a combined optimization in this case.

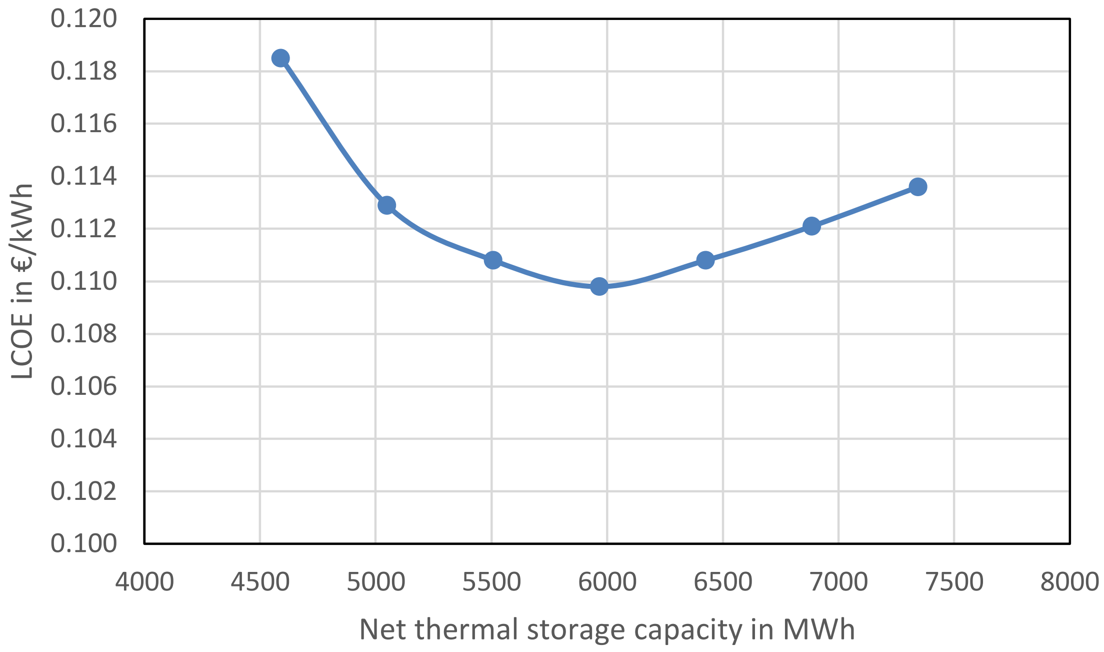


Figure 44: U-shaped LCOE curves for LCOE versus net storage capacity

As mentioned above, the operating scenarios of the CSP plant will have a considerable impact on the cost optimal storage capacity, which becomes obvious when we think about the maximum number of hours per day the power block can be operated from the storage. It is clear, that the storage capacity (in full load hours) should not exceed this maximum number. For operation scenarios like those chosen in this study, the maximum number of PB operation hours varies, since the sunset time varies throughout the year. Table 19 shows the variation of power block starting times and number of maximum operating hours per day used for the LCOE calculation.

The numbers vary from season to season with 1-hour step size. This is caused by the hourly time resolution of the simulation and the operating scenarios must be adapted to these simulation time steps. It should be noted that the software greenius allows to define the power block operating times, which means that a heat flow may be used as input for the power block (PB). This is not equivalent to power generation since the power block needs some time for start-up. During this period the model assumes heat consumption of the power block but no electricity output. Electricity generation starts with some delay after PB operation when 2 conditions are fulfilled: the minimum start-up time must be passed and the start-up energy must be provided to the PB. Typically, electricity production starts about 1 hour after the starting times mentioned in Table 19 (see Figure 46).

Table 19: Possible power block operating hours for the 2 scenarios

Season	Dates	PB Operation	Max. number of operating hours	PB Operation	Max. number of operating hours
		Night-time operation		Peaker operation	
Winter	21.11.-20.2.	16:00 – 8:00	16 hours	16:00 – 24:00	8 hours
Spring	21.3.-20.5.	17:00 – 7:00	14 hours	17:00 – 24:00	7 hours
Summer	21.5.-20.8.	18:00 – 6:00	12 hours	18:00 – 24:00	6 hours
Autumn	21.8.-20.11.	17:00 – 7:00	14 hours	17:00 – 24:00	7 hours

5.2. LCOE calculation

The calculation of LCOE in this study is based on the simplified IEA method, which is neglecting several parameters which are otherwise necessary for a full economical evaluation of power plant projects. Here the LCOE calculation is used to find the least cost design of the plant and not to evaluate the profitability of the project. The LCOE method spreads the cost over the lifetime of the plant.

The following simplifying assumptions are applied:

- 100 % debt financing
- Annuity method
- Service life = debt term
- Taxes are neglected
- Price escalation and inflation rates are neglected

LCOE is calculated according to the formula:

$$\boldsymbol{LCOE = \frac{C_{inv} \cdot CRF + C_{O\&M} + C_{ins}}{E_{gen}}} \qquad \textbf{(Eq. 1)}$$

With the fixed charge rate:

$$\boldsymbol{CRF = \frac{d \cdot (1+d)^n}{(1+d)^n - 1}} \qquad \textbf{(Eq. 2)}$$

C_{inv} total invest costs in €
C_{ins} annual insurance costs in €
$C_{O\&M}$ annual operation and maintenance costs in €
d interest rate

Table 20 shows the parameters used for LCOE calculation. Since interest rate and service life of the plant may vary from site to site, different assumptions were made, which leads to a range of LCOE values.

Table 20: Parameters used for LCOE calculation

Parameter	Values	Unit
Service life	25 - 35	years
Interest rate	3 - 6	% per year
Annual O&M costs	3	% of total investment costs
Annual insurance costs	0.7	% of total investment costs

Table 21 shows the specific cost assumptions for individual parts of the CSP reference plant. They were made by the partners and are meant as indicative values. Specific conditions in individual countries or technical modifications may lead to varying costs for these parts.

Table 21: Specific investment cost assumptions for the LCOE calculation

Part	Spec. costs	Unit	Comment
Site preparation	1	€/m²	Based on total land area
Heliostat field	100	€/m²	Based on aperture area
Tower	61706	€/m	Based on tower height, here for the 200 m tower
Receiver system	70	€/kW_{th}	Based on thermal power transferred to the molten salt
Power block incl. steam generator	810	€/kW_e	Based on nominal electrical power
Thermal storage	21	€/kWh_{th}	Based on net thermal capacity
Balance of plant	322 / 161	€/kW_{el}	Based on nominal electrical power. Costs for the night operation / peaker
Surcharge on direct investment costs	20	%	For project development, EPC margin, contingencies, etc.

5.3. Results

One major task of the techno-economic analysis is the definition of the thermal storage capacity. The capacity has been varied and several annual yield calculations have been performed.

Figure 45 shows the results of these simulations. The storage capacity was varied in steps equivalent to one hour power block operation at nominal load (4590 MWh = 10 h, 7344 MWh = 16 h). A smaller step size would have been possible but the LCOE curves are quite flat around the minimum, so one hour is considered as sufficient in this case. The optimal storage size leading to least LCOE is 5967 MWh corresponding to 13 full load hours for the plant with one 200 MW_e power block under the night-time operation scenario. Varying the financial parameters like plant life time and interest rate just shifts the curves but does not change the optimal storage capacity.

13 full load hours storage capacity fits well to the number of maximal possible operating hours (12 h during summer and 16 h during winter). A result, which could be expected but the actual least LCOE storage capacity cannot be determined exactly from the number of possible operating hours.

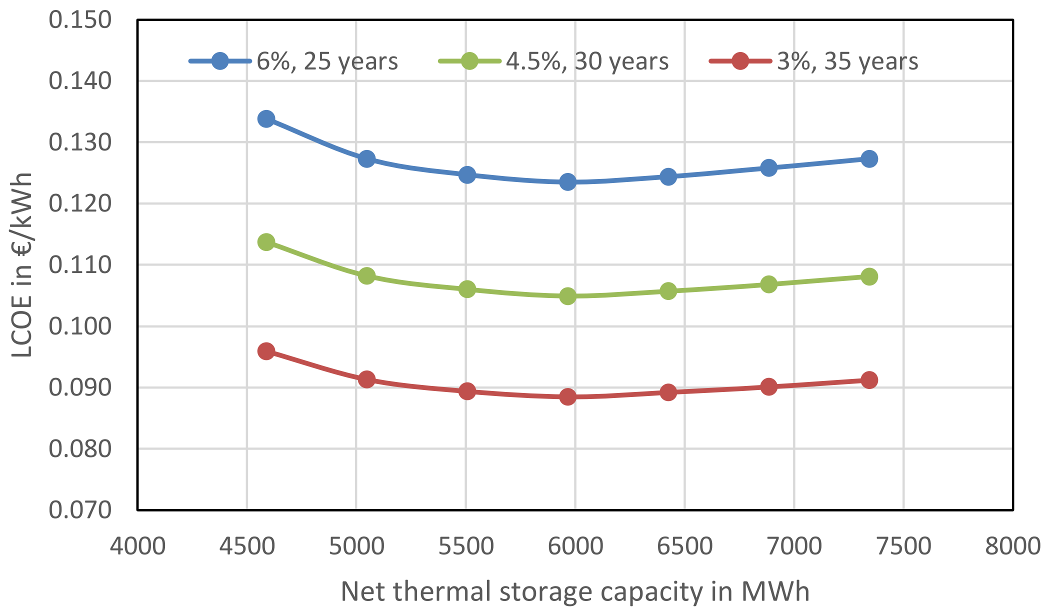


Figure 45: LCOE for different storage capacities and different financial parameters (interest rate and life time) for the CSP-Reference power plant designed for night-time operation.

Similar calculations have been done for the plant operating as peaker and the optimal thermal storage size found was 5508 MWh or 6 full load hours for the 2 × 200 MW_e plant. The corresponding LCOE values are (0.130 – 0.182 €/kWh). Higher LCOE for the peaker plant are caused by the fact that investment and O&M costs are increased since this plant needs 2 power blocks with reduced operating hours compared to the plant designed for night-time operation, while solar field, receiver, etc. are not changed.

The project partners decided finally to use a thermal storage with a capacity equivalent to 6.5 hours nominal operation of the 2 × 200 MW_e plant since this translates to the same thermal capacity of 5967 MWh as for the 200 MW_e plant designed for night-time operation while the LCOE increases only by 0.2% compared to the 6h storage. One single thermal storage design for both plants again saves engineering costs and helps to reduce the overall LCOE.
In Figure 46 the performance of the 200 MW_e plant with night-time operation during good days throughout the year is shown. The blue curve shows that days with almost ideal DNI were chosen. The receiver heat output curve in red follows the DNI curve with some delay, caused by the heat-up losses. The plants net electrical output is plotted in yellow. It starts around sunset and the plant would be able to deliver constant output throughout the whole night, even in spring and autumn, for these days with good DNI. In winter the day length is too short to charge the storage completely and thus the plant will only deliver constant output until 2:00 or 3:00 in the night. In contrast during good summer days the thermal storage is totally charged at about 16:00 and the solar field must be defocused although it would be able to deliver more heat. This part of unused heat is shown as “dumping” in Figure 46. Dumping could also occur during spring and autumn season, although it will be less than in summer. This behaviour is typical for a LCOE optimized CSP plant since the balanced storage capacity will cause some dumping during summer and will not be fully utilized during winter (at least at latitudes where distinct seasons exist).

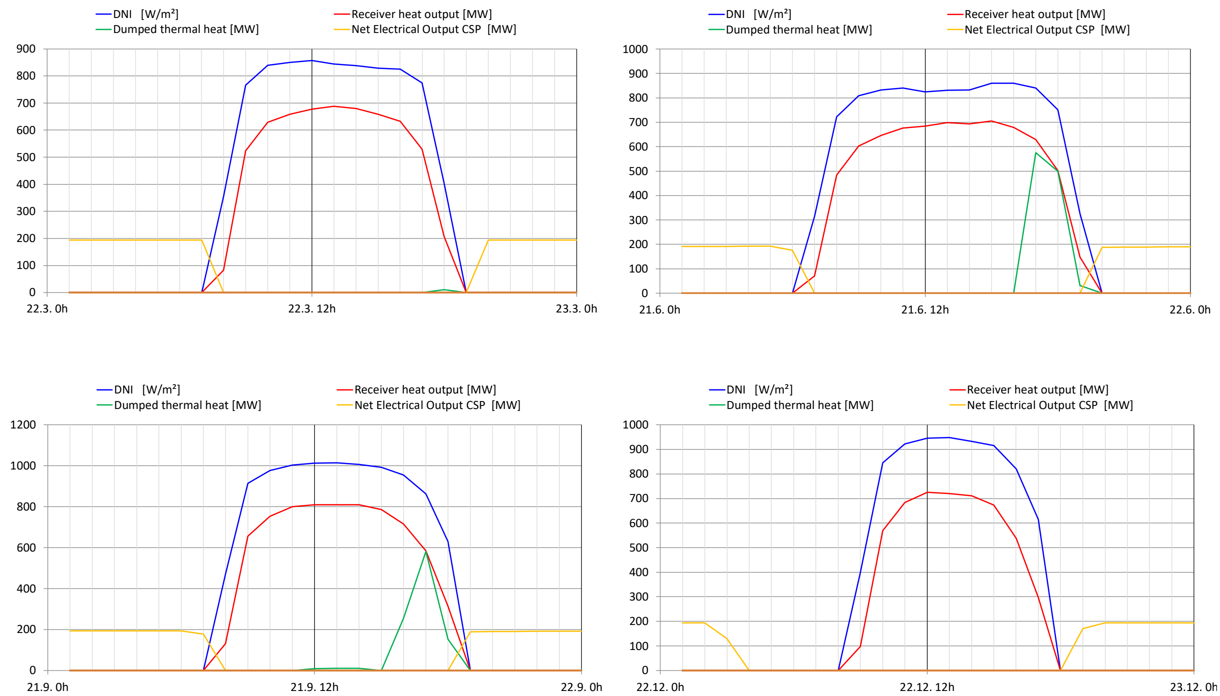


Figure 46: Performance of the 200 MW_e plant with 13 hours storage for night-time operation for good days throughout the year

Since the presumed operation modes require charging of the thermal storage during times when the plant’s power block is not running, a considerable amount of electricity is needed for operating the molten salt pumps, the solar field and the all the equipment needed for charging the storage (up to 8.5 MW_e). This electricity must be drawn from the grid or, alternatively may be generated by a small PV field located in the vicinity. Although not in the main focus of this study, we have considered this option and found that a 7.7 MW PV field could produce 80 % of the annual day time auxiliary power demand of the CSP plant an might reduce LCOE by about 1-2%, depending on the costs of electricity from the grid.

In Figure 47 the investment cost fractions of individual parts of the 200 MW_e reference plant are shown. The solar field with tower and receiver accounts for about one third of the CAPEX and power block with BoP for another third. For the peaker plant with 400 MW_e nominal output the CAPEX fraction of power block and BoP increases to about 44%.

