Techno-economic Optimization of CSP Plants

Towards a more competitive plant design and operation

KTH Industrial Engineering and Management

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Stellenbosch University, Stellenbosch

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)***

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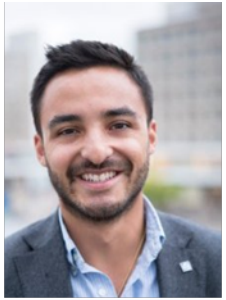
Introduction: KTH CSP R&D Group

Dr. Björn Laumert,
Assoc. Professor



Dr. Rafael Guédez
Researcher

Dr. Wujun Wang
Post-Doc

Lukas Aichmayer
PhD Candidate

Monika Topel
PhD Candidate

Jorge Garrido
PhD Candidate

Monica Arnaudo
PhD Candidate

- 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

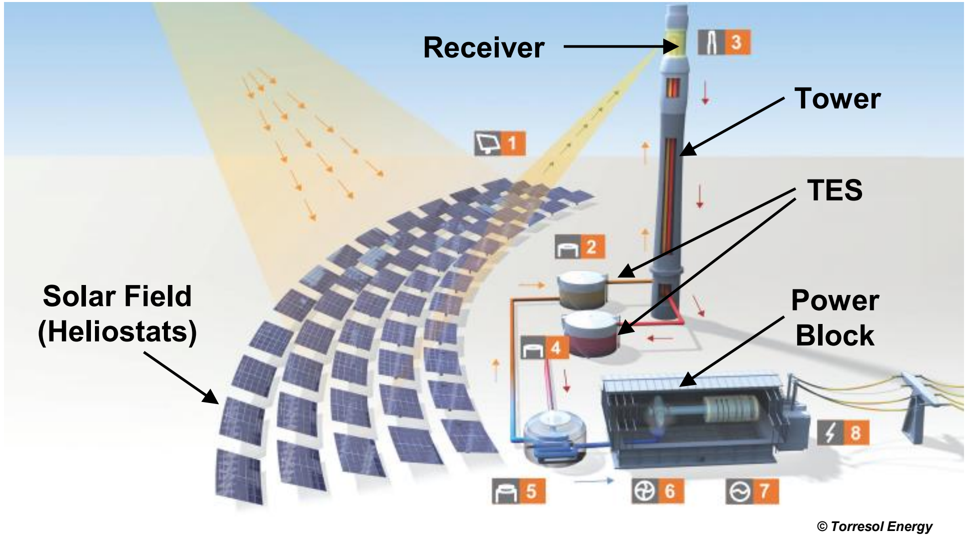
SOLARRESERVE
AALBORG CSP - your green thermal energy partner
gasNatural fenosa
eit KIC InnoEnergy
TOTAL
MASciR Moroccan Foundation for Advanced Science, Innovation and Research
DTU
EUROPEAN TURBINE NETWORK
Swedish Energy Agency
SIEMENS
ALFA LAVAL
VATTENFALL
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
LUND UNIVERSITY
e.on
UPC
ROMA TRE
CLEANERGY

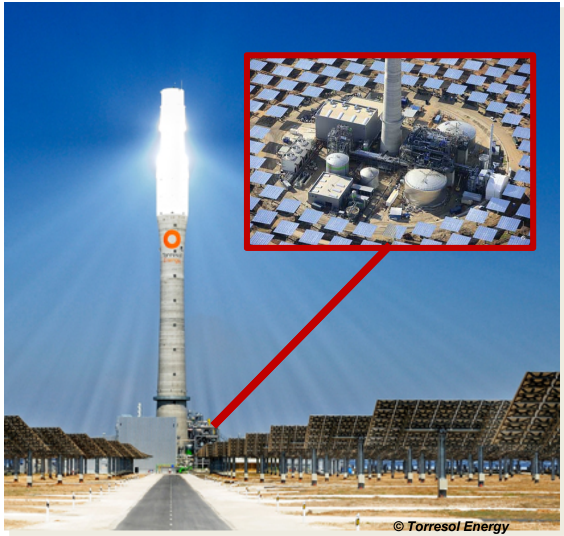
CSP: Technology Basics

THERMAL ENERGY STORAGE (TES)

