Techno-economic Optimization of CSP Plants
Towards a more competitive plant design and operation

Dr. Rafael Guédez
Researcher – Energy Department
rafael.guedez@energy.kth.se

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Agenda

• Introduction
  • KTH – CSP R&D Group
• CSP Technology Basis
• CSP Market Today
  • Outlook, Drivers and Prices
  • Project Development of CSP plants
• Techno-economic Optimization
• KTH DYESOPT in-house tool
  • Case Study for South Africa
• Conclusions
Introduction: about me

• Lead Researcher in Solar Power (CSP and PV) and Techno-economic Modeling at KTH
• Lecturer and course responsible for Large-Scale Solar Power in KTH
• Project Manager and Performance Analyst Expert at Cleanergy AB
• Director and Solar Energy Consultant at EPS

Previous Experience

• Researcher in PV-BESS and CSP plant optimization at KTH
• R&D Engineer in Solar Energy Unit at Total New Energies
• R&D Engineer at Moroccan Agency for Solar Energy

Education

• PhD in CSP Plant Techno-Economic Performance Modeling – KTH
• Mechanical Engineering – Universidad Simon Bolivar (Venezuela)
Introduction: KTH

- Sweden’s oldest Technical University
- Founded in 1827
- +12000 students
- 10 Schools
- World Rankings:
  - 36 (Times - Engineering 2017)
  - 25 (QS Top Universities – Energy Engineering 2016)
Introduction: KTH

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Introduction: KTH CSP R&D Group

- Thermo-mechanical analysis and testing of solar power plant components.
- Techno-economic optimization of solar power plant design and operation.
- Thermal energy storage integration and hybridization strategies.
- Receiver design and testing at indoor solar simulator.
Introduction: KTH CSP R&D Group

- + 20 MSc Students and affiliates
- In close collaboration with industry and other R&D institutes
CSP: Technology Basics

3 Main Blocks: Solar Field, TES, Power Block
CSP: Technology Basics

SOLAR ENERGY → HIGH TEMPERATURE HEAT → ELECTRICITY

THERMAL ENERGY STORAGE (TES)

HYBRIDIZATION

Linear Fresnel reflector (IFR)
Central receiver
Parabolic dish
Parabolic trough

© DLR
CSP Market Today

**Installed Capacity**
- **6 GWe**
- **80%** Parabolic Trough
- **20%** Tower
- **70%** w/ STORAGE

Spain 2.4 GW - USA 1.9 GW

**Tendered - Under Construction**
- **2 GWe**
- **50%** Parabolic Trough
- **50%** Tower
- **100%** w/ STORAGE

China 1 GW - Morocco 0.7 GW
CSP Deployment Drivers

- **Technical**: Renewable and dispatchable (highly efficient and reliable storage)
- **Macroeconomic**: Local content of CSP plants is one of largest for renewable projects
- **Technical Developments** – Higher efficiencies
- **Cost Developments**:

![Graph showing reduction in installed cost over time with different scenarios]
CSP 2030 Market Outlook and Scenarios

SOLARPACES - ESTELA (2016)

Current policy
27 GWe

Moderate policy
130 GWe

IRENA (2014)
87 GWe

IEA 2D (2015)
155 GWe

* For a 200$/kWh combined battery and battery BOS costs and increased lifetime
* For PV systems (module + BOS) of 1$/W
CSP Market Outlook: Prices

- CSP is generally seen as less competitive on the basis of $/MWh
- We are seeing aggressive PPA bids, yet higher than other renewables e.g. PV
- It is now being understood that its value relies on its dispatchable attribute.

This has led to tech-specific tenders with time-of-use tariffs (hourly)

This means that the optimum design and operation of each plant is unique to each tender and location
CSP Project Development: Bid Tenders

There are multiple stakeholders involved in the value-chain of the development of a CSP plant under a competitive bid tender. Each one with different interest → so PPA price is not the only design objective.

This makes the optimum design and operation more challenging and also dependent on the actual stakeholder.
a number of design objectives shall be considered in the evaluation of CSP plants and also dependent on the stakeholder

These are all relevant decision criteria and often conflicting

Optimization Trade-offs
CSP Performance Indicators

**TECHNICAL**

- Annual Yield ($E_{\text{net}}$) [GWh]
- Capacity Factor (CF) [%]

\[
\text{Annual Yield} = \frac{\text{Annual Yield}}{8760 \times \text{Nominal Capacity}}
\]

**ENVIRONMENTAL**

- Annual Specific CO₂ Emissions [kg CO₂/MWh]
  \[
  \frac{\text{Annual CO₂ Emissions}}{\text{Annual Yield}}
  \]

**FINANCIAL (Costs)**

- Investment Costs (CAPEX) [$]
- Annual Operational Costs (OPEX) [$/y]
CSP Performance Indicators

FINANCIAL (Performance)

Levelized Cost of Electricity [$/MWh]

\[
LCOE = f(CAPEX, OPEX, Yield, DR)
\]

\[
DR = WACC = f\left(\frac{Eq}{Debt}, IRR_{Eq}, i_{debt}\right)
\]

Constant price for breakeven

Internal Rate of Return (IRR) [%]

\[
IRR = DR \rightarrow NPV = 0
\]

\[
NPV = \begin{cases} 
\text{Disc. Cash inflows} \\
- \text{Disc. Cash outflows}
\end{cases}
\]

Project acceptable if
IRR Project > IRR min (owners)

Higher IRR project → better
CSP Performance Indicators

FINANCIAL (Performance)

Levelized Cost of Electricity [$/MWh]

\[ \text{LCOE} = f(\text{CAPEX}, \text{OPEX}, \text{Yield}, \text{DR}) \]

\[ \text{DR} = \text{WACC} = f\left(\frac{\text{Eq}}{\text{Debt}}, \text{IRR}_{\text{Eq}}, i_{\text{debt}}\right) \]

Constant price for breakeven

Minimum PPA Price [$/MWh]

\[ \text{min Price at which IRR project} \geq \text{WACC} \]

Different from LCOE

depends on hourly tariff schemes and usually public numbers relate to average or base PPA price
CSP Techno-economic Modeling

a number of design objectives shall be considered in the evaluation of CSP plants and also dependent on the stakeholder.