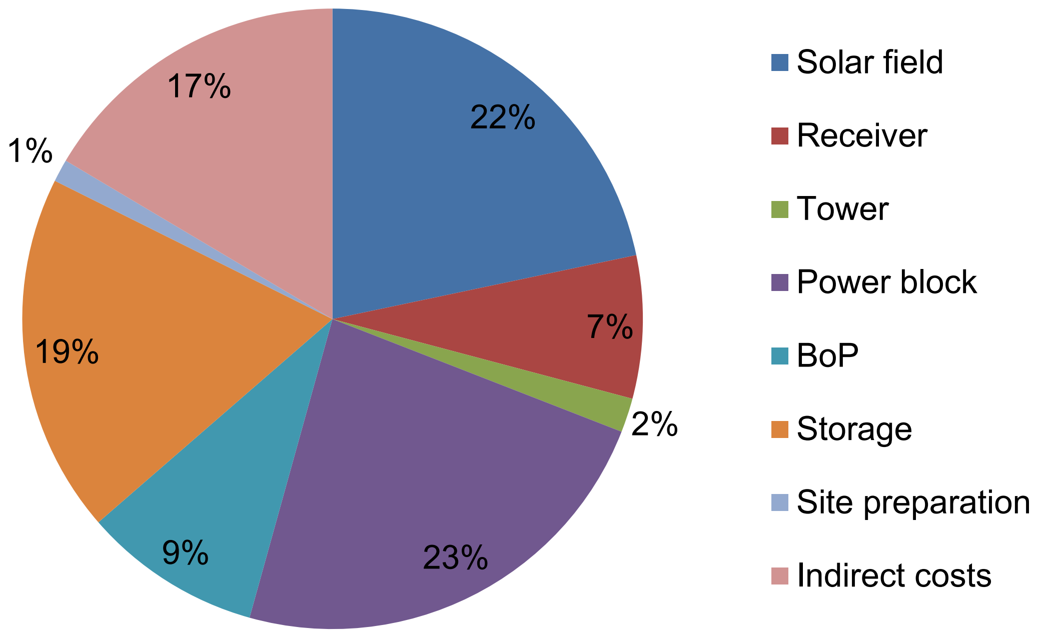


Figure 47: Distribution of Investment costs for the 200 MW plant with 13 hours storage

Table 22 shows the main design parameters of the two reference plant configurations. Much more details are given in the appendix.

Beside LCOE calculation this kind of annual performance simulations may also be used for other purposes, e.g. to examine the impact of oversizing the solar field, dimensioning the plant for a certain capacity factor, receiver overload, etc.

Table 22: Important design parameters of the reference CSP plant

Part	Plant for night time operation	Plant designed as peaker	Unit
Power block nominal output	200	2×200	MW_e
Solar multiple	1.6	0.8	-
Solar field aperture area	1.5		km²
Tower height	200		m
Receiver design power	700		kW_{th}
Thermal storage capacity	5967		MWh_{th}

6. Risk Analysis and Bankability

Part of the acceptance of a plant design is typically a detailed analysis of the risks for the project. This includes a detailed investigation in all directions, followed by recommendations and assessment of mitigation measures to risks identified, to make the project a success. This procedure needs also to be applied to this CSP reference power plant. However, this report outlines only a design study, risks cannot be fully described.
Wherever possible this section will outline risks evolving from the selection and design of technical components and their arrangement. These are mainly from technical nature, but for some specific topics also with environmental or commercial background.

6.1. Technology Readiness Level

Solar tower technology is not new on the market. First solar towers were operated in the eighties (Solar One and Two) to prove the concept and operated for more than thirty years. First commercial operated towers emerged in Spain in 2007 and are still in operation. Nevertheless, the number of towers worldwide is small, and significant changes and improvement can be observed from one to the next plant built. Consequently, there is no standardization in the solar components of the plant, different as for the conventional part where typical equipment from conventional steam power plants is embedded.

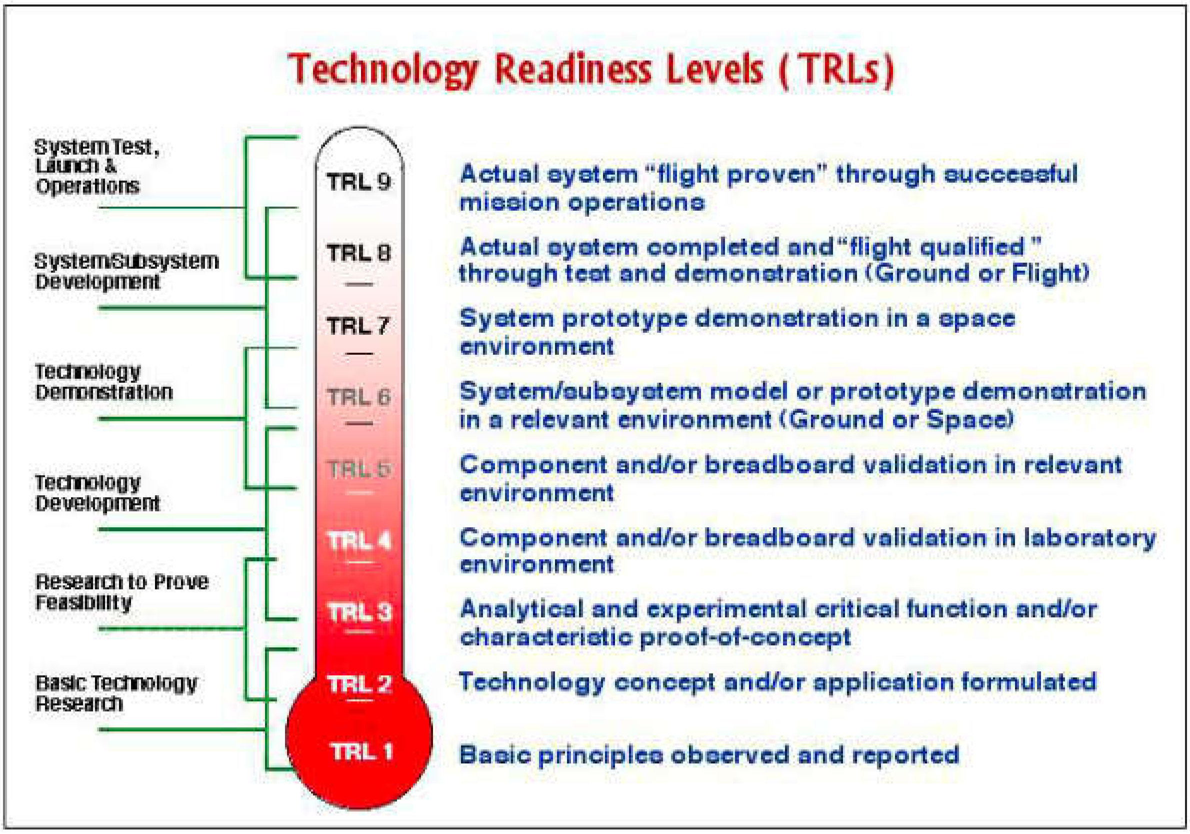


Figure 48: Technology Readiness Levels – Thermometer Diagram (TEC-SRS, 2008)

For this reason, a short discussion is given to characterize the power plant equipment with the Technology Readiness Level, which is used for highly innovative equipment.

A more detailed description especially for CSP plants can be found with De Rose (De Rose, 2017b)
For the conventional water/steam cycle and power generation there is no need to discuss, as all equipment is in commercial use for years and decades and have proven record. The same applies to the Thermal Storage System (TES). TES are used in commercial solar power plant systems for more than 15 years, and with the experience made the design and arrangement has not changed significantly. For both systems this includes pumps, valves, piping and associated equipment.
The only equipment found very individually for each solar tower plant are the Heliostats and the Solar Receiver on top of the tower, including the control software. Implemented systems confirmed commercial maturity.
For the Heliostats, we’re speaking about a component produced in larger numbers, and for some companies we can observe a development in size and sophisticated design from tower projects up to date. The selected Heliostats in this project show a similar development, these components are already installed in a tower project in China and proving their reliability and performance. Thus, we can speak about the highest level for TRL.
The Solar Receiver for each tower is an individual design tube bundle arrangement. The principle is the same and are applied in all solar towers the same, sourcing from the typical principle of heat exchangers in the fossil fired power plant. Solar radiation on the surface of the tube is converted into heat, the tubes are ‘cooled’ on the inside with a coolant (the HTF) for the later use in a steam generator. The difference is in the arrangement of the tubes and associated equipment, and the risk is with the decision of the designer how close he approaches the material limits. Consequently, also for a solar receiver we can speak of a top TRL.
Often underestimated, but of upmost importance, is the control system and associated I&C equipment with the Heliostats and Solar Receiver. To steer the process of heat generation, the control system needs to move the heliostats in a very controlled manner to build a ‘picture’ on the receiver surface. This picture needs to follow a certain pattern to optimize the heat transfer, to reduce the risk of areas of too high radiation (hot spots), and to make the best use from solar radiation especially under difficult weather patterns (cloud passage, wind and gust). In the same time this control system needs to organize the flow inside the tubes to take care of an optimal and material conform heat distribution, not to initiate unwanted material change in the tube or the HTF.
Again, for this CSP reference plant an I&C system is considered by the partners that is able to follow the condition made and integrated in the models and simulations, and is executed in at least one operating plant.
That gives us the confidence that this plant and components are on the top level of the TRL, even though highly sophisticated equipment and software is part of the design and executed in only few plants.

6.2. Risk Analysis

6.2.1. Concept

The selected design for this plant needs a fair evaluation on risks for the developer and or later owner of the plant.
This report will not be able to provide a full and detailed risk assessment for a solar tower project, as too many parameters cannot be covered with the CSP Reference Plant. However, main key risks identified from a technical perspective will be discussed, and additional risks to be considered in the variation and further detailing of this conceptual design will be indicated.
There are many different approaches for a risk assessment, all of them with a different focus in mind. In the following section we will analyse our selected design and equipment focusing on operation safety and reliability, possible risks coming from innovative solutions or known market restrictions today. This analysis has no claim on completeness and shall not replace a full and comprehensive risk analysis for a full project.
The risk analysis will be limited to risk arising from the conceptual design and selection of key equipment. It cannot cover risks from the selection of suppliers, construction and construction provider, Operator, legislation, insurance or market, beside other.

Risk Impact
The risk impact is indicated as an effect on the Project Objective in case the risk occurs. This may deviate between different project objectives and is given as indicative only, with the following categories:

- Very Low
- Low
- Moderate
- High
- Very High

Risk Potential
The risk potential is indicated as a likelihood a risk appears. Quite a number of influences can change the evaluation of such risk potential, like the selection of qualified service and equipment providers, implemented quality system, time and cost efforts, resources. Thus the risk potential may deviate between different project objectives and is given always as indicative only, with the following categories:

- Very Low
- Low
- Moderate
- High
- Very High

6.2.2. Technical Risks on selected equipment:

Major components may be grouped into the following systems for evaluation:

- Heliostat and Solar Receiver,
- Solar Field and Tower
- Steam Generator System
- Steam Turbine Generation Set
- Thermal Storage and Molten Salt System
- Control System
- Other

6.2.2.1. Heliostat and Solar Receiver

Different to parabolic trough technology the solar tower still needs to reach full commercial maturity. This regards to the equipment and design of the solar path, like heliostat and solar receiver technology, heliostat and receiver arrangement and control of the whole system. To achieve an optimized system with highest reliability and good performance, the designer needs to bring profound knowledge and tools, which are not available free on the market. Consequently, to reduce the risk impact as well as the risk potential, it is recommended by other that the design for the heliostats and receiver should be from one hand, including the Solar Field arrangement. With this concept clear interfaces and system conditions are provided between the heliostats and the receiver for the design, construction and testing as well for the conditions necessary in the solar field and for the tower structure. In this way, the risk potential can be reduced largely, even if different suppliers are involved.

Clear interfaces and system conditions shall be provided for the design and construction of the receiver as well for the conditions necessary in the solar field and for the tower structure.
It cannot be excluded, that the provider of the solar technology may not be available anymore after the plant has started commercial operation. Thus, early preparation needs to be considered to be able to maintain and repair the components in the solar field. This does not only include a careful stock management, but also securing access to the manufacturing tools and suppliers of the components, e.g. of the heliostat. To reduce the risk impact of a larger damage during operation of the plant (e.g. a storm damage of a larger scale, exceeding the stock replacement capabilities), it needs to be considered if the owner of the plant may gain access to the intellectual property of the supplier, to be able to remanufacture his equipment or at least to fit in comparable parts in case the supplier is not anymore present on the market. Only a limited number of solar towers is realized for commercial operation, and none of them can claim operation over a full lifetime. It must be noted, that for each tower in operation there is a different design for the Heliostats, sometimes a scaled up and improved version of a predecessor, sometimes a completely different design. However, a heliostat is a quite simple system required to perform a very precise movement, equipped with mirrors with high optical quality.

In the early stages of the heliostat selection the weather pattern needs to be considered. Having a climate with high wind gusts, but otherwise clear skies, the heliostat may need to withstand higher wind loads with high optical accuracy to result in maximum plant performance. Thus, a detailed weather data file in high resolution (e.g. minute interval) may become mandatory. This also improves the preparation for the control system and improves the performance model accuracy, see also 4.2.3.

Another topic is the cleanliness of the mirrors. The design needs to consider soiling and cost of cleaning. A strategy is always depending on the site and the location in the solar field, and fully developed only after few years of operation. With growing local experience, the starting assumptions for average cleanliness and cost for washing the mirrors will be changed and optimized. An automation concept using unmanned cleaning robots needs to consider an adequate design and arrangements of heliostats. All these considerations need to be balanced with the performance of the plant, having a moderate risk potential on the performance of the plant, but are done in this concept in a limited form only following the selected sample location and weather pattern, and a simplified washing cycling.

The selected designer for the solar field and heliostats in this reference plant can provide a good reference and set of experience, and the heliostats chosen are in commercial operation.

The solar receiver is one of the components under heavy load stress. Daily cycling over a wide range of temperatures, asymmetric heat loads on the surface, sudden changes from outside (heat flux or wind gust) or inside the tubes (pressure drop) beside other requires a careful lifetime and fatigue investigation. Although similar conditions may apply in a comparable boiler arrangement in fossil firing, only few solar receivers are realized. A careful failure mode and effect (FEMA) analysis for receiver tube to header, tube bundles and other connections is recommended. Experience from existing towers in operation is positive, as long as the heat flux is kept reasonable. In addition, good access for check and maintenance from both sides is recommended.

Consequently, also for the selected receiver in this concept operational experience is limited. However, the design approach is conservative, leaving enough space in all directions to offer a reliable service.