SOLAR ENERGY → HIGH TEMPERATURE HEAT → ELECTRICITY

HYBRIDIZATION





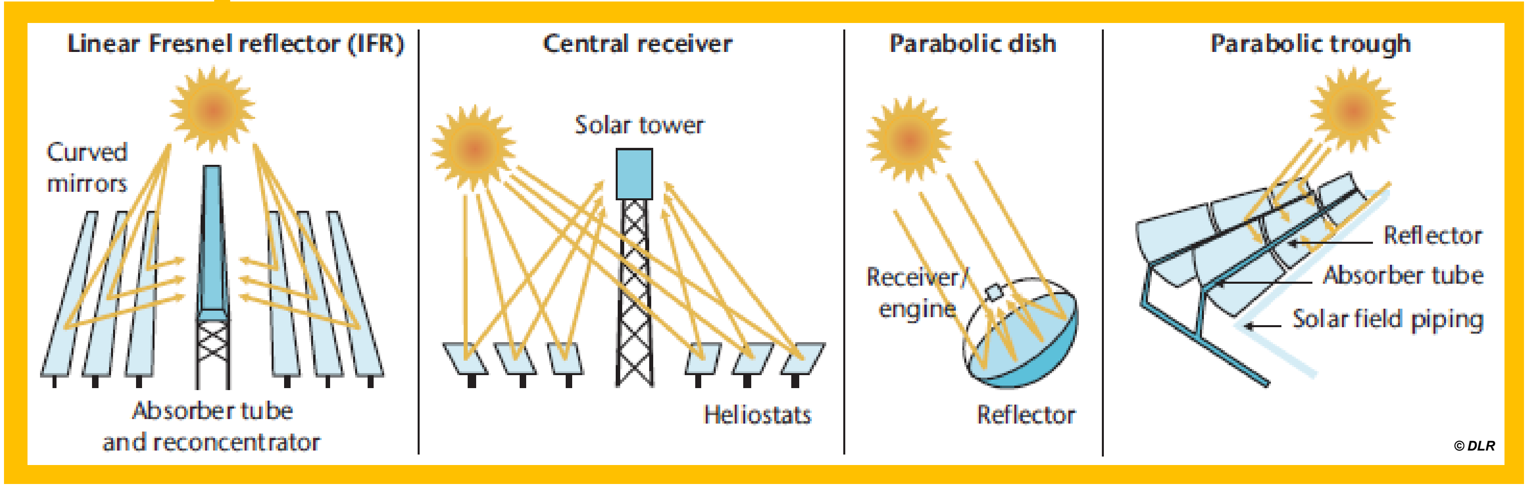
3 Main Blocks: Solar Field, TES, Power Block

CSP: Technology Basics

THERMAL ENERGY STORAGE (TES)