These are all relevant decision criteria and often conflicting.

Optimization Trade-offs
DYEOPT - Power Plant Modeling

The Dynamic Energy System Optimizer is a simulation tool developed for the techno-economic design and operation optimization of power plants

- With +7 years of R&D in academia
- With +30 publications as part of +8 R&D projects with industry

DYEOPT

for power plant design and operation

technical + financial plant performance models tailored to requested degree of detail
Power Plant Modeling in DYESOPT

Design Objectives (e.g. min LCOE and max CF)

Location
Cost Model
Input Limits

PROCESS 4: Multi-Objective Optimization

Select Inputs: Tech, Financial, Weather

PROCESS 1: Power Plant Design Component Sizing

PROCESS 2: Annual Dynamic Simulation

PROCESS 3: Techno-economic Calculations

Techno-Economic Indicators (e.g. LCOE)

Optimization Trade-Offs (e.g. min LCOE vs max CF)
Process 1: Power Plant Nominal Design

Nominal design for specific conditions
e.g. Solar positioning and Irradiance (Location)

**SOLAR FIELD SIZE (SM)**
- Mirror area / reflectivity
- Receiver Rating / geometry
- Tower height

**TES CAPACITY**
- Tank specs
- Loss Coefficients
- Minimum tank levels

**POWER BLOCK CAPACITY**
- Cycle Layout Design
- Live steam and reheat conditions

**MULTI-PARAMETER**
- NOMINAL DESIGN FOR SPECIFIC CONDITIONS
- e.g. Solar positioning and Irradiance (Location)
Process 2: Annual Dynamic Simulation

**INPUTS:** plant size, weather, TES dispatch-strategy, start-up limitations

**OUTPUTS:** hourly generation, yield, capacity factor, ...

Example: Simplified model of a 100 MWe molten salt CSP tower plant with 6h storage (TES) for spot market in Seville, Spain
Process 3: Techno-Economic Calculations

BOTTOM-UP COST MODEL – LOCATION AND TECH DEPENDENT

Local Economics
(e.g. discount rate)

Market Conditions
(e.g. electricity price)

\[ C_n = C_{ref,n}(X_n/X_{ref,n})^{yn} \]

Ref. Data: Literature / Quotations / Industry Reports / Industry coop
Process 4: Multi-Objective Optimization

To identify Trade-Off Curves between conflicting objectives

To provide decision-makers with universe set of solutions

A, B and C are optimal configurations
D is sub-optimal (’naive design’)

Genetic Algorithms used to address:
- Discontinuities / non-linearity
- Local optima
DYEOSOPT – Case study

OBJ 1: Minimize Investment (CAPEX)
OBJ 2: Maximize Profits (IRR_{PROJECT})

Location Data (i.e. Meteo & economics)
- Technical Reports
- Industry
Sizing and operation of sub-blocks has a clear impact

PB size, SF size, TES size and dispatch are decisive
Case Study: Influence of Price Tariffs

S1: Two-Tier Tariff

S2: Pool Price Tariff (WEPS)

S3: Fixed Daytime Tariff

IRR [%] vs. CAPEX [USDx10^6]

Gross Power [MWe]
Case Study I: Influence of Price Tariffs

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<td>353.1</td>
<td>99.6</td>
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<td>20.9</td>
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Optimums are different for different market conditions
One should not compare projects built under different conditions / locations
DYESOPT: Power Plant Models

- Molten Salt Solar Tower Plant (e.g. Crescent Dunes type)
- Molten Salt Solar Tower Plant with Thermocline Storage Tank
- Direct Steam Generation Tower Plant (e.g. Ivanpah)
- Parabolic Trough CSP Plant

- Hybrid Solar Gas Turbine Power Plant
- Hybrid Parabolic Trough CSP Plant (e.g. Shams)
- Hybrid Solar Tower with 2-tank TES and PV (e.g. Midelt CSP)

- Utility-scale PV power plant (optional BESS and tracking)

- Combined Heat and Power (CHP) Plant
- Combined Cycle Gas Turbine (CCGT) Plant
Models can be used to:

- Evaluate performance of specific plant configurations
- Identify optimum plant configurations for a location
- Determine impact of using new technology and components
- Evaluate feasibility of new power plant concepts and hybrids
- Determine impact of storage and operation strategies
- Determine impact of technical operational enhancements

to assist investment and decision-making

Research – Policy – Developers – OEMs
Engineering (EPCs) – Investors – Operators
Key Takeaways

• CSP is positioning as the most competitive solar-only technology for large capacity factors – its deployment though requires of adequate policy design

• The design and operation of a power plant is dependent on the location and policies i.e. weather, remuneration schemes, and financials

• At KTH we work on understanding the impact of tender design, cost projections and technology advancements on the optimum design and operation of CSP plants. We collaborate with R&D and industry.

• This work is needed to support decision making throughout the whole value chain: R&D – Policy – Development – Engineering – Operation

• We have started a collaboration with STERG in which we share modeling tools and experience for joint publications - we look forward to expanding our collaboration.
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