6.2.2.2. Solar Field and Tower Structure

This section will discuss the considerations on civil aspects for the Solar Field and the Tower structure.

The solar field arrangement should remain with the designer of the optical path. Few considerations should be made for practical issues like maintenance and easy washing of the heliostat mirrors, to keep operation costs low. This concept does not consider any special terrain conditions. However, soil conditions like large layers of sand, or a rocky terrain may require intensive preparation of the solar field area and change in heliostat foundation, to be clarified the earliest.

The tower structure is not uncommon as a civil building, and together with a suitable sized foundation is not seen as a risk. Construction is recommended with the slipform method, to be performed by an experienced company.

As the tower together with the solar field is an outstanding assemble, quite a number of considerations need to be clarified with external parties, like public acceptance to a landmark structure, influence on aviation and environmental impact – most popular are bird migration issues. Such points need to be discussed very sensitively, as the risk impact may become high at a very late stage of the project realization. With careful preparation the risk potential will remain low.

Not selected with this concept is the method for erection of the receiver on top of the tower. Typically, the receiver tube bundles are installed as panels on ground and lifted outside of the tower to the top. This method is proven, and the risks are known (e.g. time delay due to wind or poor weather restricting the lifting of objects). Anyway, the decision about the receiver assembly and erection methods should be defined early to make proper considerations in the design of the civil and mechanical structures, as the period of receiver assembly is very sensitive e.g. to weather influences and may become a medium risk potential.

The project site usually is qualified with a high risk of erosion. There are no risks of flooding, but on the other hand the site as problem caused by erosion. In fact, the risk of erosion is estimated in most of the site at levels between 5 and 10 t / ha and year.

The strong risk of erosion is mainly due to several factors:

- Intensity of rainfall
- Low capacity of earth to withstand erosion due to flow action (incision in earth), the inclination and length of the slope
- Shortage of vegetation

Certain protection measures can reduce erosion, as discussed above. Erosion and dust emittance are part of the environmental investigation to begin of the project development. Such a study proposes or requires certain measures to control, or minimize such effects, thus bringing the risks to a minimum.

6.2.2.3. Thermal Storage and Molten Salt System

Main risks with the TES can be with the tanks and tank foundations itself, main salt pumps and valves, up- and downward piping in the tower.

Key risk could be with the environmental impact in case of salts leakage, and the operational risk with the salts (freezing).

The inventory should be a proven mixture of two salts, which are in use on practically all CSP plants worldwide and have shown high reliability. Even in the occurrence of solidifying salt in piping or other equipment, solutions are available to overcome a blockage or to repair in reasonable time. Risks can be minimized with consequent electric trace heating and careful surveillance. Operation of the salts is proven and properties for the heat exchange are known. Risk impact is low, risk potential is low.

As the salts will be heated up to about 565 °C, materials for the hot storage tank and piping needs to be selected carefully from higher quality grades, and foundation needs to be arranged accordingly. Issues are known with the tank itself from at least two plants. Even though details are not published, those issues could be explained with lack of quality during construction and commissioning. A mitigation measure regarding tanks and tank foundation is a consequent and careful quality assurance during construction and commissioning. In

addition, a salt leak detection system should be installed to have earliest information about the size of a possible leakage. The risk potential will be low, but the risk impact is moderate to high.
As well for the tanks and the piping attention shall be taken to proper and high-quality welding. Automatic welding should be preferred, and a high number (best 100%) check with x-ray examination should be performed during construction or after any repair. Even though the risk impact is low, the risk potential may become moderate to high.
Special care should be with the design and construction of the riser and downcomer in the tower. This reference plant offers only a conceptual design, a detailed design needs to be performed by the potential supplier covering all potential operation modes and transient conditions, as well as excited or forced vibrations on the pipes. As only very few solutions are realized up to date, this equipment should be modelled very carefully with suitable tools and software. The risk potential is very low, but the risk impact very high.
Pumps and valves are available on the market with proven records for the design applied. Selected equipment should be from an experienced supplier and should be tested carefully during commissioning. Risk impact is moderate, but risk potential may become high.

6.2.2.4. Steam Generator System

The steam generation system is comparable to systems also with parabolic trough technology. The principle approach and setup is similar, however for steam generation with molten salt the temperatures for superheating the steam are higher. Such systems are mature and offer operational experience and reliability.
However, the space around a solar tower is limited and arrangement will be very compact, thus requiring a careful layout for proper, reliable and safe operation and maintenance.
Known issues from operation with steam generators can often be sourced on a lack of quality during construction, or operation of the equipment outside the vendors boundary conditions.
To reduce the risk potential and impact to a minimum, the design of the steam generation system should be consistent with the operation model and modes requested, and certain safety barriers should be implemented to protect the equipment against an impatient operation.

6.2.2.5. Steam Turbine Generation Set

The steam turbine generation system is a mature system, with a lot of operational experience worldwide. In solar plants only a handful number of manufacturers can prove references, the market of suitable turbines is small.
To get a successful machine, at the beginning of the design the operation concept should be discussed in detail, and decisions need to be made about times of low or no production.
Considering the operation concept with the high numbers of start-ups and shutdowns, a reliable system should be implemented. In such a case the risk impact and potential of this system to the plant performance can be kept to a minimum.

Observing the market in Spain, it is noticed that the drastic change in market condition has shifted the basic condition for the operation of a solar plant. The required adjustment in operation modes and the resulting change e.g. in the operation of the power generation system may have an impact on the lifetime of the power generation system, but not being the key risk to the plant, thus the risk impact and potential is very low with this system.

6.2.2.6. Control System

Typically, a solar power plant consists of at least three main control systems: one for the BOP, one for the steam turbine system and one for the solar field.
Key factor for the successful operation of the control systems are carefully defined interfaces, the design of the maximum possible automatic control with the minimum possible operator actions, and a proper implementation.
For the BOP and the ST proven solutions with a lot of references are available on the market, with manageable risks. Different is the condition for a control system for the solar part. Similar to the solar field and receiver only few solutions are realized on the market, and each control system needs to be tailored to the selected solution and components. It is therefore recommendable that the control system for the heliostats and the receiver operation and necessary subsystems should be from one hand.
Risk to the performance may arise from several points, to be covered by a solar field control system. Key task is the organization and control of the numerous heliostats, to steer them in a suitable manner for focusing on the receiver, to operate the receiver accordingly not to leave the operating boundary conditions (heat flux or local temperatures too high, hot spots, or local cold spots prone to freeze and tube plugging, beside other). This needs proper control routines considering not only the actual and accurate timetable for the sun position, but also considering deviations e.g. due to wind, wind gusts, cloud passage or other influences misleading a solar beam. An important point to consider is the optimization of the closed loop control between solar field and turbine in order to maximize the energy production.
In addition, proper emergency measures need to be implemented into the control system, like receiver tube protection, local burn through or freeze events, fast drain or unusual vibration. The control system needs to perform and react to the required heat management of the main plant. This includes the implementation of proper receiver surface control tools (IR) and receiver tube monitoring. Furthermore, the design of the control system needs to consider the necessity to operate the main components within thermal limits and eliminate trips.
The control system needs also to be designed to cover issues like bird protection during a standby mode, when the heliostats continue tracking but focus on a point or line nearby the tower, building a visible halo. Not to forget protection of aviation, when groups of heliostats are directed in a way that may blend any pilot in the area (glint and glare effects).
The system cybersecurity is a subject that requires special attention due to the potential threats from external parties which impose a high risk in the plant operation.
Thus, the control system may present a medium risk potential with a high-risk impact, if not designed and executed properly.
To enable a control system working reliable the solar field needs to be equipped with a reliable signalling system in the field. This concept makes no decision about a wired or wireless signal

system, as they both offer pros and cons, but decision may depend on local conditions like soil condition, availability of local frequencies, data security and much more. Furthermore, a well-designed earthing and lightning protection system needs to be considered for this concept.

6.2.2.7. Other

As another risk to be mentioned for the design and later operation of the plant is with the execution of a performance model.
Such a model determines not only an expected production and revenue but lays down fundamental decisions in the operation of the plant. Again, performance models useful for the commercial realization of a plant are not available free on the market but mostly with the provider of services for the design and realization of the solar field. Known issues are with the intransparent parameter selection for transient conditions, like cloud passage, start-up and shutdown. Calculation results can only be as good as the input data.

6.3. Further Risks and when they may apply

This report cannot cover a full discussion of risks for the conceptual plant presented. However, based on this concept in a further step developing the project, the following aspects need to be considered having influence in the technical design of the plant and consequences for the realization.
From a technical perspective environmental issues are a key influence and places relevant risks to the project success. In addition, a careful selection of suppliers and vendors is required, checking their references and available capabilities. The construction and commissioning of the plant needs special attention and sufficient time. Earliest the requirements for operation and maintenance needs to be implemented in the design.
Furthermore, social impact of the project should be considered from the beginning, as well as the possible financial, commercial and market framework in which the project will be placed.
A solar tower plant as described is a complex machinery, which can be changed and adapted to new situations and conditions (like change of demand), but only in a very limited way.

6.4. Bankability

6.4.1. CSP Market Overview

CSP plants have been built in about 25 countries, by 2020, nearly 100 CSP plants have begun commercial operation, of which, 14 CSPs are based on solar tower technology (Mehos M. H., 2020). Several large tower projects are in development in China, Chile, and Dubai based on the molten-salt storage where the storage capacities are mainly designed for 6 to 16 hours of full-load turbine operation.

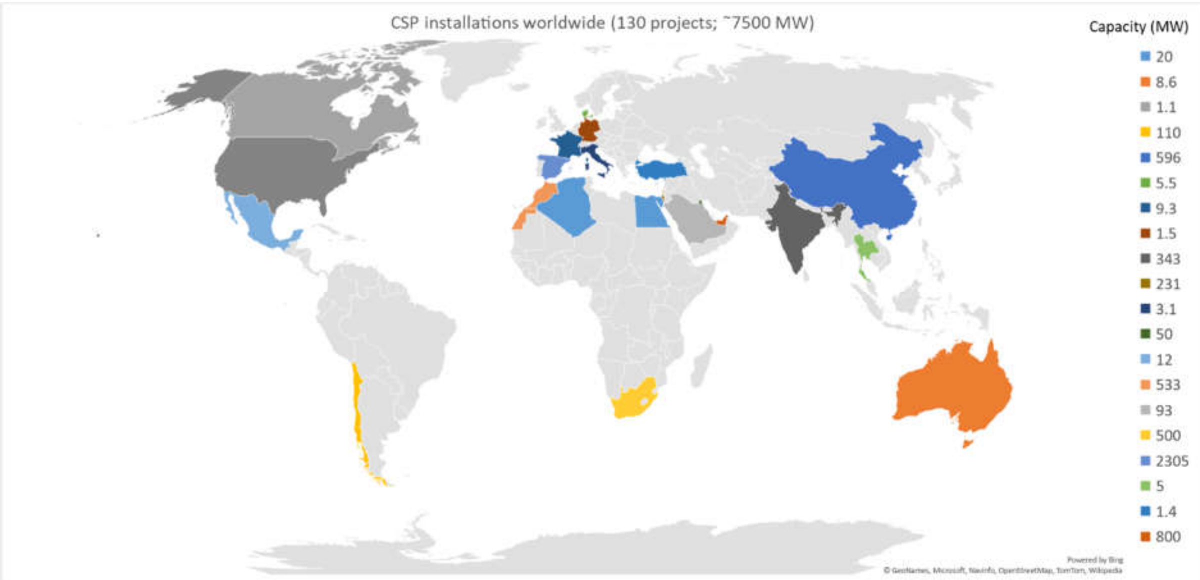


Figure 49: CSP installations worldwide (Thonig, 2020)

The first wave of CSP development occurred in the United States during the 1980s, while the second wave later started in Span in 2007 following their favourable FIT scheme and continued to expand across many regions such as South Africa, Morocco, Israel, Chile and the United Arab Emirates (UAE). More recently, CSP projects are now being implemented in China.

When it comes to capital expenditures, the cost trend is declining for CSP systems. Figure 50 shows the LCOE trend of CSP projects- between 2008 and 2020 the world average LCOE for CSP systems has been reduced by over 120% from 0.29 USD/kWh to 0.13 USD/kWh and it would further continue to decline.

Notably cost variation could be attributed to various elements such as cost of land, chosen technology type (e.g. tower, parabolic trough, Fresnel etc.) or the use of thermal storage system (with or without). For instance, for a 100 MWe CSP plant, at least 12 hours of thermal storage can be provided by a combination of one hot-salt tank and one cold-salt tank with an additional capital cost in the order of $\$40/kWh_t$ (Mehos M. H., 2020).

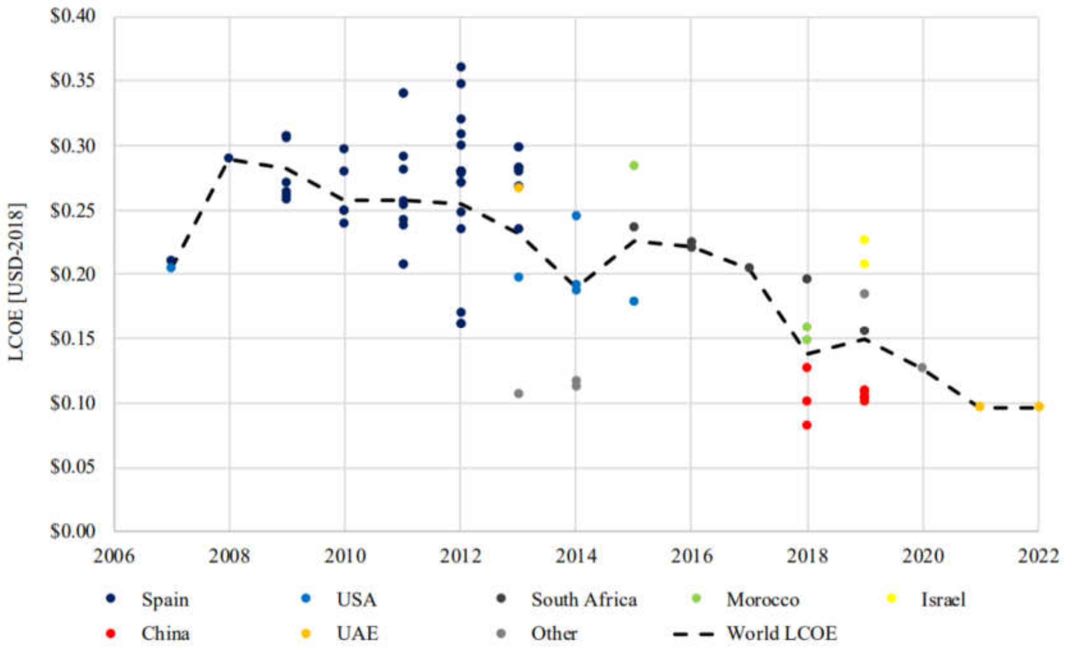


Figure 50: Levelized cost of electricity (LCOE) of the 77 solar-only commercial CSP stations for 2006–2018 (operational) and 2019–2022 (under construction) (Mehos M. H., 2020)

The following table shows LCOE of selected tower projects with storage system that were constructed in the last five years:

Table 23: LCOE of power tower systems with thermal storage (Thonig, 2020)

	Name	**Country**	**Year**	**Technology**	**Capacity MW**	**Storage hours**	**LCOE USD/kWh**
1	Noor Energy 1 / DEWA IV - 100MW Tower	United Arab Emirates	2021	Power Tower	100	15	0.10
2	Atacama I / Cerro Dominador	Chile	2020	Power Tower	110	17.5	0.13
3	CEEC Hami - 50MW Tower	China	2019	Power Tower	50	8	0.10
4	NOOR III	Morocco	2018	Power Tower	150	7	0.15
5	Khi Solar One	South Africa	2016	Power Tower	50	2	0.22
6	Crescent Dunes Solar Energy Project	United States	2015	Power Tower	110	10	0.18

6.4.2. Business case for solar tower system with thermal storage

The value proposition of CSP technology is that due to its high dispatchability and flexibility it can generate power for peak periods and/or at night with the use of thermal energy storage. Many CSP plants use time-dependent pricing i.e. time-of-delivery (TOD) schemes that incentivize periods (e.g. off-peak, on-peak) when power dispatch might have the highest value. The use of thermal energy storage optimizes the solar capacity factor.
A hypothetical business case of a CSP tower project with molten salt storage has been defined in section 5.