SOLAR ENERGY → HIGH TEMPERATURE HEAT → ELECTRICITY

HYBRIDIZATION



CSP Market Today

6 GWe Installed Capacity

80% Parabolic Trough

20% Tower

70% w/ STORAGE

Spain 2.4 GW - USA 1.9 GW

2 GWe Tendered - Under Construction

50% Parabolic Trough

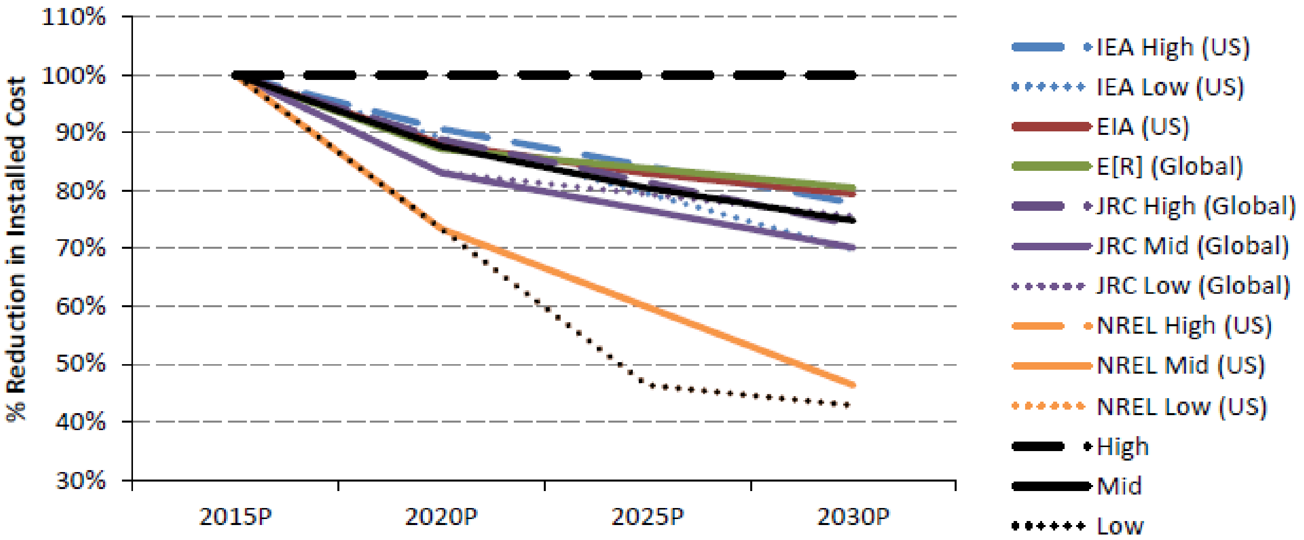
50% Tower

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:**



CSP 2030 Market Outlook and Scenarios

SOLARPACES - ESTELA *(2016)*

27 GWe — *Current policy*

130 GWe — *Moderate policy*

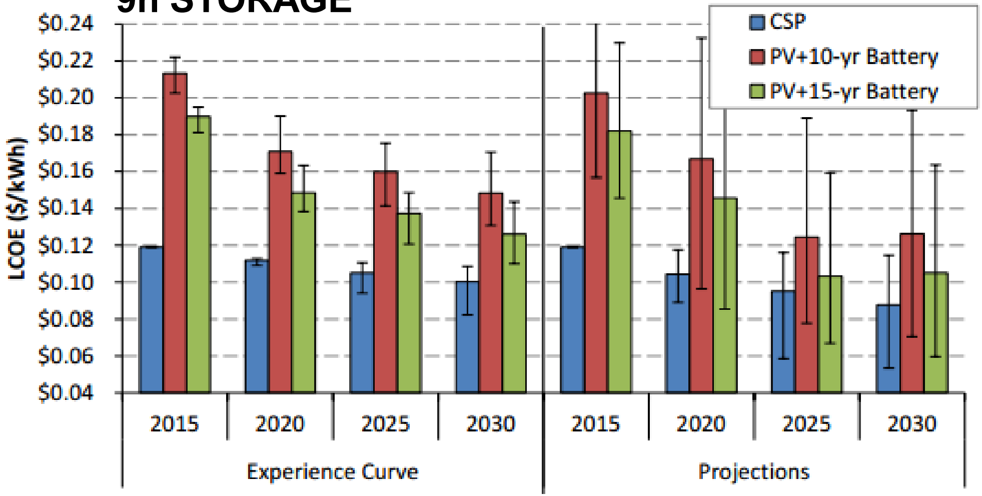
IRENA *(2014)*

87 GWe

IEA 2D *(2015)*

155 GWe

9h STORAGE



* For a 200$/kWh combined battery and battery BOS costs and increased lifetime

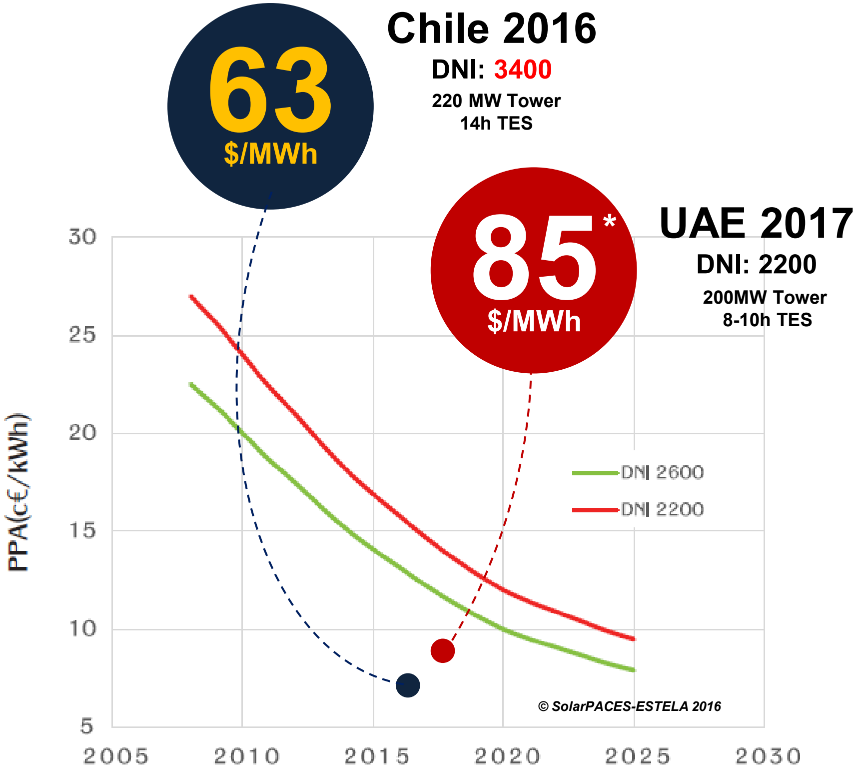
* For PV systems (module + BOS) of 1$/W

CSP Market Outlook: Prices

- CSP is generally seen as less competitive on the basis of $/MWh
- We are seeing aggresive 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

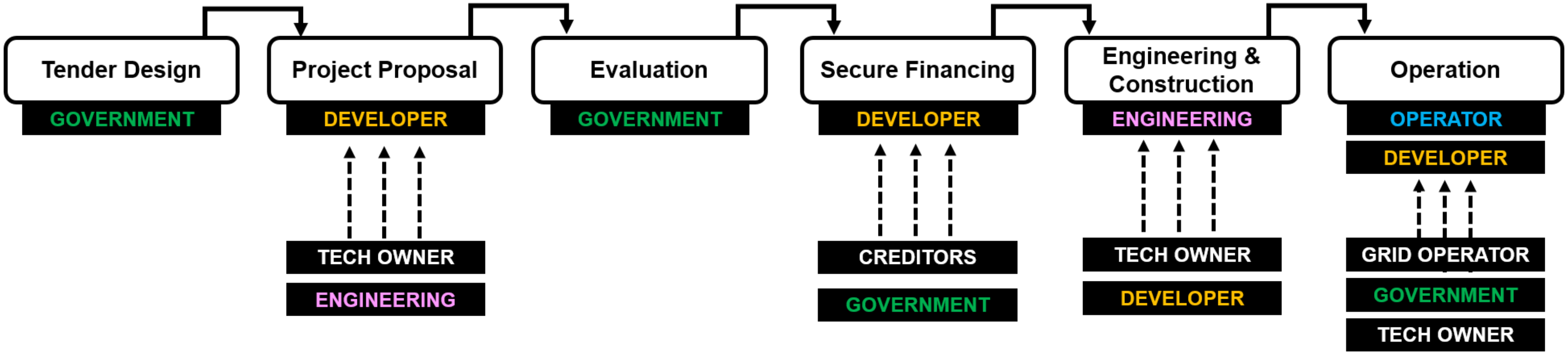


* Expected in DEWA tender

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

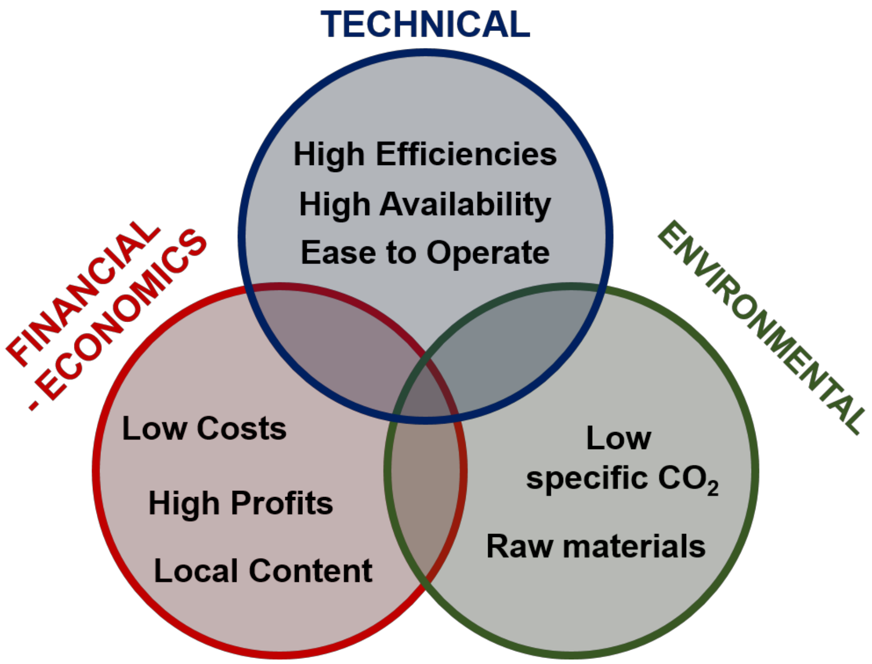
CSP Techno-economic Modeling

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



CSP Performance Indicators

TECHNICAL

Annual Yield (E_{net}) [GWh]

Capacity Factor (CF) [%]

$$\frac{Annual\ Yield}{8760\ \times Nominal\ Capacity}$$

ENVIRONMENTAL

Annual Specific CO_2 Emissions [kg CO_2/MWh]

$$\frac{Annual\ CO_2\ Emissions}{Annual\ Yield}$$

FINANCIAL (Costs)

Investment Costs (CAPEX) [$]

Annual Operational Costs (OPEX) [$/y]

CSP Performance Indicators

FINANCIAL (Performance)

Levelized Cost of Electricity [$/MWh]

$$\frac{Disc. Cash\ Outflows}{Disc. Electricity\ Generation}$$

$$LCOE = f(CAPEX, OPEX, Yield, DR)$$

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

Constant price for breakeven

Internal Rate of Return (IRR) [%]

$$IRR = DR \rightarrow NPV = 0$$

$$NPV = \begin{Bmatrix} Disc. Cash\ inflows \\ - Disc. Cash\ outflows \end{Bmatrix}$$

Project acceptable if
IRR Project > IRR min (owners)

Higher IRR project → better

CSP Performance Indicators

FINANCIAL (Performance)

Levelized Cost of Electricity [$/MWh]

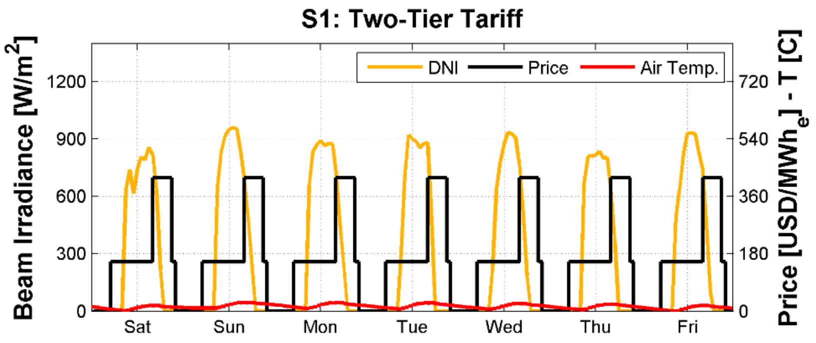
$$\frac{Disc.\,Cash\ Outflows}{Disc.\,Electricity\ Generation}$$

$$LCOE = f(CAPEX, OPEX, Yield, DR)$$

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

Constant price for breakeven

Minimum PPA Price [$/MWh]



min Price at which IRR project ≥ WACC

Different from LCOE

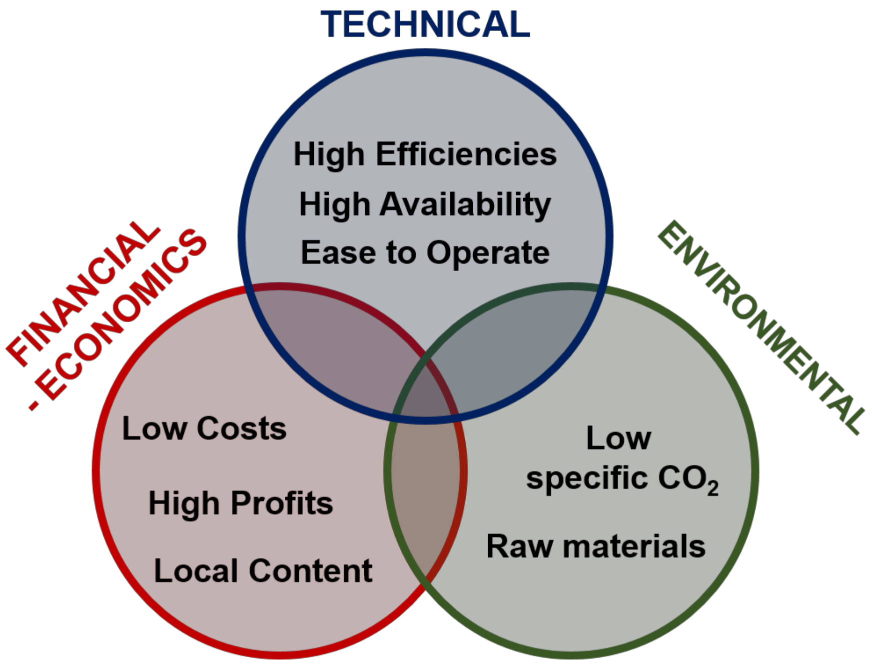
depends on hourly tariff schemes and usually public numbers relate to average or base PPA price