6.4.3. Financing Landscape

Historically, public utilities have been the primary owner and operator for power generation projects however, in recent years participation of IPPs (Independent Power Producers) in power generation have increased which has also resulted increase of private-sector financing in power generation. For RE based generation projects (between 2013 and 2018), private financing dominates over public financing. Most CSP projects to date have been developed as IPP projects having long-term power purchase agreements (PPAs) with the off-takers (utilities or system operators). IPPs invest in CSP technology and recover their cost from the sale of the electricity. CSP projects usually have 20-year or longer PPA terms, and most projects have at least 25-year PPA terms in order to allow then to recover their costs at acceptable tariff levels.

Most IPP projects are tendered as build–own–operate (BOO), build–operate–transfer (BOT), or build–own–operate–transfer (BOOT) basis using project finance (Special Purpose Vehicle) structure that allows the use of private sector debt from commercial banks or a mix of private and public sector debt aided by concessionary financing from development banks or development finance institutions (DFIs). As opposed to commercial financing, extended by mainly private commercial banks, concessionary financing offers more favorable terms to eligible projects in terms of lower interest rate, longer grace and loan periods than regular commercial bank loans in return for positive economic, environmental and social impacts desired by the project. In CSP projects, often the EPC is also a sponsor or equity investor in the project.

For an IPP with a long term PPA backed by one or more financially strong off-takers, the financing terms would be in-line with standard commercial project financing terms:

- Financing structure: 60% debt, 40% equity (standards for most current conventional energy projects)
- Loan terms: 8-10 years for private banks, 12 - 15 years for public banks
- Interest rate: 2 - 4.5 % (local currency) + national interbank loan rate

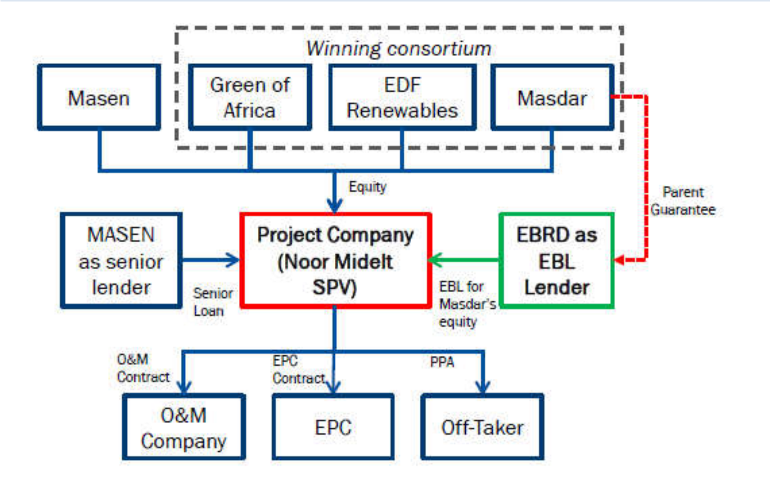
A CSP financing case study:
Noor Midelt project, Midelt, Eastern Morocco (Lastours, 2020)

Project scope: Financing of a hybrid solar plant combining PV and CSP
Project objective: To provide stable baseload solar power at a tariff that competes with conventional power
Key project parameters

- **Around 800 MW total installed capacity: 600 MW PV and 190 MW CSP**
- **5 hours of thermal energy storage (molten salt)**
- **Project cost: USD 800 million**
- **Build-Operate-Transfer (BOT) structure with a 25-year PPA**
- **Implementation status: Under construction; tender awarded in May 2019**

Project sponsors: EDF Renewables, Masdar and Green of Africa
Financing arrangements:

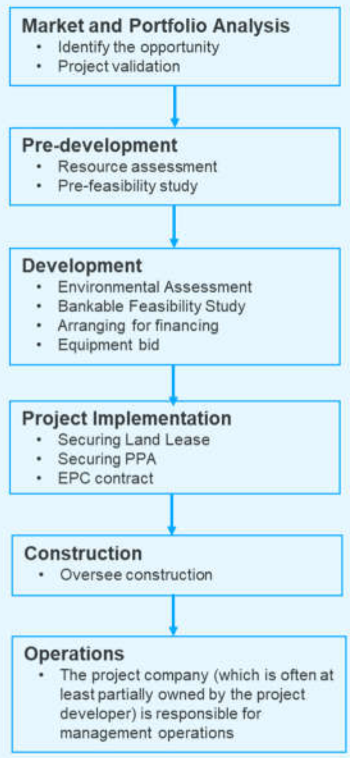
- **Masen offers senior dept to the project**
- **EBRD provides a multicurrency Equity Bridge Loan of approx. EUR 45 m equivalent to the SPV, to bridge sponsor equity**



Financing arrangements of the Noor Midelt project, Midelt, Eastern Morocco

6.4.4. Financing Strategies of Project Developers

The role of the project developer, also called the Sponsor, is to take a project from idea to reality. A project developer manages the entire project development process and carries (or contracts for) among others, the market and portfolio analysis, development, implementation, construction and operational tasks.



Project development process

Typically, a project developer will bring 30-40% equity to the project and either sell their share once the project is up and running or add it to their operational portfolio. Project financers require a project developer who can lower the construction risk. This means a project developer (local or foreign) require experience in developing projects of a similar scale and in similar technology. In case of CSP projects, often a project developer will be an EPC who can also bring their experience to the project. An investor will require a suitable return for their investment, typically in the range of 14%.

A project developer's role is to implement a project while minimizing risks. This entails dealing with:

- Permitting Issues – minimizing risks due to delays in the permitting processes which generate additional costs.
- Regulatory Issues – navigating the regulatory environment which is particularly important in new markets where there is often insufficient regulatory regimes or insufficient stability of regimes. A solid and stable regulatory framework is essential to achieve project financing.

6.4.5. Overview of Debt Finance Environment

In 2017-2018, annual renewable energy investment reached, on average, US$ 337 billion, of which US$14 billion investments were made for CSP and solar thermal projects. Project developers continued to be the main actors within private finance, providing an average of 56% of total private finance in 2017-2018, mainly through balance sheet finance (debt or equity). Project-level financing (either debt or equity) is usually provided by sponsors relying on the project's cash flow for repayment, whereas balance sheet financing is provided through equity and debt investments in the recipient institution or entity. Notably, 2% of total investments in 2017-2018 (equivalent to USD 7 billion annually) can be considered as concessional financing representing low-cost project debt as well as grants.

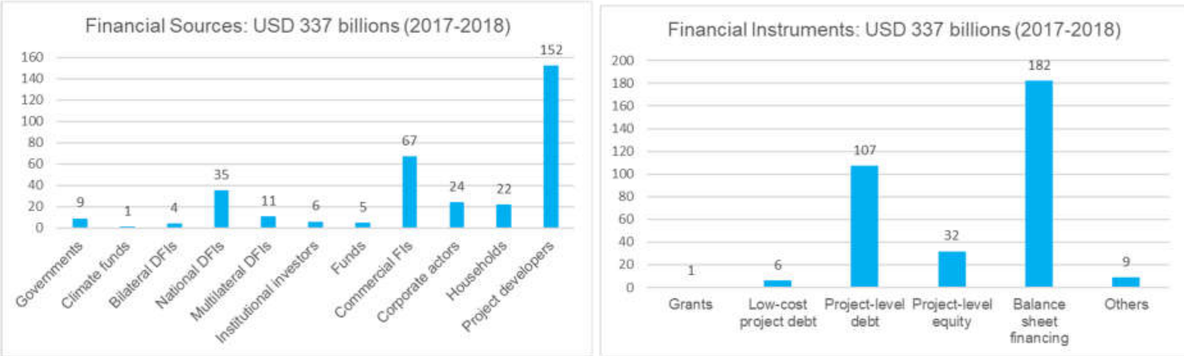


Figure 51: Financial Sources and Instruments (IRENA and CPI, 2020)

6.4.6. Overview of Financial Products/Instruments of select DFIs

Large scale renewable energy projects are highly capital intensive. Most development banks offer several types of financing products ranging from grants, to concession loans (soft loans) to quasi commercial loans and loans to private sector under commercial terms. Development finance institutions (DFI) often create consortiums to reduce individual risk and increase political leverage, just as project developers, suppliers and equity investors will build partnerships to leverage experience and know-how as well as spread their risk.
The following table shows indicative financing terms and conditions of selected development banks in CSP projects. These terms will vary from project to project and depends on the financing needs and risk level of the specific project.

Table 24: Lending products and terms of selected development banks (relevant to CSP)

Development Bank	Lending products/ terms relevant to CSP projects
World Bank Group	The two primary entities of the World Bank Group are important for financing of renewables: The International Bank for Reconstruction (IBRD) which provides concessional debt financing to government entities (with a sovereign guarantee required) and the International Financing Corporation (IFC) which provides commercial debt financing for private projects (under the IPP model). In addition, to the debt financing tools available through IBRD and IFC, the World Bank also administers the Clean Technology Fund (CTF) that has strong focus on renewables. **The IFC loans:** • IFC provides funding for private sector (for-profit) investments in developing countries. These loans have a conventional loan structure and market rate terms • The IFC can make loans to intermediary banks, leasing companies, and other financial institutions for on-lending.

	• Financing terms constitute up to 25% (Greenfield) or 50% (Expansion) of total project cost through a combination of (Younger, 2017): • **Development equity:** Up to 8 million or 50% of development budget • **Project equity:** Typically, up to 20% stake for IFC's account • **Mezzanine:** Subordinated loans, income participating loans, convertibles and other hybrid instruments • **Senior Debt and Structured Products:** Fixed or floating rates (US or Euro) as well as some local currency finance; long maturities (up to 20 years), grace periods and repayments commensurate with project cash flows; structured loans at commercial rates; swaps and risk management products; tenor extension solutions for local commercial banks • Most IFC loans have maturities of 7-12 years, though this is determined on a case by case basis. For a project with a strong 20-year PPA a loan term of up to 15 years (including grace period) is possible. **IBRD loans** (World Bank Group, 2020)**:** • The IBRD loans money to directly to a government agency, A Sovereign guaranty always required for IBRD funded projects • The IBRD Flexible Loan (IFL) is the leading loan product of the World Bank for public sector borrowers of middle-income countries with long maturities up to 35 years (average repayment maturity is 20 years) • The price of the IFL reflects IBRD's AAA credit rating and the pricing include the interest rate, front-end fee and commitment fee. The interest rate consists of a market-based variable reference rate and a spread. The reference rate varies by currency (currently 6-Month LIBOR for USD, JPY and GBP and EURIBOR for EUR). The borrower may choose between two types of spreads: a variable or a fixed spread. • IBRD Flexible Loans are subject to a one-time front-end fee of 0.25% on the committed loan amount, and a commitment fee of 0.25% per annum on undisbursed balances. The standard lending spread comprises a contractual spread of 0.50% and an annual maturity premium.

EBRD	• The EBRD funds up to 35% of the total project cost for a greenfield project or 35% of the long-term capitalization of an established company (EBRD, 2020)
	• The EBRD may identify additional resources through its syndications programme
	• Additional funding by sponsors and other co-financiers is required. Typical private sector projects are based on at least one-third equity investment
	• Loan features:
	    • Usually range between €3 up to €250 million; fixed or floating rate; senior, subordinated, mezzanine or convertible debt; denominated in major foreign or local currencies; short to long-term maturities up to 15 years; project-specific grace periods may be incorporated.
	• Equity investments:
	    • Equity ranging from €2 million to €100 million in private sector projects
	    • Equity return expectation: market rate return from equity investments

KfW	• The business units KfW Development Bank – Public Sector Projects and KfW IPEX Bank GmbH - Commercial Financing of the KfW banking group play a vital role in the development of renewable energy projects • KfW Group offers a wide variety of financial products from both public and private sector projects, varying on the scale from very concessional to near commercial terms. • Budget funds delivered as grants or low-interest concessional loans • loans that comprise a mix of budget funds and KfW funds (development loans) • KfW funds extends loans at the market rate via the KfW IPEX Bank (promotional loans) • Due to overhead and transaction costs, KfW does not normally invest in project of less than 20 mil. EUR. • Financing Terms: • The loan conditions for each project depend on the project itself; the sector/technology, the nature and cost-effectiveness of the project, the economic situation of the country, etc. (KfW Entwicklungsbank, 2020)

Table 25: KfW Loan Product Structure

	1	2	3	4
Product Type	Development	Concessional loans	Semi-Commercial	Promotional Loans
Debt / Equity	100 % Debt 20% local portion, (Civil works, site, etc.)	+/- 80% Debt 20% equity (or in-kind contribution)	+/- 70% Debt	KfW IPEX Bank KfW DEG
Conditions	Very concessionary	Concessionary terms	Discount on commercial terms	Commercial terms
Notes	Concessional loans (KfW + governmental grant)	Current stage of CSP	Current stage of Wind (in Egypt)	Private Sector projects
Tenor	ca. 30 years	ca. 15 years	ca. 12 years	
Program	Bilateral Cooperation			
		Pricing module		

AFD (The French Development Agency)

- AFD (AFD, 2020) offers a variety of financial products ranging from concessional debt products with sovereign guarantees for public projects to private sector financing at quasi commercial rates.
- Products:
  - Financing terms depend on the specific project. For example, a developing technology such as CSP might be qualify for concessional terms, whereas a Wind project may not.
  - Public sector projects: AFD targets projects with their participation between 30-100 mil. EUR, with the average around 50 mil. per project. Loans can have a loan length of up to 20 years with a grace period of up to 7 years.
  - Private sector projects: The AFD subsidiary PROPARCO (Proparco, 2020) specializes in private sector financing and can offer equity and debt financing in commercial terms. Loan amounts are between 2 - 100 mil. EUR with a Debt/Equity ratio of 60/40 and can have a loan length of up to 15 years.

- Structured financing and guarantee mechanisms via SUNREF credit line to partner banks for eligible clean energy products on favorable terms (long-term loans up to 100% of the investment costs based on maturity of green financing market, type of investment, target client base)

African Development Bank (AfDB)

- Loans to public entities and private sector, categorized as Sovereign Guaranteed Loans (SGLs) or Non-Sovereign Guaranteed Loans (NSGLs).
- The ADB participates in project financing for renewable energy project up to about $150 mil USD, willing to invest in Wind, CSP and PV projects.

Sovereign Guaranteed Loans (SGLs) for public sector:

- The project must be a sustainable project with positive social impact
- The maximum loan length is 20 years (including a grace period of up to 5 years)
- The standard loan products for SGL are Variable Spread Loans (VSL), Enhanced Variable Spread Loans (EVSL), and Fully Flexible Loans (FFL)
- Loan pricing:
    - FFL=Base Rate + Funding Margin + Lending Spread + Maturity Premium
    - EVSL = Base Rate + Funding Margin + Lending Spread
    - VSL = Base Rate + Funding Margin + Lending Spread
    -

Table 26: KfW African Development Bank SGL applicable lending rate (August 2020- January 2021) (ADB - African Development Bank, 2020a)

Loans Approved after 21-Jan-2009					
VSL, EVSL, FFL	USD	EUR	YEN	ZAR	
Floating Base Rate (a)	0.315	-0.399	-0.03	3.725	3.625
Funding Margin [benefit (-) / cost (+)] (b)	0.04	-0.09	0.00	0.02	0.02
Lending Spread (c)	0.80	0.80	0.80	0.80	0.80
Applicable Lending Rate (a + b + c)	1.155	1.311	0.769	4.545	4.445

- In addition to the Applicable Lending Rate, a Maturity Premium might be applicable for loans with Average Maturity>12.75 years.

- The floating base is dependent on the currency which is based on the 6-month LIBOR for USD and YEN, 6-month EURIBOR for Euro, 3-month JIBAR for ZAR. The funding margin is based on the Bank's average cost of borrowings relative to LIBOR/EURIBOR/JIBAR for each loan currency.

Non-Sovereign Guaranteed Loans (SGLs) for private sector:

- The project must be a sustainable project with positive social impact, particularly regarding job creation. To be a sustainable private project it requires a return of at least 25%.
- For private projects 30% equity is needed and ADB will finance a maximum of 30% of project costs (i.e. max. 60% of debt requirement).
- Maximum loan length is 15 years (including a grace period of up to 5 years), though 5-7 years is common.
- The standard loan product for NSGL is a Fixed Spread Loan (FSL).
- Lending Rate = Floating Base + Risk Based Credit Spread

Table 27: African Development Bank NSGL applicable lending rate (August 2020- January 2021) (ADB - African Development Bank, 2020b)

Fixed Spread Loans				
	USD	EUR	YEN	ZAR
Floating Base Rate (a)	0.31488	0.000	0.000	3.625
Lending Spread (b)	Specific to each project			
Applicable Lending Rate	(a + b)			

- The floating base is dependent on the currency which is based on the 6-month LIBOR for USD and YEN, 6-month EURIBOR for Euro and 3-month JIBAR for ZAR. The funding margin is based on the Bank's average cost of borrowings relative to LIBOR/EURIBOR/JIBAR for each loan currency.
- The risk-based spread for private projects (IPP) is dependent on the specific properties of each project, generally ranges between 1.5 - 3%.

European Investment Bank

- EIB offers various debt, equity and guarantee products to private and public sector
- Loans for the private sector (EIB, 2020):
  - The EIB typically covers up to 50% of a project's total cost. These loans typically start at €25 million. Most common debt

	products are Corporate loans, Growth finance for mid-caps, Project finance loans and Corporate hybrid debt
	• EIB adds a margin on top of its funding interest rate to cover the risks and administrative costs associated with each operation. The interest rate or guarantee fee reflects the credit risk profile of the individual project.
	• Loan period: typically, up to 10 years; for project finance up to 30 years or more.
	• Equity investment:
	  • Equity investments represent 10% to 20% of the fund size, with a maximum of 25%. The loan tenors reflect the fund's life – normally 10-12 years, but up to 25 years or more.
	  • Common equity products are Venture debt or Quasi-equity debt (minimum €7.5 million, covering a maximum of 50% of the total investment cost), Infrastructure and environmental funds for climate action and/or infrastructure projects, and SME & Mid-cap funds (between €5 and €100 million investment size)
	  • Co-investments between €25 and €60 million for climate action an infrastructure projects but can go up to €200 million under certain conditions.
	• Guarantee products:
	  • Guarantees in support of SMEs, mid-caps and other objectives and Credit enhancement for project finance.
	  • The project finance credit enhancement product includes Funded and Unfunded structures. Funded structures take the form of a subordinated bond/loan tranche with a defined repayment schedule sculpted in line with the senior debt repayment profile. Unfunded structures are irrevocable and unconditional guarantees, providing a revolving first-demand guarantee facility in the form of a letter of credit or equivalent instrument. Maximum size around €200 million or 20% of the nominal of credit-enhanced senior bonds.
	  • The risk-sharing guarantee for small- and medium-sized enterprises or mid-caps by covering a portion of possible losses from a portfolio of loans. Reimbursement for a fixed percentage of incurred losses typically amounts to a maximum of 50%.

6.4.7. Financing risks and pre-requisites to attract financing in CSP projects

In general, banks are not able to exclude or reduce risks for all participants in a project which means financing risk is interlinked with the unfavourable legislation, change in policy and market situation or technology risk. Banks and sponsors face following risks when financing an investment:

Technical risks refer to the reliability and functioning of technical parts	**Performance risks** cover management and controlling abilities of the business owner/manager	**Market risks** include price risks, volume and demand risks	**Policy risks** unclear policies, sudden changes or low reliability of policies affect demand for RE investments
Financial risks includes changes in interest rates, exchange rates, commodity prices, inflation etc.	**Legal risks** relate to uncertainties and inconsistencies at the legal and judicial level	**Country risks** depend on overall political stability, targets, socio-economic disturbances, etc.	**Force majeure** natural disasters or other incidences, but this risk is similar across the region

Figure 52: Category of risks in financing and investment

Banks have been operating under certain country, legal and financial risks by using different hedging strategies, but the knock-out criteria for financing RE projects are the market and policy risks. Under the given market and policy situation a financing institution would only be willing to finance a large investment if the firm can demonstrate that they have a solid off-taker for their product (which helps to ensure the loan can be repaid). As an alternative, banks can approve loans for those companies that provide enough collateral and serve a broad and rather stable market (either internal or external), which is less dependent on unclear policies. Similarly, IPP based CSP projects would require an enabling policy framework comprised of commercial, legal, and governmental supports (e.g. permission, licenses etc.). An appropriate financial framework would provide long-term off-take agreements and other incentives that ensure financial sustainability of a CSP plant. Between 2007 and 2013, the favourable feed-in tariff (FiT) policy for CSP projects in Spain- that allowed 25 year off-take contracts with high fixed price on top of market time-of-delivery price - resulted in tremendous uptakes of CSP projects. Recently, competitive bidding process has replaced the FIT scheme in many countries like in the United States, South Africa, Morocco, Israel, and the United Arab Emirates, through which further international spread of CSP projects can be seen. In the PPA, capacity payment provision (take-or-pay provision) is desired in order to reduce power off-take risks for the CSP plants. It is utmost importance that the PPA comes from a creditworthy entity which will significantly reduce financing risks in the CSP projects.

Besides the market and policy concerns, solar tower technology has certain technological challenges. Compared to the different types of CSP technologies that exist today, solar tower is at an earlier stage of commercial maturity given that fewer plants have been built so far. There is performance and design concerns in tower projects that need to be addressed to raise the confidence of the financiers. Because technology risk of CSP may results in lower

annual outputs, resulting in volatile cash flows. This risk is usually mitigated through the design performance guaranty provided by the EPC.
Financing CSP projects is in general difficult due to the length of time required for CSP project development, financing, and construction (about 3 years in general). Performance risk of CSP technology is another major concern which is reflected in the ramp-up period during construction. The ramp up period ensures the performance of the plant as per the design criteria. Longer construction and ramp-up periods discourage many commercial banks to consider financing in CSP projects due to individual lending policies. Moreover, lengthy environmental and permitting issues can have a significant impact on the cost (i.e. cost overrun) and financing of the CSP plants. Simplified procedures on the other hand can expediate all types of permissions and license requirements and hence the financial closing process. There are also operational uncertainties that the project will underperform or earning less revenues. In practice, if operating costs are higher than anticipated the debt payment coverage comes from company cash flow, thus lowering equity investor returns. Or, (depending on the PPA structure) if O&M turns out lower than expected the returns to equity investors increase. Therefore, lenders try to shift risks as much as possible to the borrower, i.e. the borrower shall compensate the credit default with securities. Subsequently, if the borrower can provide the collaterals and bear all these risks, a financial closure is possible. This Molten Salt CSP Reference Power Plant concept study may provide a sound base for a financial institution to build up trust in the presented design. As the concept is discussed by independent experts, and if adjusted properly to the project condition, it will take out a number of technical risks to the project and project execution and build up more confidence in the foreseen performance of such a plant.

6.4.8. Financing institutions’ requirements

Financial institutions will strive to maximize their profits. Subsequently, banks minimize costs and hence, risks. Financing institutions’ overall credit decision criteria is the expected return including risk aspects and collaterals as well. To be able to assess the expected return and to keep risks low banks have to screen thoroughly any potential borrower. In order to do this, they require documents that prove the reliability and profitability of the company or project (feasibility study, cash-flow analysis, contracts and agreements). Further, they need to verify any given information on expected revenues, cost, investment, property, etc. For this, banks ask for diverse supporting documents (PPA, supply contract, ownership documents, etc.). Beyond that, in case of a credit default, they need securities (mortgage, guarantees, transfer of securities, release of covenant, etc.) to recover at least a partly compensation/repayment of the principal in case of default.

Table 28: Loan application process and documents that have to be handed in by project sponsors (Brandy Gunn, 2020)

Steps	**Working capital loans for firms**	**Investment loan (corporate financing)**	**Project finance (investment loan)**	**Leasing (corporate financing)**	**Guarantee for bidding, performance or down payment**
Annual balance sheets (recent 3 years) including cash flows, assets and liabilities and a recent interim financial position during the year (if applicable)	x	x		x	x
Company licence: - industrial development authority - investment authority - commercial register	x	x	X (for project)	x	x
Land ownership documents	X	X	X	X	X
Tender documents			X		X
Subcontracts: - Supplier (raw materials), - Supplier (equipment)	no need for hard evidence	X	X	X	X
Sales contract (final product) or construction contract or service contract		(x)	x	?	x
Invoice of financed equipment or materials	x	x	x	x	?
Feasibility study: - technical feasibility - market feasibility - financial feasibility (cash flows, business plan) - political or legal feasibility		 X x	X X X X X	 x	no need if the exposure is only contingent
Track record of enterprise	x	x	(X) if available	x	x
Information on partners (project or contracts)	(X)	(X)	X	(X)	(X)

Steps	**Working capital loans for firms**	**Investment loan (corporate financing)**	**Project finance (investment loan)**	**Leasing (corporate financing)**	**Guarantee for bidding, performance or down payment**
Information on board members (of enterprise)					
Information on equity holders and their liability w.r.t. the project or enterprise, (letter of responsibility)	x	x	x	x	x
Information on legal structure of project: - legal framework for shareholders (contract documents) - general information on company	 x	 x	X		X x
Information on management structure of project and qualification of manager/director	(x)	(x)	x	(x)	(x)
Cash-flow analysis: - detailed analysis on revenues, expenses (liquidity) - detailed financial analysis. ROI, equity share, ...			X X X		
List with value of tangible and intangible assets (for collateral)	(x)	(x)	x	(x)	(x)
Credit history (information is provided by bank)	x	x		x	x

Note: x = needed, (x) = possibly needed, depending on the special case.

The loan application procedure as well as the required documents and collaterals could act like a barrier for developers. The more uncertain banks are about the potential outcome of the investment, the more detailed the screening process is, the more paperwork and collateral is required.

7. Roadmap

This report covers only a small task within the development and realization of a CSP tower plant. Much more is needed to make a project a success story.
The following table indicates necessary steps to be taken, to bring a project on safe ground. The report content represents the task I B.

Table 29: Overview on typical project development for a CSP plant (BMZ, 2011)

Step	Task	Content
I. Technical Assessment	I-A Site identification	▪ Solar resource assessment ▪ Site assessment matrix ▪ Evaluation of infrastructure requirements (site location, geotechnical data, environmental issues, water supply etc.) ▪ Selection of high potential sites for Solar Power plants (preparation of long list)
	I-B CSP Plants	▪ CSP technology inputs ▪ CSP site selection matrix ▪ Plant layout ▪ O&M philosophy ▪ Investment and Operation cost estimate
	I-D Yield assessment CSP Plants	▪ Yield estimate e.g. with Greenius simulation ▪ Greenius software, manual, example simulation, troubleshooting
II. Financial and Economic Assessment	II-A Demand & Supply balancing	▪ Methodology and assumptions ▪ Input data matrix ▪ D&S Excel spreadsheet ▪ Benefit calculation (avoided fuel demand and CO2 emissions; additional demand covered) ▪ Examples and troubleshooting
	II-B Financial Analysis	▪ Estimate of Capex and Opex ▪ Assessment of parameters for Financial Viability (project IRR and NPV, DSCR, RoE, Payback, DUC) ▪ Definition of funding scenarios ▪ Comparison of funding scenarios ▪ Sensitivity analysis ▪ FAT spreadsheet, manual, examples and troubleshooting ▪ Risk identification matrix for financial risks, mitigation strategies
	II-C Economic Analysis	▪ Parameters for Economic Viability (Present Value of cost and benefits, LCOE, IRR, cost-benefit ratio, CDM revenue) ▪ Identification of the least cost option ▪ Sensitivity analysis ▪ EAT spreadsheet, manual, examples and troubleshooting
III. Business Models and Lender's Package	For CSP power plants	▪ CSP project development cycle and timeline: steps, most critical issues, mitigation measures ▪ Financing for project financed large scale CSP ▪ Organizational setup of project ▪ Cornerstones for bankability and bankability assessment matrix ▪ Checklist for of regulatory framework and policy issues (concession, tariff, etc.)