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



DYESOPT - Power Plant Modeling

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

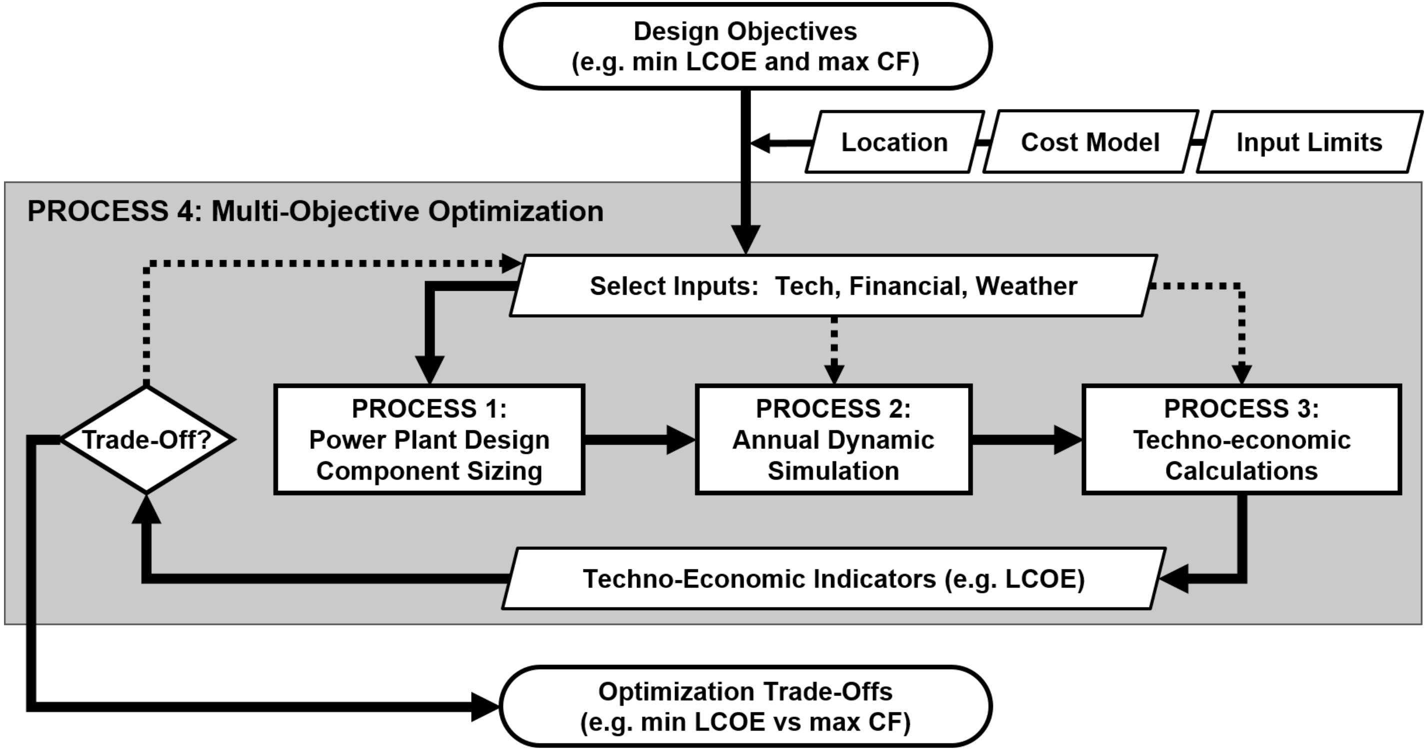
- With **+7** years of R&D in academia
- With **+30** publications as part of **+8** R&D projects with industry

DYESOPT

for power plant design and operation

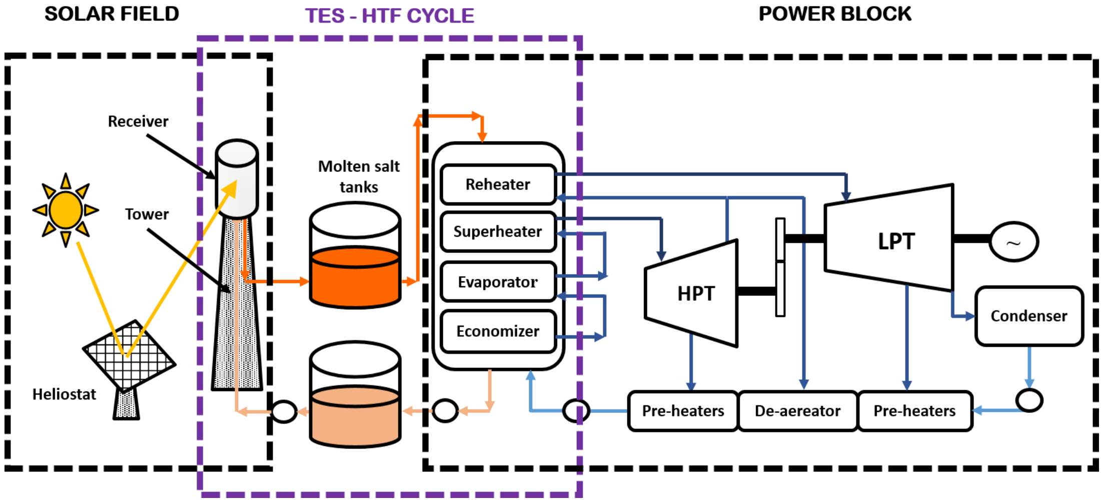
technical + financial plant performance models tailored to requested degree of detail