		▪ Strategy for identification of project partners: supplier, co-investors and lenders ▪ Checklist for permits, agreements: (grid access, EIA and SIA, construction etc.) ▪ The role of technical Due Diligence in the project cycle for CSP power plants ▪ Risk identification matrix for policy, market, strategy and organizational risks
IV. Tendering and Procurement	IV-A Procurement CSP	▪ Selection of adequate bidding procedure ▪ Inputs to the technical specification of CSP plants per package (quality standards, key qualities to be specified) ▪ Supplier and technology selection criteria ▪ Definitions of guarantees (power, yield, performance) ▪ Definition of acceptance test procedures

7.1. Timeline

Development and realization of a CSP tower plant requires a timeline of several years.

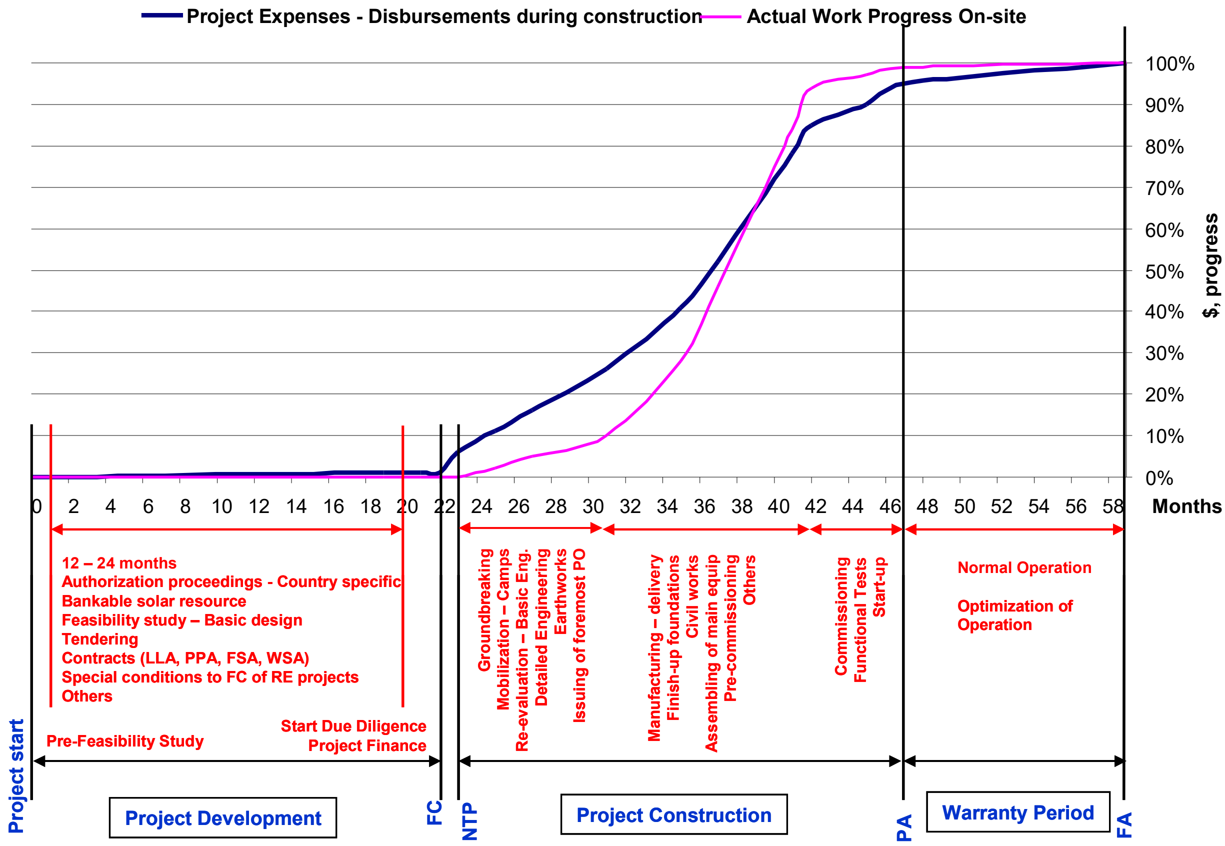


Figure 53: Example for a project life cycle for specific project condition

From the birth of the project until offering a tender usually two to five years may be necessary to prepare the necessary commercial and contractual setup. This will be followed by contract negotiations and signatures to start the realization. After successful plant construction and commissioning typically a warranty period of two to three years follows to achieve full production and guarantee the full performance of the plant. Only then the plant operates fully commercial for the remaining lifetime

.

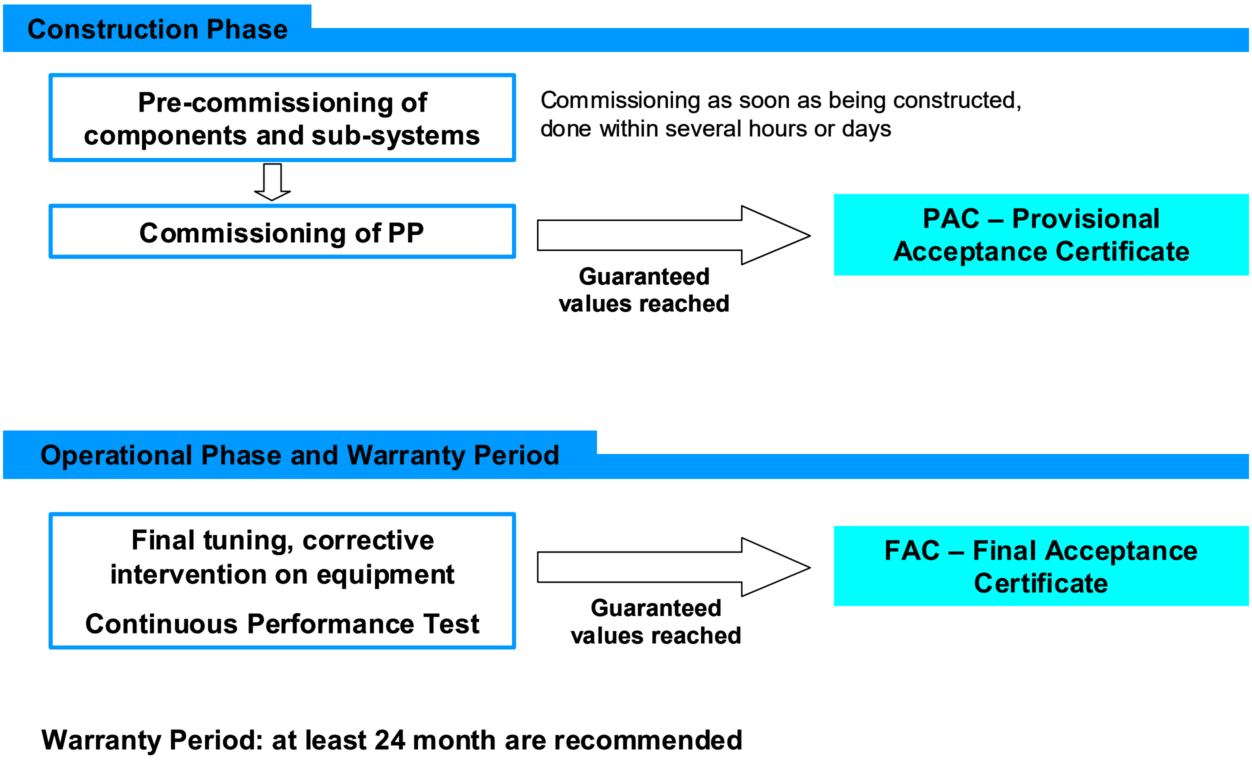


Figure 54: Typical Commissioning Process

Below a typical indicative project schedule for Engineering, Procurement until Commissioning can be found. Project duration for the EPC Contractor is here 40 months, but will differ for each project. Depending on the contractual framework and required guarantees, such a project may be realized even within 24 months, but can also extend to a much longer duration. This schedule has a period of six month before Notice to Proceed, to accelerate the progress but on the risk of the EPC Contractor. Depending on the agreed performance in the first years of operation the Plant Commissioning Period can be kept shorter. Total time depends of course on lead times for key equipment, and other influences like remote location of the site, access to labour and material, and not to forget on the progress on site and qualification of the constructor.

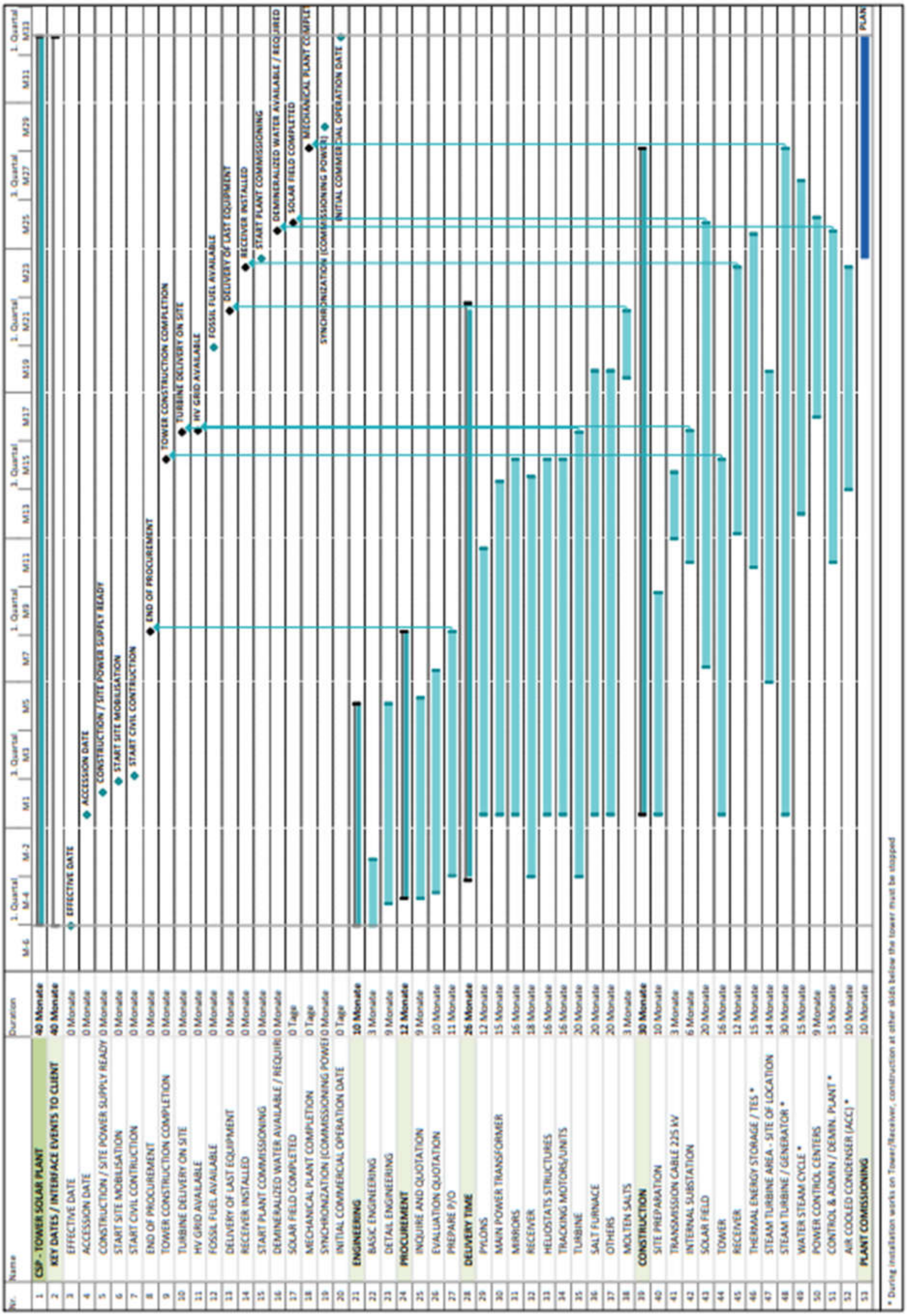


Figure 55: Indicative project schedule

8. References

ADB - African Development Bank. (2020a, 11 27). *ADB Applicable Lending Rates for Sovereign Guaranteed Loans*. Retrieved from https://www.afdb.org/en/documents/financial-information/lending-rates

ADB - African Development Bank. (2020b, 11 27). *ADB Applicable Lending Base Rates for Non-Sovereign Guaranteed Loans*. Retrieved from https://www.afdb.org/en/documents/financial-information/lending-rates

AFD. (2020, 11 27). *l'Agence Française de Développement*. Retrieved from https://www.afd.fr/en

ANSYS Inc. (2007). *Theory Reference for ANSYS and ANSYS Workbench.* Canonsburg.

ASME. (2019). *ASME Boiler and Pressure Vessel Code - Section III Rules for Construction of Nuclear Facility Components - Division 5 High Temperature Reactors.* ASME BPVC.III.5-2019.

Balz, M. G. (2015). Stellio - development, construction and testing of a smart heliostat. *SolarPACES Annual Conference 2015, Cape Town, South Africa*.

Barrett, P. R. (2015). A Unified Viscoplastic Model for Creep and Fatigue-Creep Response Simulation of Haynes 230. *Volume 3: Design and Analysis. American Society of Mechanical Engineers. DOI=10.1115/PVP2015-45671*.

Barua, B. M. (2019). Comparison and Assessment of the Creep-Fatigue and Ratcheting Design Methods for a Reference Gen3 Molten Salt Concentrated Solar Power Receiver. *Volume 3: Design and Analysis. American Society of Mechanical Engineers. DOI=10.1115/PVP2019-93572*.

Berman, I. (1979). *Final report, phases 1 and 2 : an interim structural design standard for solar energy applications.* Livermore: Sandia Laboratories energy report.

BMZ. (2011). *EMPower Utility Toolkit - Large Scale Solar Power.* UNEP.

Bradshaw, R., & Goods, S. (2001). *Corrosion Resistance of Stainless Steels During Thermal.* Sandia Report SAND2001-8518.

Brandy Gunn, T. (2020). *Engineering own composition, based on interviews with companies and banks.*

De Rose, A. (2017a). *TRL Project Technology Readiness Level: Guidance Principles for Renewable Energy technologies, ISBN 978-92-79-59753-4.* European Commission DG RTD.

De Rose, A. (2017b). *Technology Readiness Level: Guidance Principles for Renewable Energy technologies Annexes, EUR 27988 EN, ISBN 978-92-79-73697-1, pp. 12 ff.*

DLR. (2020). *greenius*. Retrieved from http://freegreenius.dlr.de

DLR, Instute of Solar Research. (2020). *Heliostat Field Performance Acceptance Test Guidelines.* https://elib.dlr.de/.

DLR, Instute of Solar Research. (2020). *SolarPACES Guideline for Heliostat Performance Testing.* https://elib.dlr.de/.