Power Plant Modeling in DYESOPT



Process 1: Power Plant Nominal Design

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



VALIDATED SUB-COMPONENT THERMODYNAMIC MODELS

MULTI-PARAMETER

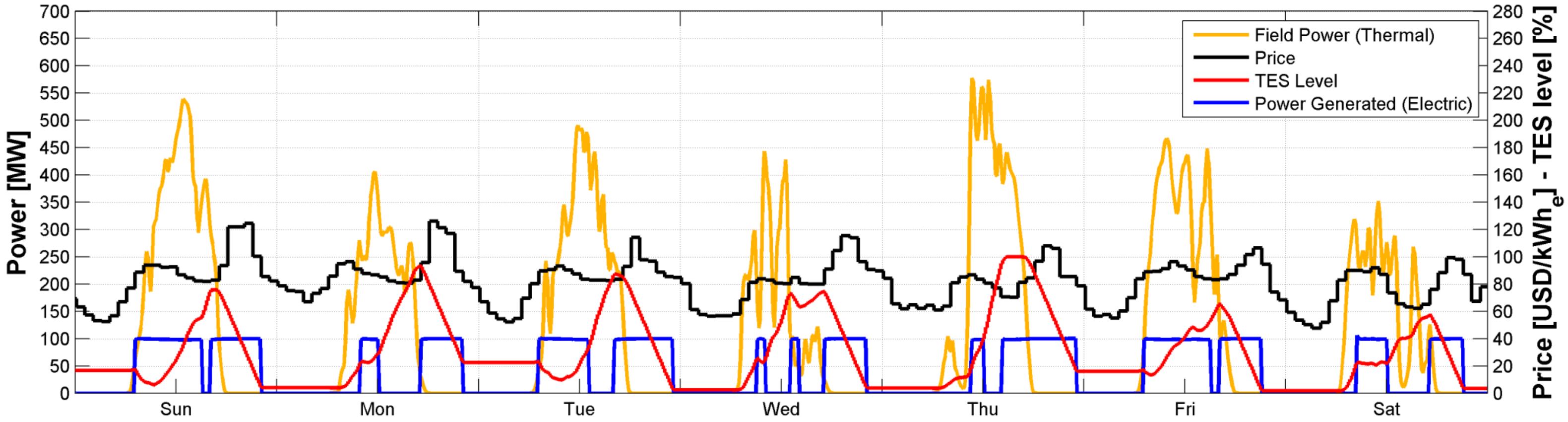
SOLAR FIELD SIZE (SM)
Mirror area / reflectivity
Receiver Rating / geometry
Tower height

TES CAPACITY
Tank specs
Loss Coefficients
Minimum tank levels

POWER BLOCK CAPACITY
Cycle Layout Design
Live steam and reheat conditions

Process 2: Annual Dynamic Simulation

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



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

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

Process 3: Techno-Economic Calculations

BOTTOM-UP COST MODEL – LOCATION AND TECH DEPENDENT

C_{PB} C_{SF} C_{TES} C_{rec} C_{site} C_{BOP} C_{tow} C_{cont} } C_{DIRECT}

$C_{DEV\text{-}EPC}$ C_{land} C_{tax} } $C_{INDIRECT}$

C_{DIRECT}, $C_{INDIRECT}$ } **CAPEX [$]**

C_{lab} C_{ser} C_{uti} C_{misc} } **OPEX [$/y]**

CAPEX, OPEX } **LCOE [$/MWh]**, **IRR [%]**

Local Economics (e.g. discount rate) ↓

LCOE [$/MWh]

IRR [%]

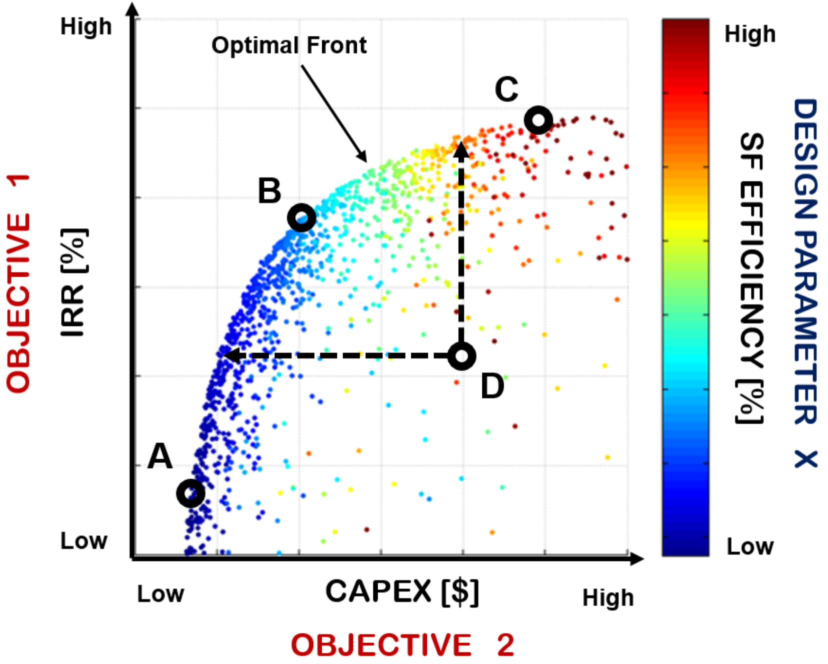
↑ **Market Conditions (e.g. electricity price)**

$$C_n = C_{ref,n}\left(X_n / X_{ref,n}\right)^{y_n}$$

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

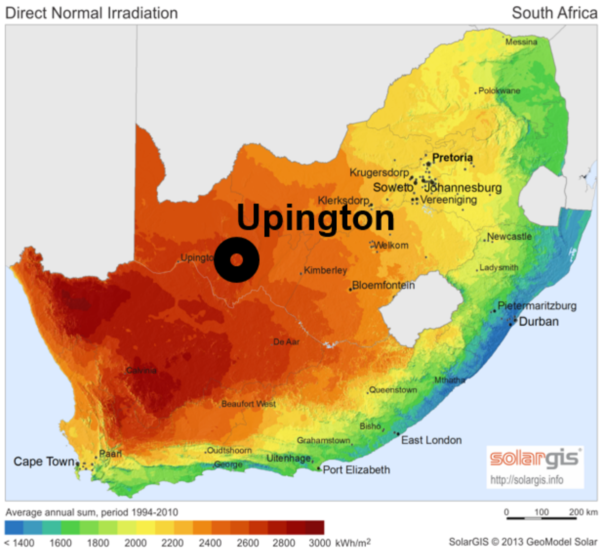
D is sub-optimal (*'naive design'*)

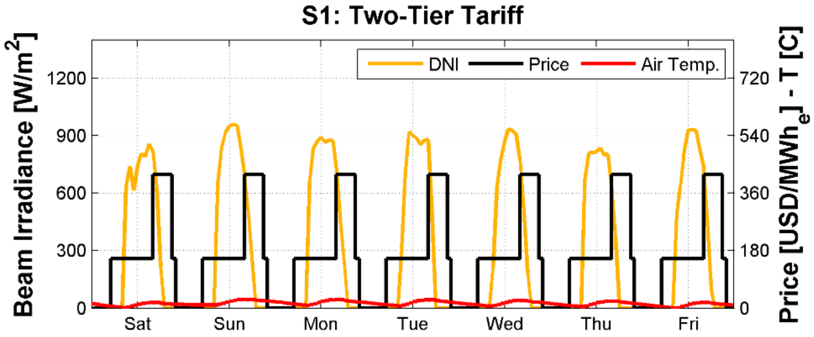
Genetic Algorithims used to address:

- Discontinuities / non-linearity
- Local optima

DYESOPT – Case study

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

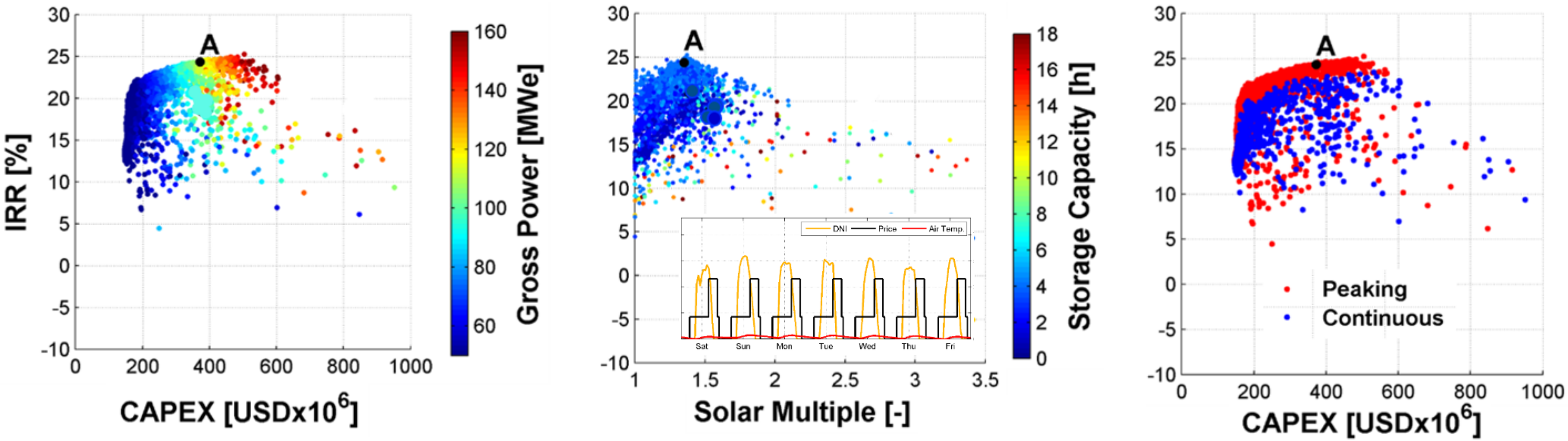




Location Data (i.e. Meteo & economics)