EBRD. (2020, 11 27). *European Bank for Reconstruction and Development*. Retrieved from https://www.ebrd.com/work-with-us/project-finance/loans.html

EIB. (2020, 11 27). *European Investment Bank*. Retrieved from https://www.eib.org/en/index.htm

Federsel, K., Wortmann, D., & Ladenberger, M. (2015, May). High-temperature and Corrosion Behavior of Nitrate Nitrite Molten Salt Mixtures Regarding their Application in Concentrating Solar Power Plants. *Energy Procedia, Vol 69*, pp. 618-625. doi:https://doi.org/10.1016/j.egypro.2015.03.071

Frantz, e. (2017). ASTRID(C) - Advanced Solar Tubular Receiver Desing: A powerful tool for receiver design and optimization. *AIP Conference Proceedings 1850, 030017.*

Gross, F., & Balz, M. (2019). *Potentially Confusing Coordinate Systems for Solar Tower Plants.* SolarPaces Conference 2019.

Gross, F., Landman, W. A., Balz, M., & Sun, D. (2019). Robust Aim Point Strategy for Dynamic Solar Tower Plant. *SolarPaces Conference.* Daegu.

HelioCSP. (2019, 4 5). *SolarReserve to miss fin close deadline for 150-MW Australia Concentrated Solar Power project*. Retrieved from http://helioscsp.com/solarreserve-to-miss-fin-close-deadline-for-150-mw-australia-concentrated-solar-power-project/

HelioCSP. (2020, 10 10). *Supcon Solar 50 MW Concentrated Solar Power plant reveals remarkable performance*. Retrieved from http://helioscsp.com/supcon-solar-50-mw-concentrated-solar-power-plant-reveals-remarkable-performance/

IRENA and CPI. (2020). *Global Landscape of Renewable Energy Finance, ISBN 978-92-9260-237-6.* Abu Dhabi: International Renewable Energy Agency.

Keck, T., Gracia, J., Eizaguirre, I., Sun, D., Balz, M., & Iriondo, J. (2020). *Solar Field Experiences from Hami Solar Tower Project.* SolarPaces Conference.

Keck, T., Schönfelder, V., Zwingmann, B., Gross, F., Balz, M., Siros, F., & Flamant, G. (2020). *High-Performance Stellio Heliostat for High Temperature Application.* SolarPaces Conference.

KfW Entwicklungsbank. (2020, 11 27). *Financial Products*. Retrieved from https://www.kfw-entwicklungsbank.de/Internationale-Finanzierung/KfW-Entwicklungsbank/Aufgaben-und-Ziele/Unsere-Finanzprodukte/

Kistler, B. L. (1987). *Fatigue Analysis of a Solar Central Receiver Design Using Measured Weather Data.* Sandia National Laboratories.

Lastours, G. d. (2020). Best Practice in Financing CSP Projects: An EBRD view, World Bank MENA Concentrating Solar for Power and Heat . Online Conference April 1-2.

M. Laporte-Azcué, P. A.-G.-S. (2020). Deflection and stresses in solar central receivers. *Solar Energy 195*, pp. 355 - 368.

Mehos, M. H. (2020). *NREL Concentrating Solar Power Best Practices Study*. Retrieved from https://www.nrel.gov/docs/fy20osti/75763.pdf

Mehos, M., Price, H., Cable, R., & Kearney, D. (2020). *Concentrating Solar Power Best Practices Study.* https://www.nrel.gov/docs/fy20osti/75763.pdf: National Renewable Energy Laboratory. NREL/TP-5500-75763.

NREL. (2020b). *Concentrating Solar Power Projects*. Retrieved from https://solarpaces.nrel.gov/

Proparco. (2020, 11 27). *Proparco - Groupe Agence Française de Développement*. Retrieved from https://www.proparco.fr/en reve. (2020, 2 7). *reve*. Retrieved from https://www.evwind.es/2020/02/07/the-closure-of-solarreserve-an-isolated-case-of-the-concentrated-solar-power-industry/73461

Röger, M., Blume, C., Schlichting, T., & Collins, M. (2020). Status Update of the SolarPACES Heliostat Testing Activities. *SolarPaces Conference.*

Smith, D. (1992). Design and optimization of tube-type receiver panels for molten salt application. *Solar Engineering 2*, pp. 1029-1036.

SolarPACES. (2011). *guismo project*. Retrieved from http://www.solarpaces.org/wp-content/uploads/SolarPACES_ATR_2011.pdf

SolarPACES. (2017). *Guideline*. Retrieved from SolarPACES Guideline for Bankable STE Yield Assessment: http://www.solarpaces.org/wp-content/uploads/SolarPACES_Guideline_for_Bankable_STE_Yield_Assessment_-_Version_2017.pdf

SolarPACES. (2020). *CSP projects around the world*. Retrieved from https://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/

TEC-SRS. (2008). *TRL Handbook, issue 1 revision 6, TEC-SHS/5551/MG/ap.*

Thonig, R. (2020, 11 27). *CSP.guru Energy Transition Dynamics group, IASS Potsdam*. Retrieved from https://csp.guru/data.html

VDI. (2006). *VDI-Wärmeatlas (10. Auflage).* VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen .

VdTÜD. (2009). *Werkstoffdatenblatt 546 12.2009.*

Weinrebe, G., Giuliano, S., Buck, R., Macke, A., Burghartz, A., Nieffer, D., . . . Blume, K. (2019). *HELIOKONTUR+ Kostensenkung bei Solarturmkraftwerken durch optimierte Heliostatkonturen plus angepasstes Turm- und Felddesign.* TIBKAT 1697318746.

World Bank Group. (2020, 11 27). *IBRD Financial Products*. Retrieved from https://treasury.worldbank.org/en/about/unit/treasury/ibrd-financial-products/ibrd-flexible-loan#1

Younger, D. (2017). IFC's Project Financing of Concentrated Solar Power Plants: Workshop on CSP Markets, System Value & Financing.

9. Appendix

9.1. Different configurations

Name	Short name	Configuration	Atmos -phere	Salt temperatures	Design Receiver power	Receiver type	Storage capacity
				[°C]	[MW_{th}]		[hours]
Nighttime operation	V 1 - 200 MW	200 MW night time operation	clear	290 - 565	700	External	> 12h
Peaker operation	V 2 – 2* 200 MW	400 MW peaker	clear	290 - 565	700	External	5 – 6 h

9.2. General Specifications: Site, Fluid Properties, Heliostats

No.	Specifications	Unit	Value	Remark
	Site			
1.	Site		Ouarzazate (Morocco)	
2.	Latitude	[°] N	31.06	
3.	Longitude	[°] E	-6.87	
4.	Height above sea level	[m]	1288	
	Design Point			
5.	Annual sum of DNI	[kWh/m²a]	2518	Source: Meteonorm 6.1
6.	Ambient temperature (min / max /mean)	[°C]	-0.3 / 18.8 / 38.9	Source: Meteonorm 6.1
7.	Rel. Humidity (mean)	[%]	38	Source: Meteonorm 6.1
8.	Ambient pressure	[mbar]	890	Source: Meteonorm 6.1
9.	Wind velocity (mean / max.)	[m/s]	3.3 / 13.0 (hourly)	Source: Meteonorm 6.1, @10 m above ground
10.	Atmospheric extinction Clear sky		$\eta_{atmo} = 0.99321 - 0.0001176 \cdot \mathrm{SLR}^2 + 1.97 \cdot 10^{-8} \cdot \mathrm{SLR}^2$ for SLR ≤ 1000m. $\eta_{atmo} = e^{-0.0001106 \cdot SLR}$; for SLR > 1000m	
	Heat transfer fluid			
11.	Heat transfer fluid (HTF)		Solar Salt	Solar Salt: 60% $NaNO_3$ + 40%KNO_3
12.	Density @ 290°C	[kg/m³]	1906	See Appendix 5.1
13.	Specific heat capacity @ 290°C	[kJ/kk K]	1.493	See Appendix 5.1
14.	Dynamic viscosity @ 290°C	[mPa s]	3.5	See Appendix 5.1

No.	Specifications	Unit	Value	Remark
15.	Operating temperature range	[°C]	min. 260 , max. 585	
	Heliostat			
16.	Heliostat Type	[-]	2-axes tracking multi facet glass-metal heliostat, mounted on pylon	Stellio Type
17.	Apertur width	[m]	~ 9 m	
18.	Apertur height	[m]	~ 9 m	
19.	Number of mirrors per heliostat	[-]	10 + 1	horizontal x vertical
20.	Reflektive area of single mirror	[m²]		
21.	Optical height (Pylon)	[m]	~4.5	Center of heliostat
22.	Total reflective area per heliostat	[m²]	48.5017	
23.	Reflectivity HFLCAL (annual mean)	[%]	89.34	as product of reflectivity, cleanliness, availability: 0,94*0,96*0,99
24.	Beam quality	[mrad]	3.0	No wind
25.	Canting	[-]	On-axis	
26.	Electricity consumption tracking	[kW]	~0.02	Mean demand of single heliostat Peak 0.18 kW
27.	Slope error	[mrad]	1.06	1 dim, v_wind < 4 m/s
28.	Tracking error	[mrad]	0.6	V_wind < 4 m/s
29.	Root mean square deviation of sun-shape	[mrad]	2.73	

9.3. Technical Specifications

No.	Specification	Unit	Plant designed for night time operation Value	Plant designed as peaker Value	Remark
	Solar field				
	Solar Multiple (SM)	[-]	1.6	0.8	
30.	Shape	[-]	360°		Surround field
31.	Number of Heliostats	[-]	30’927		1.5 km² mirror area
32.	Optical efficiency @DP	[%]	68.2		
33.	Tracking error	mrad (RMS)	0.5		3-s-wind speed < 4 m/s @ 10 m
34.	Slope error	mrad (RMS)	1.28		3-s-wind speed < 4 m/s @ 10 m
35.	Distance tower – first row	[m]	130		Distance from tower center to first row of heliotstats for 200 m receiver centroid height
36.	Land usage	[km²]	8.1		
	Tower				
37.	Number of towers	[-]	1		
38.	Height	[m]	~220		Incl. Receiver
39.	Diameter	[m]	~20		Considered for shadowing
	Solar Receiver				
40.	Type		Extern, cylinder, tube receiver		
41.	Optical height receiver	[m]	200		Height receiver-mid
42.	Aperture area	[m²]	1305		
43.	Receiver height h	[m]	22.8		Height for solar field design
44.	Receiver diameter d	[m]	18.8		Apparent diameter for solar field design
45.	h/d-ratio (aspect ratio)	[-]	1.21		
46.	Thermal power @DP	[MW_{th}]	700		(heat input by pump not considered)
47.	Thermal receiver efficiency @DP Without wind	[%]	89.4		(heat input by pump not considered)
48.	Nominal salt temperature at receiver entrance	[°C]	290		
49.	Nominal salt temperature at receiver exit	[°C]	565		
50.	Nominal salt mass flow	[kg/s]	1669		
51.	Flux density at aperture (max. / mean)	[W/m²]	945 / 634		
52.	Angle of receiver	[°]	0		Angle between receiver normal and ground
53.	Pressure-loss in receiver	[bar]	13.7		

No.	Specification	Unit	Plant designed for night time operation Value	Plant designed as peaker Value	Remark
54.	Geodetic delta of pressure overall receiver	[bar]	5.1		
55.	Overpressure receiver	[bar]	0		Adjusted by control valve (no additional pressure-loss)
56.	Pressure-loss control valve	[bar]	2		2 bar at 1102.26 kg/s (Cloud-Standby im Design point)
57.	Pressure-loss connection pipes receiver	[bar]	0.5		Connecting pipes from Inlet to outlet vessel
58.	Pressure inlet vessel @ DP	[bar]	20		Sum of pressure-loss receiver + periphery Is controlled to constant value
59.	Geodetic delta of pressure in riser	[bar]	35.3		
60.	Pressure-loss in riser	[bar]	0.6		
61.	Nominal pressure pump	[bar]	57.9		Sum of pressure-loss inlet vessel + riser + connecting pipes
62.	**Inlet, outlet & emergency vessel**				
63.	Emergency flushing time	[s]	30		
64.	Volume inlet vessel	[m³]	77.7		
65.	Height inlet vessel	[m]	9.2		
66.	Volume outlet vessel	[m³]	55.2		
67.	Height inlet vessel	[m]	6.7		
68.	Volume emergency vessel	[m³]	80		
69.	Height emergency vessel	[m]	9.4		
	Molten salt pumps				
70.	Configuration of cold salt pumps	[%]	6 * 20		Number of pumps and percentage of total power
71.	Minimum part load of single cold salt system	[%]	15		
72.	Maximum load of cold salt pumps	[%]	120		Operating boundary receiver
73.	Nominal power consumption per cold salt pump	[kW]	1800		
74.	Nominal efficiency cold salt pumps	[%]	76		
75.	Nominal head of cold salt pumps	[m]	329		
76.	Nominal capacity per cold salt pump	[m³/h]	786		
77.	Configuration of hot salt pumps	[%]	4*50	6*25	Number of pumps and percentage of total power

No.	Specification	Unit	Plant designed for night time operation Value	Plant designed as peaker Value	Remark
78.	Minimum part load of single hot salt system	[%]	25		
79.	Maximum load of hot salt pumps	[%]	110		Operating boundary steam generator / PB
80.	Nominal power consumption per hot salt pump	[kW]	440		
81.	Nominal head of hot salt pumps	[m]	65		
82.	Nominal capacity per hot salt pump	[m³/h]	1127		
83.	Nominal efficiency hot salt pumps	[%]	76		
	Storage				
84.	Type		1 cold and 2 hot salt tanks		
85.	Storage medium		Solar Salt		Solar Salt: 60% $NaNO_3$ + 40%KNO_3
86.	Capacity	[MWh]	5967		
87.	Capacity in full load hours	[h]	13	6.5	
88.	Nominal pressure	[bara]	1		Open to the atmosphere
89.	Operating temperature – hot tank	[°C]	565		
90.	Volume per hot tank	[m³]	16900		
91.	Operationg temperature – cold tank	[°C]	290		
92.	Volume cold tank	[m³]	30600		
93.	Shell height (all tanks)	[m]	12.5		
94.	Storage heat losses	[%/d]	1.08		Loss per day in percentage of overall capacity
	Steam Generator				
95.	Steam generator type		Natural convection		
96.	Nominal heat delivered per unit	[MW_{th}]	230		
97.	Number of units		2	4	2 units for one 200 MW power block
98.	Nominal salt mass flow rate	[kg/s]	582		Per SG unit
99.	Molten salt inlet temperature	[°C]	560		
100.	Molten salt inlet pressure	[bara]	4		
101.	Molten salt outlet temperature	[°C]	301		
102.	Pressure drop molten salt	[bar]	2.5		
103.	Steam mass flow rate (LS/RH)	[kg/s]	83 / 75		Per steam generator unit
104.	Steam pressure abs. (LS / RH)	[bara]	140 / 37.4		
105.	Steam temperature (LS / RH)	[°C]	550 / 550		
106.	Pressure drop (LS/ RH)	[bar]	6 / 3.1		

No.	Specification	Unit	Value Plant designed for night time operation	Value Plant designed as peaker	Remark
107.	Feed water temperature	[°C]	245		
108.	Feed water pressure	[bara]	146		
109.	Volume drainage tank	[m³]	133	264	
110.	Length drainage tank	[m]	8	10	
111.	Nominal head drainage pump	[m]	40		
112.	Nominal capacity drainage pump	[m³/h]	95	190	
113.	Nominal efficiency drainage pump	[%]	76		
	Steam turbine				
114.	Type of steam turbine		Single reheat condensing		
115.	Gross nominal output	[MW_{el}]	200	2 * 200	
116.	Heat input	[MW_{th}]	459	2 * 459	
117.	Gross cycle efficiency	[%]	43.6		
118.	Live steam conditions ▪ pressure ▪ temperature ▪ mass flow rate	[bara] [°C] [kg/s]	140 550 174	140 550 2*174	
119.	Reheat steam conditions ▪ pressure ▪ temperature	[bara] [°C]	41 550		
120.	Steam conditions at turbine outlet ▪ pressure ▪ temperature ▪ quality	[mbar] [°C] [kg/kg]	135 51.8 0.936		
	Condenser				
121.	Condenser type		ACC		Condenser fans equipped with variable speed drives
122.	Nominal heat flow	[MW_{th}]	264	2*264	
123.	Steam mass flow rate	[kg/s]	116	2*116	
124.	Nominal power consumption	[MW_{el}]	6.6		Strong decrease in part load
	Overall plant				
125.	Number of steam turbines	[-]	1	2	
126.	Nominal output (gross)	[MW_{el}]	200	400	
127.	Nominal output (net)	[MW_{el}]	188	376	Cold salt pumps are not operating
128.	Heat input power block	[MW_{th}]	459	918	
129.					