- Technical Reports
- Industry

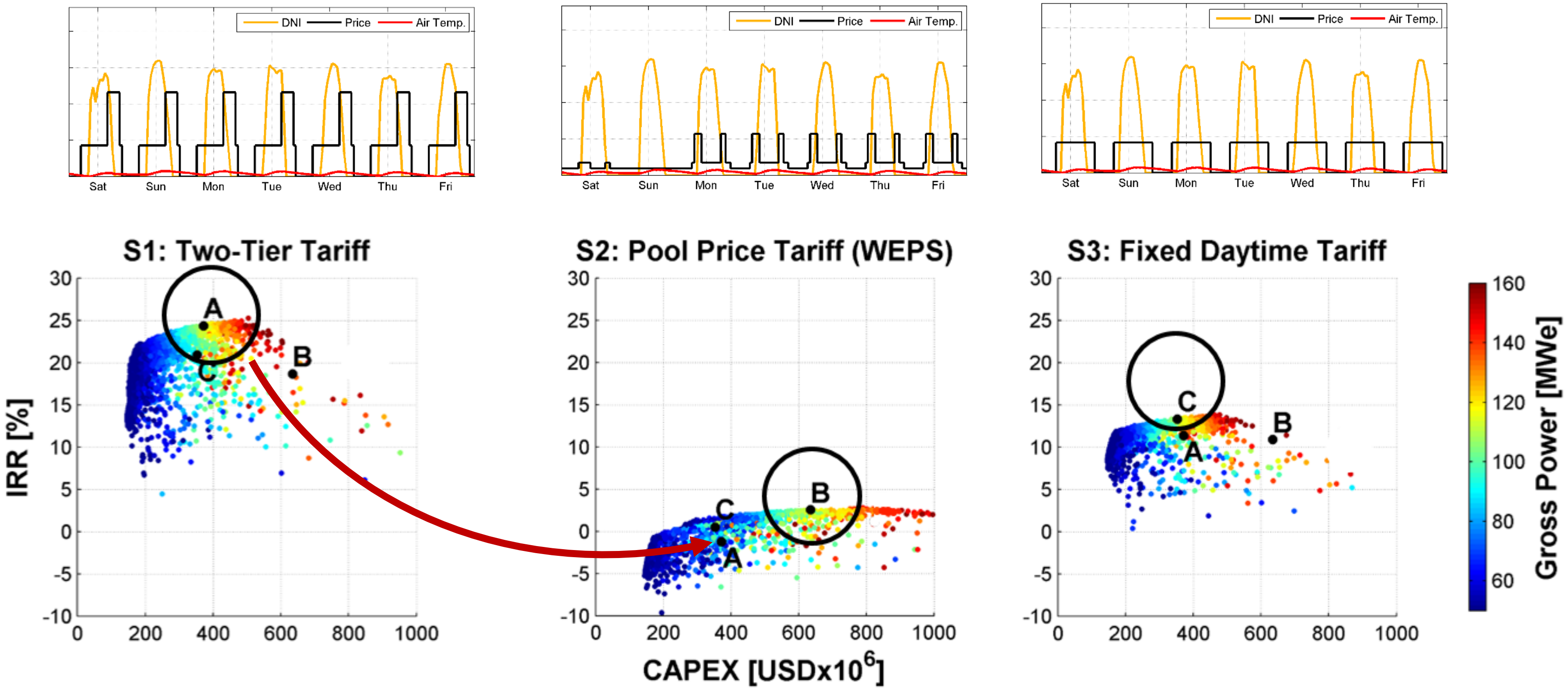
DYESOPT – Case study



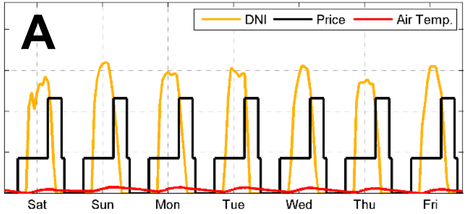
Sizing and operation of sub-blocks has a clear impact

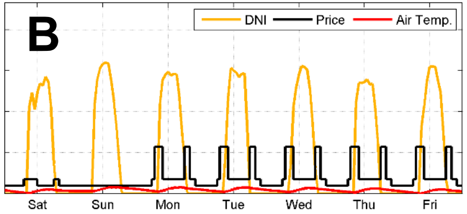
PB size, SF size, TES size and dispatch are decisive

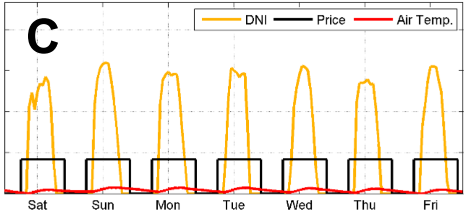
Case Study: Influence of Price Tariffs



Case Study I: Influence of Price Tariffs







	IC [MW_e]	TES [h]	SM [-]	Tower height [m]	Operating Strategy	CAPEX [USD×10⁶]	LCoE [USD/MW_e]	F_{cap} [%]	IRR [%]		
									S1	S2	S3
A	110	4	1.35	176	Peaking	371.8	106.5	38.6	24.4	-1.2	11.4
B	110	14	2.60	235	Peaking	635.0	89.4	74.6	18.7	2.6	10.9
C	110	1	1.38	186	Continuous	353.1	99.6	39.5	20.9	0.5	13.3

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

DYESOPT

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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