No.	Specification	Unit	Plant designed for night time operation Value	Plant designed as peaker Value	Remark
	Dynamical behavior				
130.	Nominal power consumption during storage charging	[MW_{el}]	8.4		During the day at nominal receiver load
131.	Therm. Energy consumption steam generator and power block	[MWh_{th}]	230	2 * 230	For cold start
132.	Start-up time steam generator and power block	[h]	2		
133.	Solar field / receiver start-up energy	[MWh_{th}]	41		

9.4. Cost and Financial Parameters

	Specic investment costs				
134.	Solar Field	[€/m²]	100		Based on reflecting area
135.	Tower cost	[€/m]	61706		Height measured from ground to center of receiver. For the 200 m tower
136.	Receiver system	[€/kW_{th}]	70		Based on design thermal power transferred to the molten salt Including cold salt pumps
137.	Land	[€/m²]	1		Per land area, only for preparation, fence, roads etc. Actual land costs assumed 0
138.	Thermal storage	[€/kW_{th}]	21		Including solar salt and hot salt pumps
139.	Powerblock incl. ACC and steam generator	[€/kW_{el}]	810		
140.	Balance of plant	[€/kW_{el}]	322	254	
	Financial parameters				
141.	Interest rate	[%]	6		Varied during parameter study 3 - 6
142.	Lifetime	[a]	25		Varied during parameter study 25 - 35
143.	Surplus for indirect cost	[%]	20		Varied during parameter study 15 - 20
	O&M				
144.	Annual O&M cost incl. insurance replacement, electrity, water, etc.	[%/a]	3		Based on total investment costs (delivery, installation, commissioning, and indirect costs)

145.	Cost for electricity from the grid	[€/kWh]	0.10	Might be reduced with a PV plant close by to provide electricity for SF operation during daylight hours
146.	Annual insurance cost	[%/a]	0.7	Based on total investment costs

9.5. Solar Salt Properties

Heat transfer fluid and storage material is Solar Salt (60% $NaNO_3$ + 40%KNO_3 by weight). In literature one may find varying properties. We have used the following ones.

Properties of fluid Solar Salt

Property	Symbol	Value	Unit	Comment
Minimal temperature	T_{min}	290	°C	30°C above Liquidus
Maximal temperature	T_{max}	560 (Air)	°C	To limit decomposition
Heat capacity	c_p	1443 + 0.172 * (T in °C)	J/(kgK)	
Density	ρ	2090 – 0.636 * (T in °C)	kg/m³	
Viscosity	μ	22.714 – 0.12 * (T in °C) + 2.281E-4 * (T in °C)^2 – 1.474E-7 * (T in °C)^3	mPa s	
Heat conductivity	k	0.443 + 1.9E-4 * (T in °C)	W/(mK)	

References:

Bonk, A., Sau, S., Uranga, N., Hernaiz, M., Bauer, T. Advanced heat transfer fluids for direct molten salt line-focusing CSP plants. Progress in Energy and Combustion Science 67 (2018). http://dx.doi.org/10.1016/j.pecs.2018.02.002

Pacheco J, Ralph M, Chavez J, Dunkin S, Rush E, Ghanbari C, et al. Sand 94-2525: Results of molten salt panel and component experiments for solar central receivers. Technical Report Albuquerque: Sandia National Laboratories; (1995).

9.6. Guideline for Heliostat Performance Testing

HELIOSTAT PERFORMANCE TEST	
Photo or simplified scheme of general heliostat configuration	
Heliostat manufacturer name	HeliostatFactory
Name of heliostat model	Superb
Serial number(s) or other identifier(s)	P4
Total number of heliostats investigated	1
Name and address of testing laboratory	R&D Testing Center, Street Name, City, Country
Testing location	Plataforma Solar de Almería, 04200 Tabernas, Spain
Date of testing period	30.04.17 - 30.07.17
Date of erection of heliostat	01.04.17
Reference to guideline version	SolarPACES Heliostat Performance Guideline v0.99 from 21.08.18
Report format	This report and data CD
Date, signature and stamp of independant qualification organization/company	

Figure 56: Typical testing report of a sample heliostat (1)

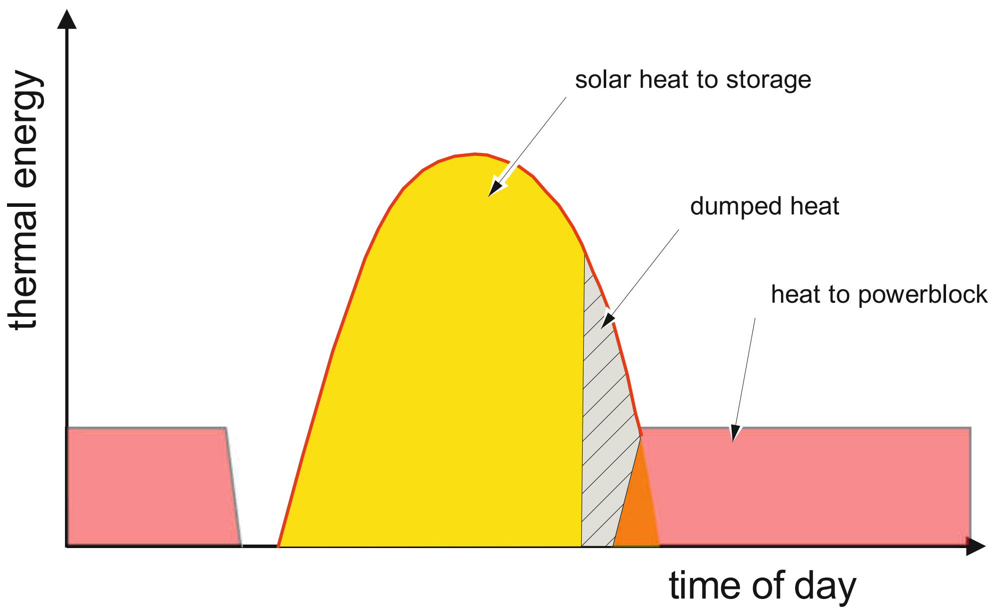
n	Full Parameter Name (Symbol)	Value	Unit	Meas.Technique	Measurement Report
1	HelioConfig.General.Type	T-shape	-	-	
2	HelioConfig.Conc.Outline	rectang.	-	-	
3	HelioConfig.Conc.Dimension	[6.6; 6.7]	m	Laser dist.meter	Hel_Main.pdf
4	HelioConfig.Conc.ReflectiveArea	40.1	m²	Laser dist.meter	Hel_Main.pdf
5	HelioConfig.Panel.Outline	rectang.	-	-	
6	HelioConfig.Panel.Dimension	[3.0; 1.1]	m	Laser dist.meter	Hel_Main.pdf
7	HelioConfig.Panel.Number	[2; 6]	-	-	
8	HelioConfig.Panel.Type	glass mirror panels	-	-	
9	HelioConfig.Panel.Material	silver coated glass	-	-	
10	HelioConfig.Axes.Alignment	[az. axis vert.; el. axis horiz.]	-	-	
11	HelioConfig.Axes.HeightOfSecondaryAxis	2.14	m	Laser dist.meter	Hel_Main.pdf
12	HelioConfig.Axes.DistanceConcToSecondaryAxis	0.1	m	Tape meter	Hel_Main.pdf
13	Optics.Panel.CurvatureMounted	flat	-	-	
14	Optics.Panel.CurvatureMethod	tension-less	-	-	
15	Optics.Conc.NominalShape	parabolic	-	-	
16	Optics.Conc.NominalShapeNumericValue	[55] or [25;1500] or matrices	m	-	
17	Optics.Conc.HelioRefOrientationTemp	[az=0°; el=30°; T=20°C]	-	Inclinometer	Hel_Shape.pdf
18	Optics.Conc.SD_SamplingRate	1000	values/m2	-	Hel_Shape.pdf
19	Optics.Conc.SD_ShareEvalSurf	97	%	-	Hel_Shape.pdf
20	Optics.Conc.SD_2D	RMS: 2.06 (100%)	mrad	Deflectometry	Hel_Shape.pdf
21	Optics.Conc.SD_2D*	RMS: 1.54 (98%)	mrad	Deflectometry	Hel_Shape.pdf
22	Optics.Conc.SD_2DHighFraction	RMS: 9.83 (2%)	mrad	Deflectometry	Hel_Shape.pdf
23	Optics.Conc.SDx /SDrad	RMS: 1.76 MEAN: 0.19 STD: 1.76 (100%)	mrad	Deflectometry	Hel_Shape.pdf
24	Optics.Conc.SDx* /SDrad*	RMS: 1.10 MEAN: 0.00 STD: 1.11 (98%)	mrad	Deflectometry	Hel_Shape.pdf
25	Optics.Conc.SDxHighFraction/ SDradHighFraction	RMS: 9.75 MEAN: 9.75 STD: 0.35 (2%)	mrad	Deflectometry	Hel_Shape.pdf
26	Optics.Conc.SDy /SDtan	RMS: 1.08 MEAN: -0.03 STD: 1.09 (100%)	mrad	Deflectometry	Hel_Shape.pdf
27	Optics.Conc.SDy* /SDtan*	RMS: 1.08 MEAN: -0.03 STD: 1.09 (100%)	mrad	Deflectometry	Hel_Shape.pdf
28	Optics.Conc.SDyHighFraction / SDtanHighFraction	RMS: - MEAN: - STD: - (0%)	mrad	Deflectometry	Hel_Shape.pdf
29	Optics.Conc.SD_NonGaussianDistr	No	-	Deflectometry	Hel_Shape.pdf

Figure 57: Typical testing report of a sample heliostat (2)

30	Optics.Conc.SDmat	2 matrices, see CD	mrad	Deflectometry	Hel_Shape.pdf +CD
31	Optics.Conc.SD_NonResolvedStruct	No	-	Deflect.+Visual	Hel_Shape.pdf
32	Optics.Conc.SD_DiffBetwRegions	No	-	Deflect.+Visual	Hel_Shape.pdf
33	Optics.Conc.DefGravity_deltaSDmat	5 x 2 matrices and elevation vector, see CD	mrad	Photogrammetr.	Hel_Shape.pdf +CD
34	Optics.Conc.DefTemp_deltaSDmat_perK	2 matrices, see CD	mrad/K	Photogrammetr.	Hel_Shape.pdf +CD
35	Optics.Reflectance.SolarWeightedSpecular2.3	92.5	%	Reflectom.	Refl_Report.pdf
36	Optics.Focus.Variability	fix focal length	-	-	
37	Tracking.Axes.Concept	[el.motor/gear dr.; el.motor/gear dr.]	-	-	
38	Tracking.Axes.Control	[closed loop; cl. loop]	-	-	
39	Tracking.Axes.MinMaxRangeAxis1	[-80; 80]	°	Inclinometer	Hel_Main.pdf
40	Tracking.Axes.MinMaxRangeAxis2	[-180; 180]	°	Inclinometer	Hel_Main.pdf
41	Tracking.Accuracy.Track_2D	RMS: 1.06	mrad	Beam on target	Hel_Track.pdf
42	Tracking.Accuracy.Track_ax1	RMS: 0.75 MEAN: 0.01 STD: 0.75	mrad	Beam on target	Hel_Track.pdf
43	Tracking.Accuracy.Track_ax2	RMS: 0.75 MEAN: 0.00 STD: 0.75	mrad	Beam on target	Hel_Track.pdf
44	Tracking.Accuracy.TrackingTimeCorrelationAx1Ax2	[0.1; -0.2]	-	Beam on target	Hel_Track.pdf
45	Tracking.Accuracy.TrackingAx1Ax2Correlation	0.2	-	Beam on target	Hel_Track.pdf
46	Tracking.Safety.EmergDefocusTime	[15; 20]	s	Inclinom.+Clock	Hel_Track.pdf
47	Tracking.Safety.StowPosition	face down, -10°	- /°	Inclinometer	Hel_Track.pdf
48	Control.Instrumentation.Communication	wired, RS485	-	-	
49	Control.Power.SupplyType	electrical	-	-	
50	Control.Power.InputType	230 V	-	-	
51	Control.Power.InputPowerEmergDefocus	[397; 450] @ 21°C	W	Power meter	Hel_Power.pdf
52	Control.Power.InputPowerColdStart	[189; 200] @ 15°C	W	Power meter	Hel_Power.pdf
53	LimitsTol.WindSpeed.NormalOperation	8	m/s	-	
54	LimitsTol.WindSpeed.ReducedOperation	20	m/s	-	
55	LimitsTol.WindSpeed.GustSurvival	40	m/s	-	
56	LimitsTol..OperatingTemp	[-20;50]	°C	-	
57	LimitsTol.Lifetime.Overall	25	years	-	
58	Cost..Total	1'900 (Morocco)	€	-	
59	Cost..SpecificWithoutFoundation	120	€/m²	-	

Figure 58: Typical testing report of a sample heliostat (3)

9.7. Operation of the plant



Operating scheme of the plant in night time operation mode